Real-Time Sensor Data Integration for BIM-Based Hydraulic Structure Monitoring

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Key words: BIM, SensorThings API, MQTT, digital twin, real-time monitoring, edge computing

SUMMARY

In many countries, civil engineering structures face challenges from ageing infrastructure, increased inspection and maintenance needs, while at the same time lacking effective real-time digital monitoring methods. This article focuses on hydraulic structures such as locks, weirs, and dams that are essential for waterway transportation. We introduces an advanced approach to combine real-time sensor data and Building Information Modeling (BIM), where a Common Data Environment (CDE) serves as the central environment for structuring, visualizing, and analyzing sensor-based monitoring data within a digital twin framework, improving maintenance and operational efficiency. The project employs the OGC SensorThings API (STA), an open standard for interconnecting Internet of Things (IoT) sensor devices, data, and applications, and the MQTT (Message Queuing Telemetry Transport) protocol for standardized, real-time data transmission and management. Future plans include the incorporation of GeoMQTT, a geospatial extension of MQTT that enables location-aware filtering and routing of sensor messages, to enhance geospatial and temporal data processing.

Edge computing optimizes data preprocessing at the sensor level, enabling real-time analysis while reducing data volume. The proposed system includes a linked data model that semantically connects sensor data to BIM components, enhancing decision-making and visualization. Initial tests demonstrate the feasibility of managing high-frequency data streams with low latency, offering significant improvements in the proactive maintenance of hydraulic structures. Planned enhancements include edge-level data processing and improved (Geo)MQTT message sequencing for robust, scalable, and efficient monitoring.

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1. INTRODUCTION

Inspection and maintenance are critical for ensuring the safety, reliability, and longevity of engineering structures, particularly in the face of ageing infrastructure and increasing operational demands. Engineering structures, such as locks, weirs, and dams, are indispensable for waterway transportation, serving as vital components of national and international logistics networks. In Germany, hydraulic structures are considered essential in supporting waterway transport, which is the third most important mode of transportation after road and rail. However, much of this infrastructure is ageing, with a significant proportion requiring extensive maintenance or replacement so as to ensure the reliability and safety of the structures. The challenge of maintaining these structures is further compounded by the economic impact and logistical difficulties that would probably arise during decommissioning. This could result in the interruption of entire waterways.

The conventional approach to monitoring hydraulic structures primarily relies on on-site inspections and manual evaluation, which are labor-intensive and insufficient for providing near-real-time insights into the structural health. Current monitoring systems lack the capability for automated transmission, and targeted use of recorded monitoring data, resulting in delays and inefficiencies. This poses a risk to the continued operation of hydraulic structures, as the data collected from these inspections is often available only in a reduced form, limiting a comprehensive understanding of the current structural condition.

To address these challenges, this paper proposes a BIM-based digital twin framework for real-time monitoring of hydraulic structures, where a CDE connected to a PostgreSQL database, functions as the core data integration system, linking sensor data with structural elements of a BIM model for automated processing and analysis. This framework continuously updates a virtual model of building structures using real-time sensor data, enabling automated detection, predictive maintenance, and efficient decision-making (Herlé et al., 2024). The main objectives of this work are to develop a practical, real-time data integration approach leveraging IoT and geospatial technologies, establish a direct connection between sensor metadata and BIM components to improve decision-making, and evaluate the system's ability to support predictive maintenance and reduce downtime.

The proposed system integrates edge computing, real-time data transmission, and a linked data model to seamlessly connect sensor metadata with structural elements of a BIM model within a web-based BIM environment. This approach enhances maintenance planning, infrastructure longevity, and operational efficiency of hydraulic structures.

2. PROJECT BIMxD BUILDING MONITORING

In the research project BIMxD Building Monitoring, funded by the Zentrales Innovationsprogramm Mittelstand (ZIM) – Central Innovation Program for Small and Medium-sized Enterprises (SMEs), a consortium of partners from academia and industry is developing an advanced, BIM-based monitoring system for hydraulic structures. This project combines real-time sensor data with BIM models, forming a Digital Twin for predictive maintenance and proactive infrastructure management.

The project is being conducted in collaboration with several key partners, including the SMEs Gewecke and Partner Consulting Engineers GmbH (Gewecke and Partner), WTM Engineers GmbH (WTM) and from RWTH Aachen University the Chair of Building Informatics and Geoinformation Systems and Geodetic Institute (gia) and the Institute of Hydraulic Engineering and Water Resources Management (IWW).

