Towards Automated Pipelines for Processing Load Test Data on a HS Railway Bridge in Spain using a Digital Twin

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Abstract –

This document presents an automated pipeline to process sensor-based data produced during load tests on digitally twinned HS railway bridges. The research is developed within the frame of the H2020 European project ASHVIN, related to Assistants for Healthy, Safe, and Productive Virtual Construction, Design, Operation & Maintenance using Digital Twins. The pipeline is developed within a digital twin application based on event-driven microservices, which integrates the ASHVIN IoT platform, the IFC building information model and an array of services dedicated to automating processes performed during the operation stage of structural assets. A load test carried out on a bridge located on a HS railway in Spain is used as a demonstrator.

Keywords –

Digital Twin; IoT; Load Tests; BIM; Automated Pipeline; Data processing; Event-based Microservice Architecture

1 Introduction

Digital twins are cyber-physical systems able to accurately track the behavior of built assets. In addition, these information constructs are called to accurately represent all relevant processes during their design, construction, and operation stages. A seamless two-way information flow is established between the real and the virtual realms. This is enabled by developing workflows based on novel technologies that are nowadays flourishing within the AECO industry (Architecture, Engineering, Construction, and Operation, namely, Building Information Modelling (BIM), the Internet of Things (IoT), Simulation and Decision-Making services.

BIM models offer high fidelity representations of all components of a project, containing both, geometrical and semantic information, that allow to manage costs, schedules, and processes from a single source of truth, enhancing collaboration among stakeholders [1]. Extensive research has been dedicated to BIM for the design and construction stages of built assets, however, BIM for operation and facility management is still in its early stage. The value of BIM during this stage of the asset's lifetime is highly dependent on real-time updates of its status. Presently, AEC industry digitalization is conceiving BIM-enabled cyber-physical systems [2]: physical assets are continuously monitored, fusing information from different sources and in multiple formats with virtual models into digital twin environments. Therefore, interoperability among information sources is a key challenge if comprehensive digital twins are expected as a solution. IoT provides the technology stack that enables interoperability, interconnecting models, stakeholders, physical assets, external applications, and other virtual representations, to facilitate the development of intelligent services with self-configuring capabilities [3]. However, there is a lack of studies describing the development of applications based on the digital twin concept for practical implementation in tasks related to civil and structural engineering. Thus, digital twin architectures and development methodologies need to be stablished.

In this paper, a case study is presented, where a digital twin application is developed to process data gathered during load tests on HS railway bridges in an automated fashion. Load tests on bridges are needed, repeatable and prone to standardize operations that represent the pivots on which the structure turns from construction to the operation stage. Therefore, automation could largely benefit stakeholders who perform this type of assessment, reducing considerably labor times and, thus, increasing productivity while reducing costs. To this end, an automated pipeline is assembled into a digital twin framework, involving users, BIM, sensors, databases, and data processing modules.

The study is developed within the framework of ASHVIN project, which is related to Assistants for Healthy, Safe, and Productive Virtual Construction, Design, Operation & Maintenance, using Digital Twins. The project provides a series of demonstrators for each scenario, including bridges, buildings, and industrial facilities. This case study is developed on a high-speed railway bridge, located in Spain. The pipeline will perform according to National standards, and results will be stored into an interoperable environment, facilitating data access to users and external applications. This will set off the development towards the full digitalization of load tests in high-speed railway bridges, providing the initial status of the structure for a digitally twinned operation and maintenance of this type of asset.

2 Description of the case study

In this chapter, the context for the development of the pipeline is described, that is, the bridge and the load test.

2.1 The bridge

The viaduct, called La Plata, is part of the Spanish national high-speed railway network. The network is owned and managed by ADIF (Administration De Infrastructures de Ferrocarril) and is operated by RENFE (Red Nacional de Ferrocarriles Españoles), a railway transport company that offers a high-speed service called AVE (Alta Velocidad Española) in which trains run over the network overpassing 300 km/h. The viaduct is in a rural environment between Plasencia and Cáceres on a 437 km branch connecting Madrid and the Portuguese border, which has been under construction recently.

