Microservice-Based Middleware for a Digital Twin of Equipment-Intensive Construction Processes

Anne Fischer[1], Yuling Sun[1], Stephan Kessler[1], and Johannes Fottner[1]

[1]Chair of Materials Handling, Material Flow, Logistics, TUM SoED, Technical University of Munich, Germany

anne.fischer@tum.de, yuling.sun@tum.de, stephan.kessler@tum.de, j.fottner@tum.de

Abstract -

Following the example set by Industry 4.0, digitization is being proven as a vital tool in equipment-intensive construction processes. Telematics data from equipment is sent to platforms. The profitable use of this data is part of today's research regarding digital twins. This paper shows the conformity to Industry 4.0 terminology and digital twin components in construction. It reveals the need for data transformation and integration to cope with the diversity of equipment fleets. Thus, this paper introduces middleware systems based on different microservices, each with a different functionality, and shows their implementation at the special foundation engineering project.

Keywords -

Middleware; Microservice architecture (MSA); Digital twin in construction (DTC); Discrete-event simulation (DES)

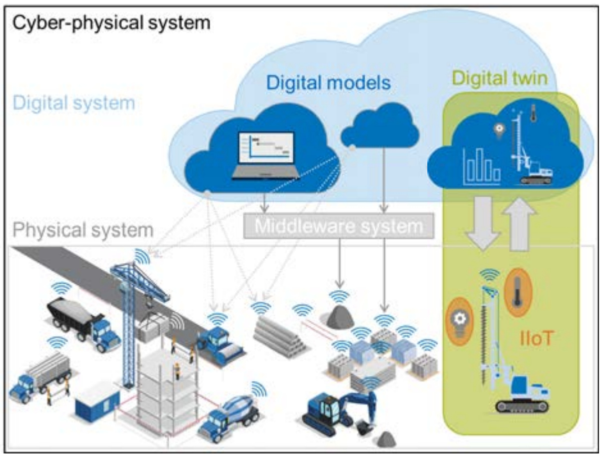

Figure 1. Overview of Industry 4.0 terms in the context of equipment-intensive construction processes

1 Introduction

Pushed by the achievements of the Industry 4.0 movement, first mentioned in Germany's high-tech strategy plan for 2020 [1], the construction industry is trying to emulate it as it has yet to profit from productivity growth following digitization [2]. The Industry 4.0 objective is to give every asset an identification understandable at any time to anyone [3]. This identification helps to digitize the physical asset as a digital twin (DT), see Figure 1.

It is hard to simply adopt the DTs of Industry 4.0 - even though the degree of digitization is increasing, as several systematic literature studies show, e.g., [4]. Limitations arise from construction-specific requirements [5]: (1) The unique character of each individual construction site; (2) Transient processes; (3) Dependence on location and weather conditions; (4) The use of different (often inoperable) technologies; (5) Strong fragmentation of the construction industry; (6) Segmentation along the product life cycle or process chain. In this context, the exchange of heterogeneous data in a construction project's life cycle must be managed before DTs are adopted [6].

As a first step, this paper introduces a middleware system as a layer to centralize data exchanges, see dotted vs. straight arrows in Figure 1. The paper clarifies the terms relating to DTs to understand the need and the requirements for middleware. It shows the implementation of a specially developed microservice-based middleware for DT of equipment-intensive construction processes. Its verification and validation show the need for data management and also point out middleware's weaknesses regarding proprietary interfaces. The paper ends with a summary and presents an outlook.

2 Background

2.1 Digital twins in the construction industry

The interest in digital technology has increased exponentially over the last decades [7]. In a discussion of DTs, it is essential first to clarify the terms and definitions [8].

Cyber-physical system (CPS): A DT is part of a cyber-physical system (CPS) [9], see Figure 1. A CPS "links real (physical) objects and processes with information-processing (virtual) objects and processes via open, partly global and always interconnected information networks" [10]. A common description for scaled CPS is, therefore, a "system of system" [11]. Cross-linking various physical assets implies an increasing standardization effort [12], e.g., RAMI 4.0 [3].