To ensure accurate evaluation of the monitoring data, a comprehensive description of the structural behavior of the hydraulic structure (e.g., dams, dikes, weirs, locks) is required. The IWW is developing a scaled demonstrator of the reference structure along with a digital representation for analysis. Throughout the project, various investigations, including load experiments, will be conducted on the demonstrator. These experiments simulate different load scenarios to analyze structural behavior. Both practical load tests on the physical demonstrator and theoretical simulations on the digital twin will be carried out. The theoretical simulations will allow for testing extreme scenarios (e.g., high pressures, flow velocities, and water levels) that cannot be physically replicated in the lab.

As part of the project, our institute (gia) is developing a comprehensive sensor and BIM data infrastructure, which plays a critical role in handling sensor data through various stages. This includes the creation of a catalog of requirements for data acquisition and data stream transmission, along with the development of algorithms for data preprocessing using edge computing, such as filtering and aggregation algorithms, to detect and correct data errors while removing irrelevant data like outliers or redundant values. These preprocessing steps reduce the data volume, allowing real-time transmission and faster, more efficient analysis.

Our work also includes designing a sensor data storage structure and developing a data management module that prepares monitoring data in a BIM-compatible format. This ensures seamless integration of monitoring data into the BIM environment. Additionally, our institute is responsible for developing web interfaces and ensuring that monitoring data can be transmitted and retrieved efficiently via real-time data management systems. The ultimate goal is to enable the continuous linkage of sensor and BIM data models, facilitating real-time monitoring and analysis.

The final software package will integrate both the evaluation module and the data management module into a BIM software extension. This extension, developed in collaboration with WTM Engineers, will serve as the key interface for real-time building monitoring. The integration will support automatic attribution of sensor data within the BIM model, allowing for continuous and accurate insights into the structural health of hydraulic structures. These insights will be visualized in user-specific formats, ensuring accessibility for both experts and non-experts.

3. STATE OF THE ART

This section provides an overview of the state-of-the-art techniques employed in the project.

3.1 Building Information Modeling (BIM) and Digital Twins

BIM is a comprehensive digital method for planning, executing, and managing buildings. In a narrower sense, it refers to the creation and utilization of a detailed digital representation of a building. This model includes all relevant data such as geometry, semantics, and relationships, making it accessible for evaluation by various stakeholders. With the help of software, stakeholders can model and store building data, allowing for collaborative analysis and decision-making throughout the building's life cycle. In addition to its traditional application for new construction, BIM has evolved to support maintenance, retrofitting, and facility management, especially for existing buildings (Volk et al., 2014). Recent innovations, such as scan-to-BIM processes (Bosché et al., 2015), are addressing the challenges posed by incomplete or outdated building documentation, which is common in older structures. For supporting the information exchange, BIM utilizes the CDE as digital collaboration platforms, which contain viewers, model checking tools and other useful analysis tools in addition to the ability to manage and version data (Preidel et al. 2018). Industry Foundation Classes (IFC) are a fundamental component in achieving interoperability within BIM processes. Developed by the buildingSMART initiative (Industry Foundation Classes, 2024), IFC is an open, vendor-neutral data format that facilitates the seamless exchange of information between various software applications used in architecture, engineering, and construction (AEC) industries. By ensuring that BIM data is compatible across different platforms, IFC enhances collaboration among project stakeholders, including architects, engineers, contractors, and facility managers (Yu et al., 2023).

Recent advancements in digital twin technology are transforming the way the built environment is managed and optimized. Digital twins, often powered by hypermedia-driven RESTful APIs, provide real-time synchronization between physical buildings and their digital counterparts, facilitating continuous monitoring and data exchange (Herlé and Blankenbach, 2024). In the context of building services engineering, digital twins integrated with BIM are used to automate processes such as commissioning, which traditionally involved manual oversight and extensive coordination between different stakeholders (Becker et al., 2022). These BIM-enabled digital twins enhance decision-making by providing detailed, georeferenced models that not only represent building geometry but also integrate energy systems and other building services for optimized performance (Blut et al., 2024). Additionally, for infrastructure projects like road construction, concepts such as "level of as-is detail" (LOAD) are being developed to ensure that digital twins accurately reflect existing conditions, improving the precision of infrastructure maintenance and upgrades (Crampen and Blankenbach, 2023). Together, these innovations demonstrate the growing role of digital twins in enhancing both building operations and infrastructure management.