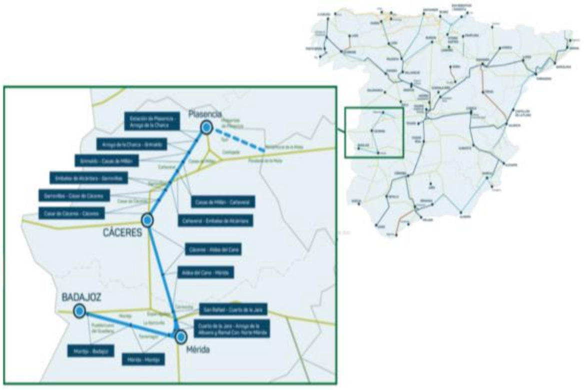


Figure 1. Representation of the high-speed railway network in Spain. The railway branch in which the bridge is located is highlighted.

The structure of the viaduct is arranged in 4 spans with a total length of 114m. The deck is 14m wide and consists of a continuous beam of prestressed concrete casted in situ that is supported by double cylindrical piles. Figure 2 shows a drone view of the Viaduct.

Figure 2. Drone view of the viaduct.

2.2 The Load Test

Load tests on the viaduct were performed by Drace (formerly Geocisa). The procedure followed the National norm provided by ADIF (NAP 2-4-2.0) regarding load tests on railway bridges under construction. According to this norm, static and dynamic actions are systematically reproduced to evaluate the structural performance of the bridge, and subsequently compared with theoretical calculations obtained from physical models.

During the static tests, the structural response is measured in a 5-step loading sequence: initial position, loading, stabilization, unloading and recovery. Dynamic tests are performed as a series of passes where the train circulates at different speeds.

Figure 3. La Plata viaduct during the execution of a static load test.

Accelerometers, strain gauges, displacement transducers and environmental sensors are used to measure vertical displacements of beams, vertical displacements at the supports, accelerations, deformations, temperature, and humidity during the realization of the tests.

After the test is completed, data is processed to obtain the parameters that describe the structural response of the bridge:

- Maximum vertical displacement

- Relative vertical displacements
- Maximum deformation
- Displacement after recovery
- Impact coefficient
- Natural frequencies and vibration modes
- Structural damping

The structure is validated if the results are in correspondence with theoretical design of the structure.

3 Digital twin enablers

BIM tools provide semantic and contextual information while the IoT paradigm enables interconnection among devices such as sensors, actuators, and personal computers, enabling digital twin capabilities. Thus, the development of the pipeline for the digital twin of the target bridge is based on its BIM model, developed according to the IFC standard, and the ASHVIN IoT platform.

3.1 The BIM Model

Industry foundation classes (IFC) is a comprehensive and structured data schema that accurately describes the built environment [4]. Recognized as an open international standard (ISO 16739-1:2018) it is meant to be usable across a wide range of hardware devices, software platforms, and interfaces.

Up to its version IFC4, the schema mainly focused on buildings, however, new extensions are arising that allow the development of infrastructure projects, including bridges, railway, roads, and tunnels [5]. The semantics, relations and properties built in the schema are the core reference for the automatic processes developed in this study.

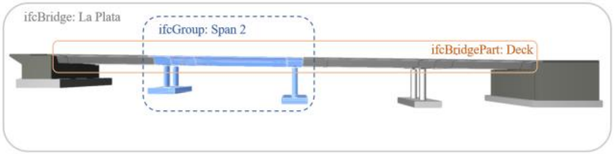


Figure 4. IFC model of La Plata viaduct where examples fort spatial structures (*ifcBridge* and *IfcBridgePart*) and semantic groups (*IfcGroup*) are highlighted.