Industrial internet of things (IIoT): The term internet of things (IoT) or industrial internet of things (IIoT) is one part of the CPS, see Figure 1. It concentrates on the connectivity of the assets [13]. The IIoT enables bidirectional data flow within and between DTs [14]. Various reliable protocols are available for networking IIoT devices [15, 6].Fuller et al. [14] conclude that it is one of the significant technical aspects of a DT.

Digital twin (DT): According to Kritzinger et al. [16], the degree of integration between the digital and physical model increases from digital model (DM) to digital shadow (DS) to digital twin (DT). The last allows bidirectional communication between the models to use real data, on the one hand, and to influence the real model directly, on the other hand (gray arrows in Figure 1).

Digital twin in construction (DTC): In line with the efforts in the manufacturing and health sectors, DTs have high potential in the construction industry [14]. building information modeling (BIM) can potentially be used as a digital twin in construction (DTC) for information storage and process modeling and monitoring [17]. Fundamentally, BIM is a 3D construction project description. Fed with more than geometrical data, such as time and costs, and described in a standardized format, like IFC (industry foundation classes), BIM evolved into a DTC [18]. Sacks et al. [19] strengthen the term digital twin by differing between the construction digital twin (CDT) according to Boje et al. [18] and the digital twin in construction (DTC). They thereby emphasize that DTC is more than a technology. A DTC implies a workflow. It can be classified as a dynamic model of a construction site that monitors construction in real time to generate added value from the site data [20]. However, criticism arises as BIM has weaknesses in handling big data with the help of Artificial Intelligence (AI) [19]. Furthermore, BIM is very popular in high-rise building construction but not in heavy civil engineering, where Geographic Information System (GIS) is more appropriate [21, 22]. Visual forms of representation and interaction based on web interfaces, AR/VR technologies, artificial intelligence (AI), or simulation are necessary to process the information provided and to make it available to the people on-site [4]. Sacks et al. [19] strengthen the term construction digital twin (CDT) according to Boje et al. [18] to the term DTC implying a workflow.

2.2 Components of a DTC

According to Feng et al. [23], DTCs are basically composed of five parts: (1) data acquisition, (2) data transmission, (3) data model, (4) data integration, and (5) data service.

Data acquisition: For the identification of the assets and the recording of the construction progress, sensors can be divided into three classes according to [24]: (1) Vision-based, e.g., laser scanning [25], image recognition [26]; (2) Audio-based, e.g., microphones [27]; (3) Kinematic, e.g., inertial measurement unit (IMU) [28], equipment sensors such as for hydraulic pressure or forces [29, 30], or radio-frequency identification (RFID) tags [31].

Digital models and service: Besides BIM, discrete event simulation (DES) models are digital models for predicting construction processes [32]. Data-driven DES has the benefit of being more efficient and the results have a better quality [33]. Regarding real-time simulation, studies exist using DES and data from construction equipment without describing data exchange [34]. However, as mentioned above, data exchange is one key challenge of the digital twin. Some authors tried to adapt the high-level architecture (HLA) from IEEE standard 1516 [35] [36, 37]. HLA helps running simulation models in a distributed network environment. However, to the authors' best knowledge, the standard is not further extended.

Data transmission and integration: From a manufacturer's point of view, Ghosh et al. [38] emphasize the need for IIoT but also data storage, management, and an analyzing system to arrange different DTs in a CPS fully. Feng et al. [23] come to the same conclusions for applying DTCs: Solutions to transmit and integrate heterogeneous data in the construction industry are lacking. Especially, in equipment-driven construction processes, an appropriate tool for linking heterogeneous data sources is required. However, today's construction equipment manufacturers offer their proprietary fleet management systems integrating clients' different equipment types from different manufacturers. The ISO standard 15143-3 [39] faces standards for telematics data exchange.