3.2 Sensor Data Storage and Providing

Sensor data storage and providing should be done in a as far as possible standardized way. The Open Geospatial Consortium (OGC)[1] developed the Sensor Observation Service (SOS)[2] based on the Observations and Measurements standard (O&M)[3]. It has been published in 2012 (Bröring, Stasch and Echterhoff, 2012). It defines a web service interface, which allows querying observations, sensor metadata and representations of observed features. It defines means to register new sensors and remove obsolete sensors. The interface is realized by using the Simple Object Access Protocol (SOAP)[4]. The data itself is encoded in the Extensible Markup Language (XML)[5]. SOS offers at least three service operations: GetCapabilities, GetObservation and DescribeSensor, whereas the first will retrieve a description of SOS itself, describe further operations (if available) and state what kind of measurements are recorded. The second will retrieve specific observations and their metadata. The third gives explicit information about a sensor, e.g. measurement parameters etc. (van Der Schaaf et al., 2020).

The OGC SensorThings API (STA[6]) is an open standard developed by the OGC to address the growing need for seamless communication and management of sensor data in the Internet of Things (IoT) ecosystem. With billions of sensors producing vast amounts of data, there is a need for a uniform, accessible way to handle diverse sensor inputs, manage metadata, and ensure data interoperability across platforms. STA employs a REST[7]-based architecture, which provides a lightweight and scalable approach, well-suited for the heterogeneous nature of IoT (van Der Schaaf et al., 2020).

The core of the STA is its well-structured data model (Fig. 1), which organizes sensor data into eight main entity types: *Things*, *Locations*, *HistoricalLocations*, *Datastreams*, *Sensors*, *ObservedProperties*, *Observations*, and *Features of Interest* (Liang et al., 2021):

- *Thing* represents any object that can be observed or controlled, like a weather station or a smart device.
- *Location* captures the geographic or physical location of a Thing.
- *HistoricalLocations* stores the location history of a Thing. It tracks changes in the geospatial position over time.
- *Sensor* describes the sensing device used to collect observations, including its type and properties.
- *Datastream* links a Thing to its observations by representing a continuous flow of data produced by the sensor.
- *Observation* stores the actual data point collected by the sensor at a specific time.
- *ObservedProperty* defines the phenomenon being measured, such as temperature, humidity, or pressure.
- *Feature of Interest* specifies the real-world entity or spatial region relevant to the observation.

[1] https://www.ogc.org/
[2] https://www.ogc.org/publications/standard/sos/
[3] https://www.ogc.org/publications/standard/om/
[4] http://www.opengis.net/doc/is/pubsub-soap/1.0
[5] https://www.w3.org/XML/
[6] https://www.ogc.org/publications/standard/sensorthings/
[7] https://restfulapi.net/