Load tests are specific activities included within the facility management planning of the bridge. The IFC schema also allows to accurately monitor all the activities within construction projects (*IfcProject*) through a series of controls (*IfcControls*). A Work plan (*IfcWorkPlan*) is a sub-class of *IfcControl* typically used to group activities within the same life-cycle stage of the asset, i.e, activities for construction management purposes and activities for facility management purposes. Each work plan contains a set of work schedules (*IfcWorkSchedule*), which encapsulate multiple tasks with referenced resources and actors. In this study, the load test is modeled as a work schedule within the facility management work plan. The load test includes a series of tasks (*IfcTask*) representing each individual static and dynamic measurement performed. *IfcTasks* provide a time reference which can be semantically enriched by user-defined parameters. Tasks can also be related to specific built elements of the project on which they are operating. Load test tasks are representations of single assessments that are conducted on specific bridge beams (*IfcBeam*), which have a set of sensors (*IfcSensor*) attached that monitor their behavior. Figure 5 shows a simplified schema of the load test information model for tests performed on a beam with a single sensor attached.

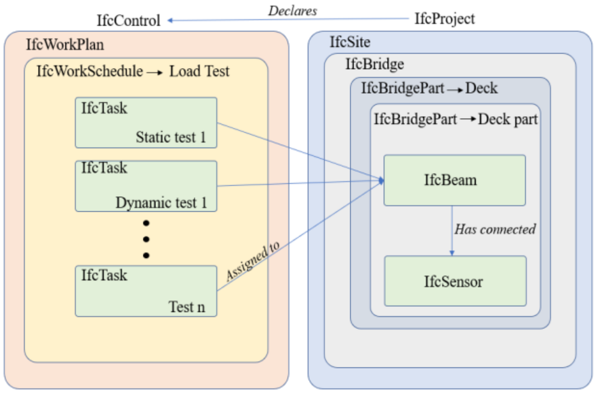


Figure 5. Relational schema of a load test for one beam with one sensor attached.

3.2 ASHVIN IoT platform

ASHVIN IoT platform is based on Mainflux, a high performant, scalable, low foot-print and open-source IoT solution which can be deployed both on the cloud and at the edge. The platform accepts connections over various protocols (HTTP, MQTT, WebSocket, CoAP and LoRaWan) enabling the two-way connection of all sorts of IoT devices.

The platform features three basic entities to perform communication between information producers and consumers: *things*, *channels*, and *users*. A *thing* represents any data source or producer. *Channels* are communication pathways through which *things* send and receive messages. Messages can be addressed to specific *topics*, providing extra semantics to the communication process, enhancing data querying and filtering. *Channels* abstract away complexities of low-level communication protocols offering a unified and easy-to-use interface for messaging. *Users* represent physical persons and organizations which own channels and things.

Data sent over the platform can be consumed as a stream via MQTT and WebSocket or can be retrieved from a structured time-series databased via a REST API.

4 The BIM-IoT integration

The integration of BIM and IoT into engineering applications remains a challenge for the industry and is positioned as one of the key milestones to generate digital twins for facility management. In this chapter, the BIM-IoT integration is addressed. A brief review of studies regarding this connection is presented. Additionally, the ASHVIN IoT platform is introduced and the integration between the platform and IFC models is proposed.

4.1 Previous works

BIM-IoT integration relays on methods for relating virtual asset contextual data and time-series data coming from their physical counterpart. Some studies linked time-series data stored in SQL (Structured Query Language) databases with private-vendor BIM tools APIs (Application Programming Interface). Desogus et al [6] integrated low-cost humidity and temperature IoT sensors and a Revit model using Dynamo visual programming tool for monitoring the indoor conditions of buildings. Time-series data was called into Dynamo through queries to an external IoT platform. Data stored in the IoT platform was mapped to elements in the BIM matching GUIDs (Global Unique IDentifier) through which queries could reach specific sensor data. Quinn et al [7] achieved integration of sensor database and Dynamo Revit using a custom .csv file and naming convention that allowed to match data with BIM model element's ID. These methods are effective; however, its development is limited by private-vendor software characteristics.