Will and Waurich [40] therefore give an overview of proprietary and typical data space approaches, and middleware systems, such as open platform communications unified architecture (OPC-UA). Existing commercial middleware solutions have been used for DTs [41] but there exist reservations on data security [14]. Ravi et al. [41] show the implementation of a DTC in robotics, using commercial services from Amazon and Rhino to store and analyze data. Fuller et al. [14] name other commercial middleware systems provided by Google or Microsoft, but emphasize data security challenges in the context of DTCs.

The construction industry has realized the need for a middleware system, but there exist only few approaches to specially developed middleware for DTC. In the following, we want to clarify this term and its specification from the viewpoint of software development.

2.3 Middleware systems

A middleware domain manages the integration and linkage of data to distributed applications or services [42]. In contrast to the common point-to-point topology where data is exchanged directly between the services, middleware serves as a translator layer, so that different services can communicate with each other [43], see Figure 1.

Communication protocols: A middleware uses different communication protocols. The transmission control protocol (TCP) is straightforward and fast. It transports data via a stream of bytes [44]. In contrast to continuous data streaming, the hypertext transfer protocol (HTTP) sends messages from a client to a server for response [45]. The communication interface for applications is the application programming interfaces (API). If the interfaces follow the design principles of the representational state transfer (REST), they are called REST-APIs, enabling, e.g., a uniform interface and layered system architecture [46]. Thus, the middleware is also a specific protocol [47].

Middleware architectures: According to Ungurean et al. [42], the following are relevant middleware systems: Distribute device data for real time systems (DDS), message queuing telemetry transport (MQTT), advanced message queuing protocol (AMQP), and extensible messaging and presence protocol (XMPP). These middleware systems are all limited to specific layers, e.g., MQTT is used only for device-to-server communication, and DDS is used for a single system. An IIoT-specific middleware is missing. Today, OPC-UA [48] is the standard middleware system to enable the real-time implementation of Industry 4.0 technologies [49, 8, 47]. OPC-UA is historically developed for the collaboration among manufacturing robots (of different robotic producers). Thus, it is interoperable among different systems.

Service oriented architecture (SOA): In recent years, there has been a lot of research into the computing paradigm of service oriented architecture (SOA) [50]. In SOA, distributed applications are built using services as the main component. These services are autonomous and platform-independent so that they can be discovered and used by service consumers dynamically. There are three components in SOA: (1) the service provider, (2) the service requester, and (3) the broker registry [51].

Microservice architecture (MSA): Microservice architecture (MSA) is similar to SOA but with some differences [52]. SOA focuses more on enterprise or even cross-enterprise software systems, which have certain requirements, e.g., being protocol-agnostic. In contrast, the application of MSA is restricted to smaller applications without the claim of scalability or generic protocol transformations. Thus, it is less complex and, therefore, easier to implement.

A microservice is a small application with only a single task, or there is only a single reason for it to changeThönes [53]. The advantages of microservices [53] are that they can be deployed, scaled, and tested independently. However, as an application grows, it becomes more challenging to make changes, so it becomes unmaintainable.

2.4 Research gap and objective

The literature review shows that the application of digital technologies to DTCs is not yet realistic. As a critical challenge, the authors identified that the interoperable connection of the components of a DTC in a CPS.A microservice-based middleware is suitable to fulfill these requirements. It orchestrates protocols and interfaces from different services in one centralized layer. Further services can be easily added as they are decoupled, allowing for independent development and maintenance.In DTC, research needs to focus on this data transmission and integration problem. In the following, we introduce the implementation of a microservice-based middleware system for the equipment-intensive construction industry.

3 Methodology

3.1 Framework

Regarding the construction industry, the authors are working on a DTC in heavy civil engineering. More precisely, their use case is pile production according to the Kelly drilling method, which is used to build deep foundations to transfer loads into the ground, e.g., for high-rise buildings or bridges. Figure 2 shows the DTC in a feedback control system. Based on the definition above, the physical asset is the equipment for drilling these piles, called a Kelly drilling rig (scheme on the right). The digital asset is the DES for project scheduling and process simulation (left two clouds). We developed a hybrid deep learning model to recognize the telematics data from the Kelly drilling rig (cloud on the bottom). The data exchange among the equipment, the DES, and the activity recognition is orchestrated by the following middleware (green arrow).