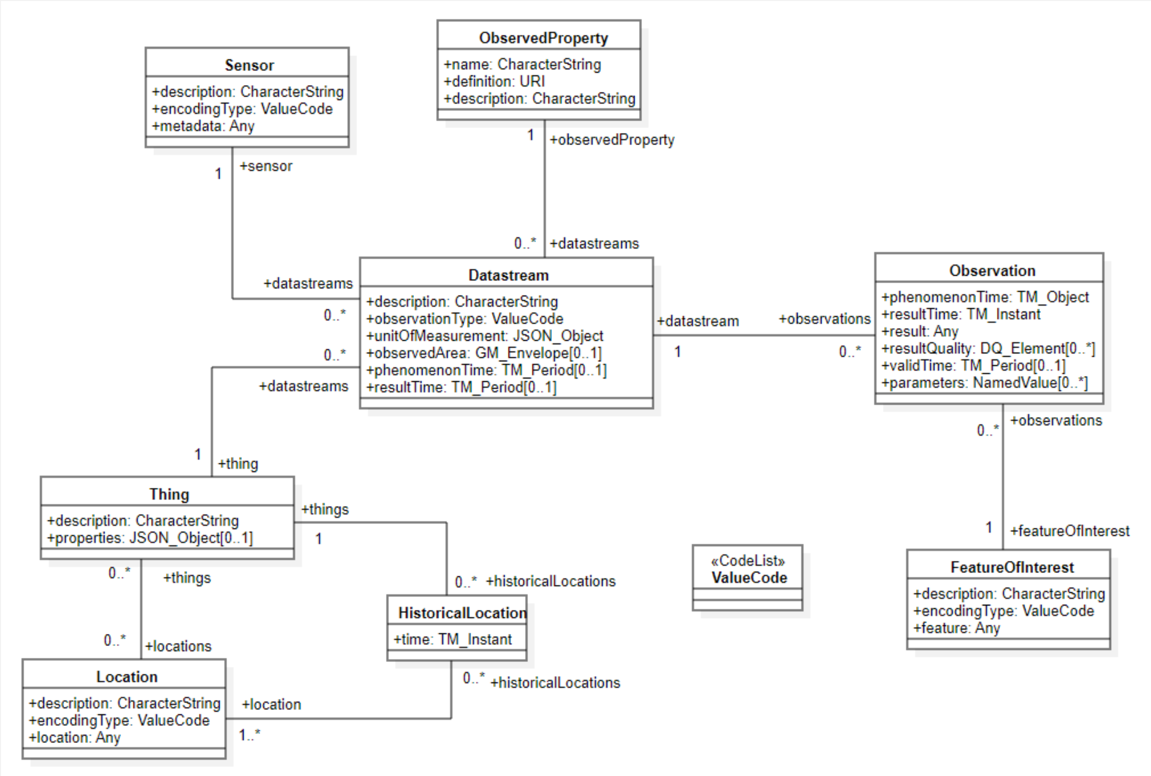

Fig. 1: The STA Data Model (Source: (Liang et al., 2021))

Each of these entities is accessed via RESTful URLs, and they are interconnected, allowing for efficient data querying and management. For example, a *Thing* can have multiple associated Datastreams, each of which records observations over time. Relationships between these entities are defined through unique identifiers and self-links in the API's JSON response format. The ability to filter, sort, and paginate results provides further flexibility, allowing users to retrieve only the specific data they need, minimizing unnecessary data transfer and improving performance.

Moreover, STA supports real-time push notifications via Message Queuing Telemetry Transport (MQTT)[8] or WebSocket[9], allowing clients to be notified immediately of any changes in the data without having to continuously poll the server. This feature is particularly useful in dynamic IoT environments, where timely updates are crucial for decision-making.

Future work will focus on expanding the *Tasking* part of the API, which allows users to control and interact with actuators or trigger on-demand processing. This will enable a new range of functionalities, such as starting algorithms based on user-defined conditions rather than incoming data, further enhancing the versatility of the STA in real-world applications.

[8] https://mqtt.org/
[9] https://websocket.org/

3.3 Message Queuing Telemetry Transport (MQTT)

The IoT allows for convenient monitoring and retrieval of sensor data via the Internet (Zanella et al., 2014). With the increasing demand for high-quality, real-time data monitoring and acquisition, particularly in smart cities, selecting an efficient communication protocol is critical to meeting these requirements. In this context, our project utilizes MQTT as the communication protocol of choice for IoT applications (Atmoko et al., 2017). MQTT, a lightweight protocol designed for *machine-to-machine* communication, is particularly well-suited for IoT environments. In this project, turbidity and pressure sensors have been selected due to their relevance in monitoring environmental conditions, and the collected data was stored in a PostgreSQL database for real-time acquisition. The use of MQTT in this system led to improved data quality and reliability.

While protocols like Hypertext Transfer Protocol (HTTP) are commonly used for web-based data exchange, they rely on a request/response model that is less efficient for IoT applications, particularly those that require constant data streaming from multiple sensors. MQTT, on the other hand, operates on a publish/subscribe model (Lampkin et al., 2012), which is more efficient for IoT because it minimizes overhead and allows for asynchronous communication. This makes it ideal for applications where devices need to exchange data with minimal power consumption and latency.

MQTT runs on TCP/IP and has very low packet overhead (as little as 2 bytes), making it highly energy-efficient (Atmoko et al., 2017). Unlike the traditional client-server model, MQTT employs a broker to manage communication between publishers (data senders) and subscribers (data receivers), allowing them to remain decoupled and operate independently. This decoupling also enables delayed message delivery, ensuring that clients can still receive data even if they are not connected at the time of transmission. MQTT is particularly advantageous due to its lightweight nature, which makes it ideal for low-bandwidth networks and resource-constrained devices. This makes MQTT especially well-suited for our devices operating over Wi-Fi, where bandwidth efficiency and power consumption are critical considerations. Its ability to function smoothly on limited network resources while providing reliable communication ensures that MQTT is a fitting choice for environments where stable and low-latency data transmission is crucial for effective sensor data monitoring.

Building on MQTT's lightweight and efficient framework, a geospatial extension, GeoMQTT[10], has been developed to integrate temporal and spatial metadata directly into the protocol. This extension introduces a new publish message type, the GeoPublish message, which incorporates timestamps and coordinates alongside the topic name.