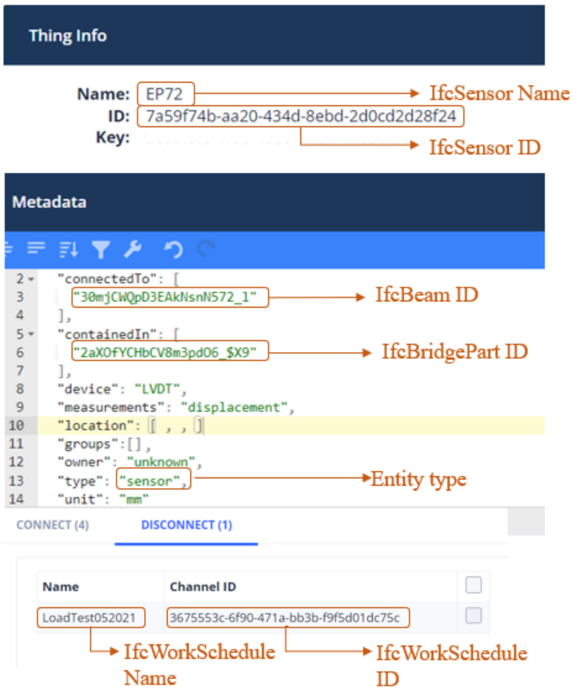
Moretti et al [8] proposed an openBIM approach to integrate IoT data and as-built information for digital twins. BIM, and IoT data were integrated in an external digital twin application. IFC data schema and IfcOpenShell were selected to store and query BIM data in JSON (JavaScript Object Notation) format, linking sensor readings to IFC objects GUIDs. The method allowed to maintain separation between dynamic and static data storage while providing a scalable approach using open-source software.

Other approaches transform BIM data into a relational database using new data schemas or create a new integrated query language using sematic web technologies [9]. These approaches are effective, however, may end up using convoluted methods where data needs to be transformed in advance.

4.2 Integrating IFC and ASHVIN IoT platform

Integration between IFCs and Mainflux communication entities is done by directly matching their GUIDs. Additionally, things and channels metadata are added with relevant contextual information included in the IFC model.

In the bridge information model of La Plata, IfcSensors, IfcTasks and IfcWorkSchedules are mapped to the Ashvin IoT platform. IfcSensors are virtual representation of devices that provide raw physical information; thus, they are represented in the IoT platform as a *thing*. IfcTasks are processes from which a result or report is expected, therefore they can also be considered as information sources, and are also assigned to a *thing*. On the other hand, IfcWorkSchedules represent a context, in which processes are organized and to which information can be referenced. Therefore, they are mapped as a *channel* in the platform. Figure 6 shows an example of this of how information of the IFC model is referenced in the ASHVIN IoT platform.



Thing Info

Name: EP72
ID: 7a59f74b-aa20-434d-8ebd-2d0cd2d28f24
Key:

Metadata

```
"connectedTo": [
  "30mjCWQpD3EAkNsnN572_1"
],
"containedIn": [
  "2aXOfYCHbCV8m3pd06_$X9"
],
"device": "LVDT",
"measurements": "displacement",
"location": [ , , ]
"groups":[],
"owner": "unknown",
"type": "sensor",
"unit": "mm"
```

Name	Channel ID	☐
LoadTest052021	3675553c-6f90-471a-bb3b-f9f5d01dc75c	☐

Figure 6. Screenshot of the Ashvin IoT platform interface. Mapping between a thing and an IfcSensor.

5 Contribution to the digital twin application

5.1 Architecture

The integration of IFC models and the Ashvin IoT platform enables the development of applications around asset information models that add advanced functionalities, such as data processing and multi-physics simulation, fostering the transition from BIM to digital twins [10].

In this study, an application based on event-driven microservices is developed to process the information produced during load tests on HS railway bridges. The event-driven architecture (EDA) is a software architecture in which decoupled microservices communicate by producing, detecting, and consuming events. Events are snippets of information triggered by any state change or any update that may provoke some reaction in the system, allowing to generate a chain of processes to accomplish some purpose. Event-driven architectures allow to create agile and scalable IoT applications, that can effectively consume data in real-time [11].

To process the load test data, two services are connected to the Ashvin IoT platform: a *BIM manager* service and a *load test processing* service.