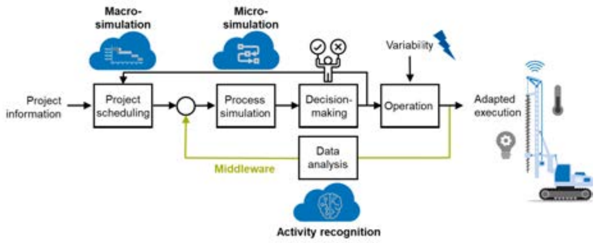

Figure 2. Feedback control system from Fischer et al. [54] including the functionality of the middleware

3.2 Implementation

Figure 3 shows the middleware architecture. It is implemented in Java 11 using the Spring Boot framework [55] and Apache Maven [56] as a build management tool on an Ubuntu system.

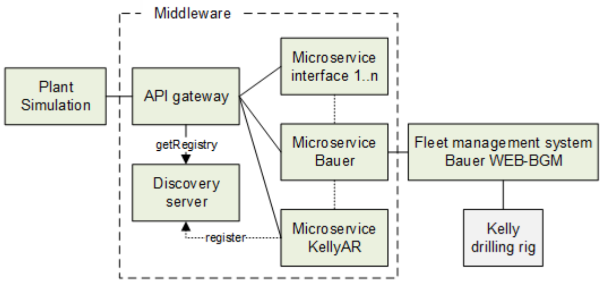

Figure 3. Middleware architecture adapted from [57]

Communication protocols: The middleware uses HTTP for internal and external communication with machine data systems via REST requests. Communication with users is handled either by HTTP or TCP.

API gateway and discovery server: The middleware consists basically of two components: (1) an API gateway and (2) a discovery server. They allow communication between the user and the microservices, see Figure 4 (left). The API gateway is the single entry point to the middleware. It provides a REST API and a TCP-based API for requesting all data from the different fleet management systems or other applications. In addition, it can translate between TCP and HTTP messages for requests and responses. The API gateway needs the discovery server to know the addresses of the microservices to transmit the requested data then. We therefore implemented a client-side server discovery using the Spring Eureka service registry and Eureka Discovery Client. Figure 4 (left) shows the components and the sequence of the API gateway: (1) The TCP requests are received and translated into HTTP requests; (2) The HTTP requests are transferred to the REST endpoint; (3) From there, they are forwarded to the implemented microservices using the locations from the discovery server.

Microservices: The middleware includes several microservices responsible for communicating with fleet management systems. Their job is to bring the different kinds of data from the construction site into a single format, i.e., hide the differences in authentication, communication formats, or from the user. Two microservices are required to realize the DTC: Bauer and KellyAR, see Figure 4 (right). The Bauer microservice connects to the proprietary fleet management system from our industry partner Bauer Maschinen GmbH in Germany. This platform receives and stores data from their Kelly drilling rigs via TC3G data modules [58]. The requests follow ISO standard 15143-3 [39]. The KellyAR microservice pre-processes the telematics data for the DES because the model requires the duration of the steps in the single construction process for production optimization [30].

3.3 Validation

Before validation, we verified the code of the middleware by the API Postman [59]. The validation of the described framework is then split into two test set-ups including a virtual and a real Kelly drilling rig. The first test-set up is used to test standardized data transfer via ISO 15143-3. The second test-set up is used to test the DTC framework including the update of the DES with the current production time. In both cases, the DES is conducted with the Tecnomatix Plant Simulation software from Siemens [60].

The DES model for the first test follows the Plant Simulation guideline for exchanging data via a network socket [61]. It includes a client socket object to enable a TCP connection to the middleware (server socket), a method object to program the way messages are sent, and string variables to monitor the requested and sent TCP messages. The required OAuth 2.0 identification within ISO 15143-3 first requires the authentication request, and then, finally, the received token is used for requesting fleet information. We received the 20 data points, according to ISO 15143-3, from a virtual drilling rig from Bauer, including o.a., header information, last known location, operating hours, and cumulative fuel used.