GeoMQTT also enhances subscription filtering by enabling clients to define temporal intervals and spatial areas through GeoSubscribe messages, in combination with the MQTT topic filter. The broker forwards messages only if all specified criteria—topic, time, and location—are met. These enhancements make GeoMQTT well-suited for applications requiring precise event filtering, improving both efficiency and relevance in data delivery (Herle and Blankenbach, 2016).

[10] https://www.geomqtt.org/

3.4 Linked Data Model for Sensor-BIM Integration

Recent advances in semantic web technologies and linked data principles have significantly improved the integration of IoT sensor data with BIM models. These approaches leverage ontologies, such as the Semantic Sensor Network (SSN)[11] and Sensor, Observation, Sample, and Actuator (SOSA)[12], to describe sensor metadata and observations. By utilizing standards like the Web Ontology Language (OWL)[13] and Resource Description Framework (RDF)[14], these methods enable semantic connections and interoperability between disparate data sources. However, challenges persist in achieving seamless attribution of sensor data to BIM components for accurate visualization and analysis. This work addresses these challenges by developing a tailored linked data model.

3.5 Structural Monitoring

Structural monitoring systems use sensors to assess the condition of structures, modernizing traditional inspections. Customized for each structure, they track parameters like deformation, displacement, temperature, crack width, and vibrations, with additional indicators like air quality in specific cases. While effective for early issue detection and predictive maintenance, these systems are not yet substitutes for on-site inspections in Germany. Limited deployment and manual data evaluation restrict real-time responsiveness. Innovations like edge computing on platforms such as Arduino[15] improve real-time processing, enabling more efficient and autonomous monitoring of building conditions. To enhance visualization and data accessibility, the BIM software DESITE md pro, extended by WTM, functions as a CDE, providing interactive BIM model viewing and sensor integration.

4. DEVELOPMENT

Within this project, gia focuses on the integration of real-time sensor data with STA, utilizing MQTT as the communication protocol. This integration aims to ensure efficient data transmission, data storage, and data provision to create a seamless link between the sensors deployed in the field and the BIM environment for data visualization and analysis. While the hardware and software development is still ongoing, some tests have already been conducted.

4.1 Data Flow Architecture

A robust data flow architecture (Fig. 2) has been developed based on STA and MQTT.

[11] https://www.w3.org/TR/vocab-ssn/
[12] https://www.w3.org/ns/sosa/
[13] https://www.w3.org/OWL/
[14] https://www.w3.org/RDF/
[15] https://www.arduino.cc/

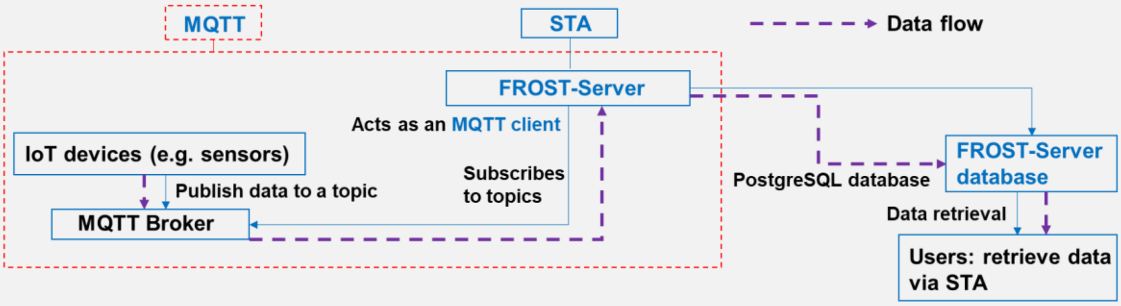

Fig. 2: Developed data flow based on STA and MQTT

The figure illustrates the data flow architecture for real-time sensor data transmission, storage, and retrieval within the monitoring system. At the core of this system is the FROST Server[16], an implementation of STA, which serves as the main database and processing hub for sensor data. Sensor data is collected and transmitted to the system via MQTT. The data flows from MQTT to STA, which provides a standardized framework for managing and accessing sensor observations and metadata.
The FROST Server acts as an intermediary, receiving data from the MQTT client, storing it, and ensuring it's accessible through STA. This setup enables efficient data storage and retrieval, supporting both live data streaming and historical data queries in the database. Users can access specific observations stored in the FROST Server's database through dedicated endpoints, such as the example link shown at the bottom of the figure. This endpoint allows direct access to an individual observation based on its unique identifier, facilitating precise data queries and retrieval. The system's architecture ensures robust, real-time data visualization and analysis, bridging the field-deployed sensors and the BIM environment. MQTT protocol is employed for real-time data transmission due to its lightweight and efficient publish/subscribe model. This architecture allows for flexible handling of high-frequency sensor data from various sources, ensuring minimal latency and low network load. This architecture allows for flexible handling of sensor data from various sources. STA organizes the sensor data into well-defined entities such as *Things*, *Datastreams*, and *Observations*. This structured approach allows for a seamless flow of information from the physical sensors to the digital twin within the BIM environment.