The *BIM manager* parses, distributes, and updates the information contained in IFC file, acting as an integration tool. At the same time, listens to external events that request for information delivery for any type of BIM-based process. It has been developed using Python [13] and IfcOpenShell [12], an open-source library that allows manipulating files in IFC format. The *load test processing* service is a data processing service configured to retrieve load test data from the Mainflux database and return a series of parameters that define the structural performance of the bridge. Analyzing load test data can become computationally intensive due to large data packets which result from recording data at high rates for long periods of time. Therefore, the service is developed with python and Julia [14] to increase performance. Application events are transmitted using MQTT protocol through the Mainflux MQTT broker, thus integrating the information processing services into the IoT platform. Figure 7 shows a schema of the application.

This application will contribute to the development of MatchFEM, one of the applications being developed in the ASHVIN digital toolkit, aiming at integrating IoT with numerical simulations to closely calibrate digital twin models with measured behavior in the real world. The flexibility and decoupled nature of the proposed architecture allow creating simulation tools as an additional service, which will be seamlessly communicated with sensors, IFC models and data processing modules. Load tests are very comprehensive use cases for demonstrating the tool, since they require data processing, simulation, verification, and calibration, to establish the initial conditions of digitally twinned bridges for further assessments.

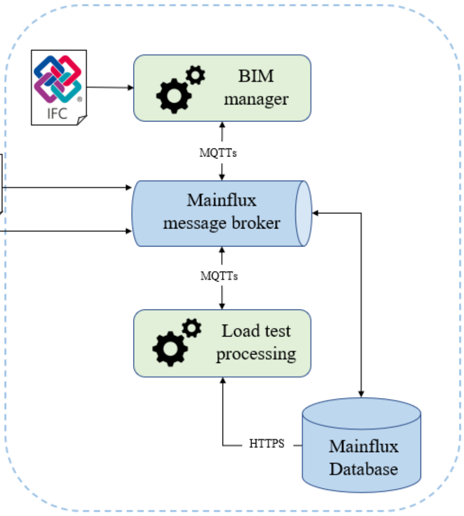


Figure 7. Schema of the digital twin application architecture.

5.2 Proposed pipeline

The asset owner assigns the execution of the load test and provides the structural Model View Definition (MVD) of the bridge, onto which the load test information model is generated. The model is uploaded to the *BIM manager* service, which checks that *IfcSensors*, *IfcTasks* and *IfcWorkSchedules* are correctly mapped in the ASHVIN IoT platform. Then, the load test is carried out, measurements for each test are taken, and data is uploaded to Mainflux database according to the bridge information model. Subsequently, the load test processing pipeline is triggered by the user.

The *BIM manager* service raises an event through the platform MQTT broker. The event message provides the following information in JSON format:

- Event type: load test processing.
- Test: *IfcTask* ID and time schedule information.
- Load test ID: *IfcWorkSchedule* ID.
- Test type: static/dynamic.
- Sensors: information including sensor ID, element to which they are connected and associated bridge span.

The *load test processing* service is subscribed to all events emitted by *the BIM manager* service, receives the event, and checks if it can be consumed. The load *test processing* service accepts the event as one of its dedicated tasks and retrieves the referenced load test data from Mainflux database. Data is subsequently processed to obtain structural behavior parameters specified in Chapter 3: sensors are grouped according to the span to which they are assigned in the IFC model. Therefore, data is analyzed span-wise. Figure 8 shows an example of Linear Variable Differential Transformer (LVDT) data of a static tests that have produced a structural response in the first span.

Subsequently, time-series are associated to support or midspan sensors. Then, the state of the structure is retrieved at three different instants: at the start of the test, at the time of maximum displacement and after unloading, when the shape of the structure is recovered. Thus, the maximum vertical displacement, the relative vertical displacement and the displacement after recovery can be obtained. A similar process is carried out to obtain the maximum deformation from strain gauges data.