However, this data does not include the construction process step duration. We therefore developed the KellyAR microservice to recognize the equipment's activities based on sensor data and calculate the duration. These sensor data could not send to the fleet management system. As a result, the implemented microservice was not needed for communication.

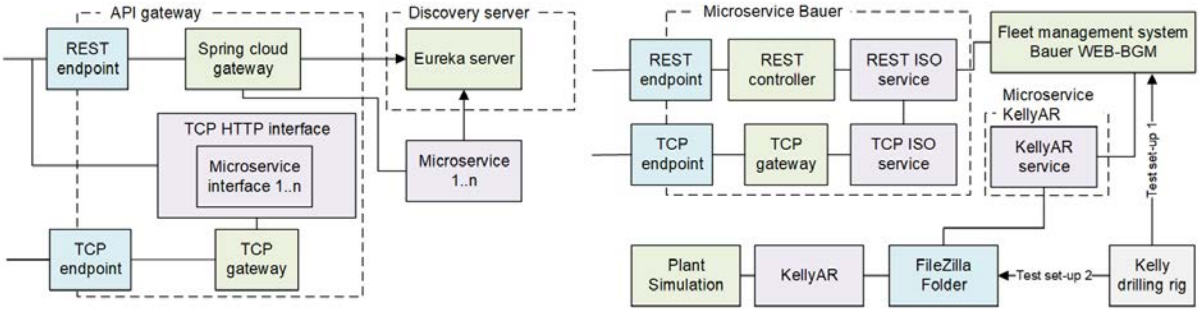

Figure 4. Middleware components and data flow adapted from [57]

Instead, we used a simple bidirectional data exchange via the open-source server FileZilla. FileZilla enables direct TCP exchange. To log into the wifi of the drilling rig and transmit the data directly to a local folder from the application, see Figure 4 right. The KellyAR microservice interprets the data and transfers it to the Plant Simulation.

4 Results and discussion

Limitations arise on the middleware verification due to a missing manufacturer API, so only data exchange via ISO standard 15143-3 [39] was tested. Further studies are needed to address the optimization of the data exchange performance, the security aspects, and the system bandwidth and connectivity on site. However, these aspects were essential for the practical and effective use of DTCs in real-world construction settings.

The validation of the middleware is further limited to a specific use case. As mentioned in Section 2, there will be various systems in a system in the future. Although proprietary APIs exist, a single implementation and validation are time-consuming. The standardization effort is highly relevant for DTCs. For commercial purposes, it is further mandatory to ensure data access, e.g., by data trustees, such as Gaia-X [62] in the automotive industry or the agrirouter [63] in the agricultural industry.

To finally achieve a DTC, the equipment sends data and receives data from the simulation model. It is not for automating the construction process by controlling the construction equipment but forecasting the construction process. The results from the simulation model, such as the remaining construction progress [64] or a cost-benefit comparison of alternative process execution [65], are therefore transferred by the people on-site to optimize the construction process.

Overall, the application of DTCs in the future requires that on-site personnel have enhanced skills to use the simulation model or to integrate new equipment. The construction industry needs to think of new job profiles in order to benefit from the Industry 4.0 technologies.

5 Conclusion

DTC is one buzzword increasingly used in the construction industry to talk about digitization. A common understanding of the terms and definitions is mandatory to push DTC further toward realization. Different relevant Industry 4.0 technologies exist to realize a DTC. Middleware is, therefore, required to orchestrate the data exchange between the physical and the digital assets of the DTC. The DTC framework described in this paper aims to support the decision-makers on-site with simulation models cyclically updated by information on the production equipment, here the drilling rig for pile production. This paper presents and discusses the implementation of specially developed microservice-based middleware. The work presented in this paper is limited as the validation of the middleware is not conducted on a real use case.

6 Acknowledgment

This research was funded by the German Federal Ministry of Education and Research through the research project “Bauen 4.0” (02P17D230). We thank our industry partner for the cooperation.

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