4.2 Data Acquisition and Data Stream Transmission

The data acquisition and transmission process was further optimized by transitioning from a Python application on a measuring computer to an application on a physical computing platform. This optimization offers several advantages:

1. The sensors used can be directly connected to the physical computing platform and integrated into the data preprocessing module.
2. A physical computing platform is significantly smaller and consumes much less energy compared to the measuring computer. This makes it suitable for deployment in large-scale environments, such as dyke bodies, where multiple data preprocessing modules can be directly attached to the sensors.

[16] https://github.com/FraunhoferIOSB/FROST-Server

3. The need to transfer measurement data to a separate preprocessing module is eliminated, streamlining the data acquisition process.

The functionality of the optimized data preprocessing module is illustrated schematically in Fig. 3 (left). For this implementation, an Arduino UNO R4 WiFi was utilized as physical computing platform, which provides the required connectivity options for controlling the pressure and turbidity sensors. The sensor connections are depicted schematically in Fig. 3 (right).

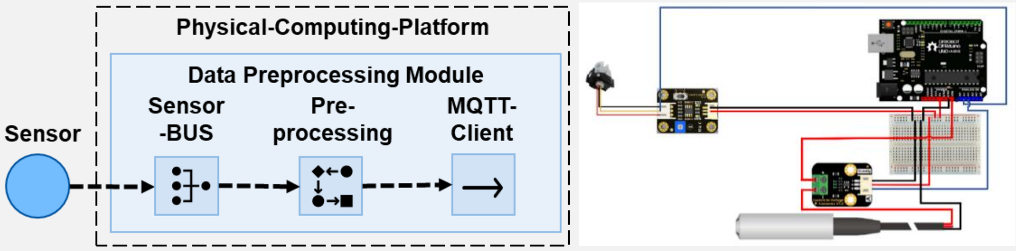

Fig. 3: Schematic representation of the further developed data preprocessing module on a physical computing platform (left), Schematic representation of the connection of a pressure and a turbidity sensor to an Arduino UNO R4 WiFi (right)

4.2 Sensor Data Storage and Providing

Efficient sensor data storage and retrieval are critical components in managing and querying large volumes of measurement data in this project. The implementation leverages STA (Fig. 4). The adoption of STA improves interoperability and scalability, making it ideal for handling heterogeneous sensor data while enabling seamless integration with existing systems.

As described earlier, measurement data is transmitted from the data preprocessing module via the MQTT protocol. The data management module, which includes the storage unit, provides a dedicated interface to connect with the data preprocessing module. Within the data management module, an MQTT broker facilitates this connection by receiving the data transmitted by the MQTT client in the preprocessing module.

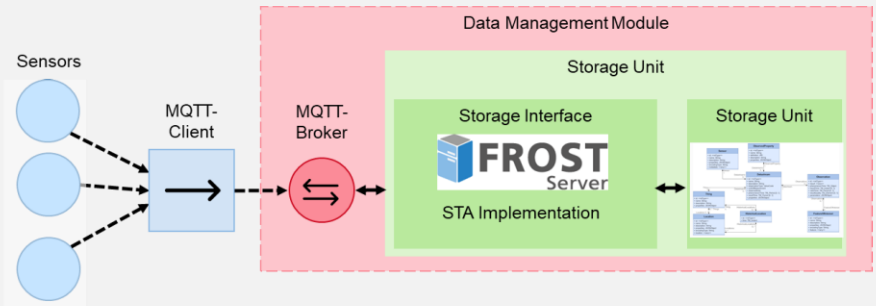

Fig. 4 Schematic representation of the data management module with MQTT broker for connecting the sensors.

The MQTT broker, integrated into the FROST Server, plays a pivotal role by transferring the incoming data to the storage unit, ensuring efficient and reliable data storage. This architecture not only optimizes data flow but also simplifies the management of sensor-generated data.

The API enables efficient querying of real-time sensor data, allowing users to monitor structural health, track sensor performance, and generate alerts when thresholds are exceeded. The standardized API architecture also ensures that the system can scale to accommodate additional sensors and data streams as needed.