Impact coefficients are obtained for each span calculating the ratio between the maximum displacement obtained in pseudo-static and dynamic tests (see Figure 9). The dynamic excitation of the structure can be allocated in time using time-frequency decompositions [15] (Figure 10) to subsequently extract the natural frequencies, vibration modes and damping factor using current Operational Modal Analysis (OMA) techniques [16]

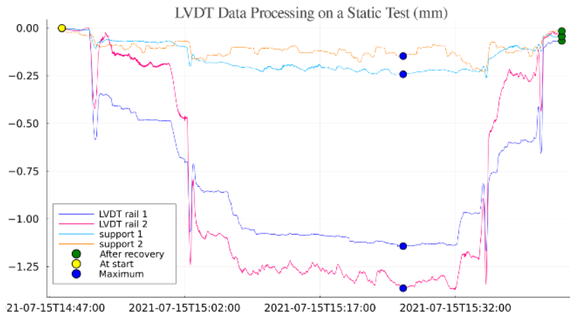


Figure 8. Data retrieved from an LVDT sensors located in the first span during a static load test.

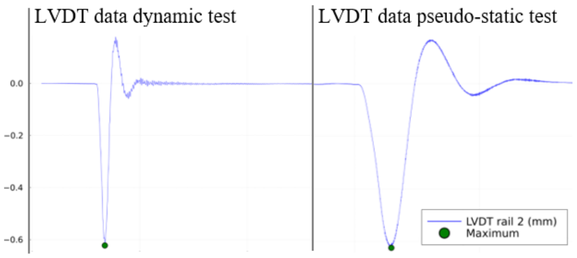


Figure 9. Comparison of LVDT data from pseudo-static and dynamic tests to retrieve impact coefficient.

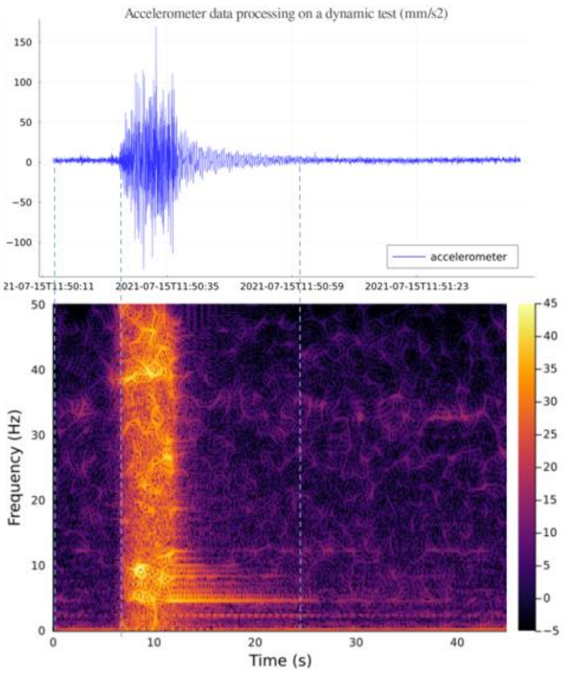


Figure 10. Accelerometer data and Wigner-Ville time-frequency transform.

The *load test processing* service publishes results to the Ashvin IoT platform using each IfcTask ID, and its corresponding key, to channels/IfcWorkSchedule_ID/Span_ID/Result_Name/subName/... Finally, it raises an event to inform the *BIM manager service* that it has accomplished its purpose. In response, the *BIM manager* service updates the status of the task to “completed” in the IFC file. Therefore, results can now be queried to the ASHVIN IoT platform by any user or third-party application using the information contained in the IFC model.

6 Conclusion

In this paper, an automated pipeline for processing data collected during load tests carried out on high-speed railway bridges is proposed. The pipeline encompasses the integration of the IoT platform of the European ASHVIN project and the IFC BIM schema. The integration is achieved within a digital twin application based on event-driven microservices which is flexible and scalable. Two services are proposed: (1) a BIM manager service that matches unique identifiers and contextual data from the IFC file into the IoT platform; (2) and a load test processing service in charge of transforming raw data into parameters that describe the structural behavior of the bridge structure. The pipeline architecture proposed can be extended with simulation services to generate full digitally twinned load tests that would generate impact at economy and productivity levels.

7 Acknowledgements

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