4.3 Linked Data Model for the Semantic Link Between Sensor and BIM Data Model

To ensure accurate attribution, a linked data model was developed, establishing a semantic connection between sensor data and structural elements in the BIM model for precise visualization and analysis (Fig. 5). Sensor metadata, including type, functionality, and spatial location, is stored in STA database instead of embedding it directly into the BIM model. This ensures consistency with sensor measurement data and creates a centralized *single source of truth*.

The linked data model uses semantic web technologies to connect sensor metadata to BIM elements. Sensor metadata is transformed into RDF format and linked to BIM components. Fig. 5 illustrates this process, where the metadata is represented as globally unique identifiers (GlobalIDs) to enable interoperability and scalability.

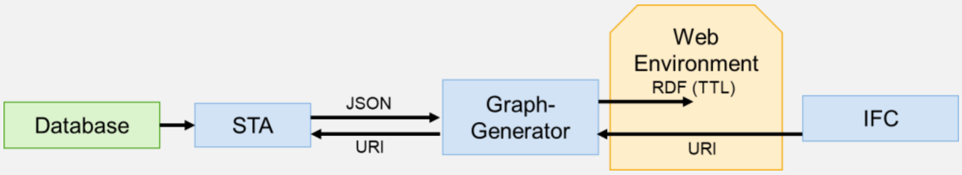

Fig. 5: Schematic representation of the link levels for the integration of sensor metadata between IFC and database.

5. TEST AT DEMONSTRATOR DIKE

The described sensor system has been deployed on a scaled demonstrator dike at IWW (Fig. 6(a) and Fig. 6(b)) to validate the implemented developments under controlled yet realistic conditions. The demonstrator dike serves as a scaled-down physical model, enabling the simulation of various hydraulic and structural scenarios while closely monitoring sensor performance. A corresponding 3D BIM model of the dike has been created for structural analysis and visualization, facilitating sensor data integration. Sensors installed on the demonstrator dike continuously collect real-time measurements of pore water pressure and other relevant parameters, which are transmitted to the STA database via the MQTT-based data flow architecture and visualized in DESITE md pro. The system generates continuous sensor data streams and BIM-integrated visualizations, providing engineers with dynamic insights into structural conditions. Additionally, the system ensures efficient data transmission, structured storage, and seamless accessibility for further analysis. The deployment at the demonstrator dike successfully validated the sensor-BIM integration, demonstrating its capability to support real-time monitoring and proactive infrastructure management.

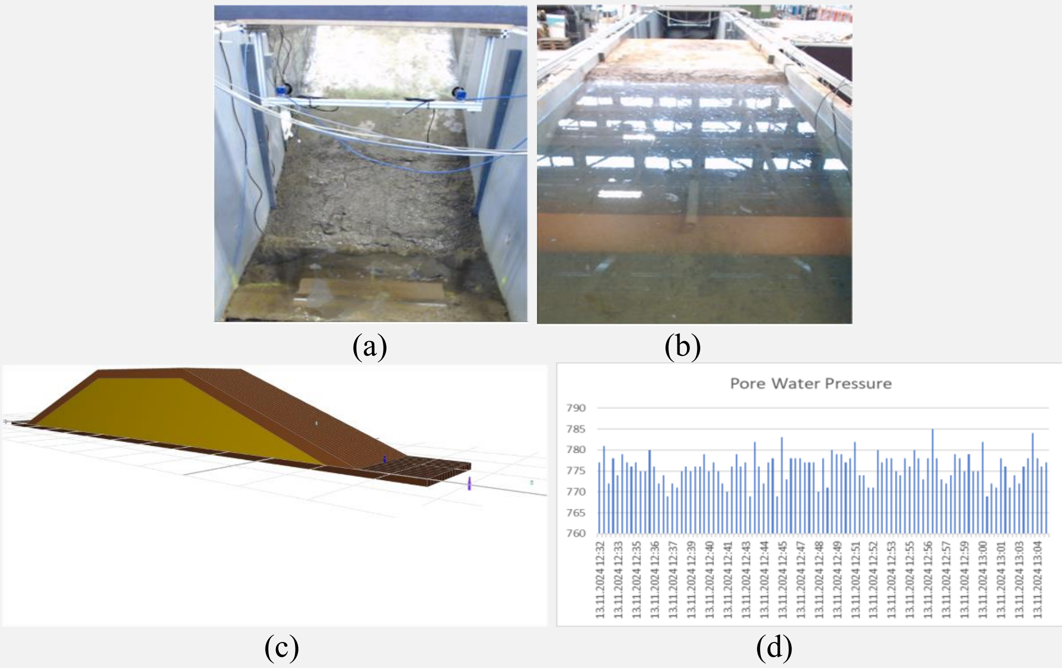

Fig. 6: (a) Land side of the scaled demonstrator dike. (b) Water side of the demonstrator dike. (c) 3D BIM model of the demonstrator dike. (d) Pore water pressure data (units: V/204,8).

As shown in Fig. 7, the linked data model enables seamless integration of sensor data, connecting BIM and sensor metadata. When a user selects a sensor in the BIM model, the system identifies its corresponding metadata using the GlobalID. This triggers a query to the database, returning details such as the sensor description and linked properties. A URL pointing to the sensor's semantically-enriched description in SSN/SOSA format is included in the response. For instance, the sensor *Porenwasserdrucksensor_1585* is described as hosting a pressure sensor, with metadata structured in RDF. This semantic framework provides a formal structure for sensor data, enabling further analysis and workflows.

The deployment at the demonstrator dike validated the effectiveness of the linked data model in providing accurate sensor-BIM integration. The system successfully facilitated interactive exploration of sensor metadata, proving its capability to enhance structural monitoring workflows and decision-making processes.

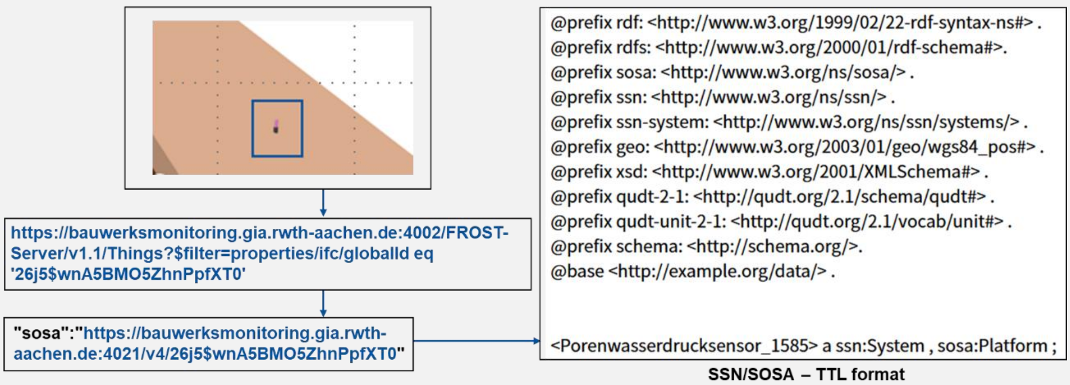

Fig. 7: An excerpt of developed linked data model

6. CONCLUSION AND OUTLOOK

The described developments and implementations present a real-time monitoring approach for hydraulic structures. Sensor data is transmitted, stored, and provided using standardized IoT and OGC frameworks. The linked data model enables seamless integration between sensor data and BIM components, facilitating the digital twinning of building structures. This approach enhances structural maintenance by automating data collection, processing, and visualization, ensuring that critical information remains accessible to stakeholders. By leveraging STA and MQTT for real-time data transmission, the system supports continuous monitoring and enables proactive maintenance decisions. The primary outputs include continuous sensor data streams and BIM-integrated visualizations. Initial tests confirm the system's capability to efficiently process high-frequency data streams with low latency, highlighting its capability to enhance operational safety and optimize infrastructure management.

Looking forward, several enhancements are planned to further optimize the system and expand its capabilities. One critical area of improvement is ensuring the correct sequence of message reception when using MQTT. As MQTT operates on a publish/subscribe model, there is a need to implement mechanisms that guarantee message order is preserved, especially when dealing with high-frequency data streams from multiple sensors. This will enhance the reliability and accuracy of real-time monitoring, ensuring that the data is processed in the correct temporal sequence. Additionally, GeoMQTT is expected to be utilized to enhance the system's capabilities by enabling geospatial and temporal filtering, allowing clients to receive only data relevant to specific timeframes or locations. Another area of development is the addition of extra MQTT layers specifically for data processing at the edge. By introducing these layers, the system can perform more advanced processing tasks directly on the data stream before it is transmitted. This form of edge computing allows for tasks such as data filtering, aggregation, or compression to be handled locally, reducing the overall data load and improving processing efficiency. The planned improvements will significantly enhance the system's robustness, efficiency, and adaptability, allowing it to meet the evolving demands of real-time structural health monitoring and data-driven decision-making.

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