Proceedings of the Estonian Academy of Sciences,
2019, **68**, 4, 364–370
https://doi.org/10.3176/proc.2019.4.03
Available online at www.eap.ee/proceedings

MANUFACTURING
ENGINEERING

Synchronizing physical factory and its digital twin through an IIoT middleware: a case study

Vladimir Kuts[a*], Gianfranco E. Modoni[b], Tauno Otto[a], Marco Sacco[c], Toivo Tähemaa[a], Yevhen Bondarenko[a], and Ruxin Wang[a]

[a] Department of Mechanical and Industrial Engineering, School of Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b] Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing – National Research Council of Italy, Giovanni Amendola 118, 70126 Bari, Italy
[c] Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing – National Research Council of Italy, Via Alfonso Corti 12, 20133 Milano, Italy

Received 26 March 2019, accepted 13 May 2019, available online 22 October 2019

Abstract. Digital twin (DT) is the virtual clone of a factory representing its static and dynamic aspects (e.g., processes, systems, products, etc.) in detail. Among the significant challenges that manufacturing company has to face to implement the DT, one of the most demanding is applying an appropriate software infrastructure, which would enable synchronization of the physical factory with its DT. In this case, it was possible to exploit wide range of capabilities of DT in its full potential. In particular, the DT was used in different conditions to enable various operations within the shop floor, to simulate and assess the factory's performance. To support companies in addressing this challenge, this paper presents a potential solution, based on the Industrial Internet of Things (IIoT) middleware, that implements a fully dual-way synchronization between the real and virtual worlds. A case study was carried out to investigate the possibilities to implement the solution. To demonstrate correctness and validity of the approach, tests were carried out in the laboratories of Flexible Manufacturing Systems, Robotics Demo Centre and ProtoLab of Tallinn University of Technology (TalTech).

Key words: digital twin, IIoT, virtual reality, industrial robots.

1. INTRODUCTION

One of the key aspects for the success of a modern factory is realizing the importance of using its digital twin (DT), which is a virtual clone of factory's manufacturing system (or part of it) that represents its static and dynamic aspects in detail [1]. The creation of this virtual representation can be exploited to enable various strategic operations within the shop floor, such as simulating and assessing the factory's performance. For example, the simulated environment provided by the DT can allow production managers and the integrators of factory's automation system to check the changes applied to the factory layout without the need to test them in the real production environment. Also, opportunities of virtual reality are used to enhance the environment. This allows users to create the envisioned factory in virtual reality (VR) and to inspect manufacturing systems in the real scale.

* Corresponding author, vladimir.kuts@taltech.ee

Authors of this research focus on a specific application of the DT – on management and control of the manufacturing systems, mainly in the field of industrial robots. In particular, the idea behind the work is that human presence can be simulated, accompanied, and enhanced by other operators remotely (multiplayer capability) by using VR tools. In previous studies of the robotics, virtual commissioning (VC) has mainly been used to create a simulation to optimize robots' algorithms during development phase. In more general manufacturing field, the simulations have been exploited to represent the complex behaviour of a system, also taking the possible consequences deriving from external factors like human interactions or design constraints into consideration. The potential of the DT has been recently analysed in various publications [1–4]. Schluse and Rossmann [2] described an idea of DT as "Versatile Simulation Database" (VSD), which is a static data container containing related algorithms/interfaces to manipulate data. Moreover, it also provides functionalities for parallel and distributed simulation. For a specific case, Grinshpun et al. [3] illustrated an application involving KUKA LWR4 robot using VEROSIM as a simulation environment. VEROSIM provides a scripting language called SOML++, where engineers can easily monitor occurring force and torque during the manufacturing simulation. Schroeder et al. [4] see DT as a composition of different models and data, and that it can be aggregated into an AutomationML model enhancing the exchange data between heterogeneous systems via a middleware named FIWARE [5].

However, according to numerous works found in the literature [6–8], a realization of the DT requires the following key features:

(a) the data acquisition via a monitoring system;
(b) setup of the detailed synchronization of the DT in order to make achievement of specific goals successful;
(c) using a data model to represent the real factory and its performance;
(d) synchronization between the real and digital factory.

This paper focuses mainly on the last feature, proposing the idea that middleware is used for synchronization of the robot and its DT, which propagates the data stream of the factory telemetry from the physical factory assets towards their digital representation and back. The presented work has also its roots in previous works from the same authors concerning an infrastructure architecture for the synchronization [7,8], and the industrial robot tests combining VR and DT [8–10]. Also, this work takes other studies in similar fields and comprising remote laboratories [11], initial design [12] and virtual training [13] as a reference. The remainder of this paper is structured as follows: Section 2 presents the software infrastructure, while Section 3 illustrates its application and evaluation within a case study. Section 4 presents the benefits of an approach based on a synchronized DT. Finally, Section 5 concludes, summarizing the major findings.

2. SOFTWARE INFRASTRUCTURE FOR THE BIDIRECTIONAL SYNCHRONIZATION OF REAL AND VIRTUAL ASSETS

Modern manufacturing systems are projected into a new era in which they will be capable of exploiting the IIoT protocol in its full potential. Leveraging this potential, manufacturing systems will become dynamic networks comprising of different kinds of physical and virtual resources. In particular, thanks to the advanced communication and networking capabilities provided by the IIoT, each production component connected to the IIoT network will be paired with its fully synchronized DT. To contribute realizing this vision, present work envisions a software infrastructure to constantly synchronize the physical components with their digital representations. This infrastructure leverages a message-oriented Industrial Internet of Things (IIoT) middleware, based on a publish-subscribe interaction [14]. The middleware handles the factory telemetry, i.e., the real-time data stream, which involves all data such as monitored controlled variables coming from the plant and actuator directives to be promptly executed on a physical resource. Thus, the middleware allows any (real or virtual) components connected to the IIoT protocol to propagate significant information to keep other interested components (information consumers) updated about occurred events (e.g., the position change of a device). Middleware can filter the content of each message and dispatches the information updates only to interested resources, where information dispatching adopts an event-based PUSH strategy, thus announcing the information updates under the form of events. Thanks to the middleware, notifications can be distributed as messages, so that the information consumers can take further evaluations and then perform some needed actions. Also, the middleware allows the interested components to specify their requests to be subscribed to the updates related to the specific contextual factory information. Specifically, each controller of the physical component (*PhysicalResourceController*), after having acquired and collected the monitored information, can share the context information with other components, and in particular with the component that manages the DT (*DigitalTwinController*). In turn, the latter can send directives to the *PhysicalResourceController*s according to the input received from the virtual environment.

Under these conditions, *PhysicalResourceControllers* and *DigitalTwinController* play the role of prosumers, i.e., they can be both, information producers and consumers.

3. THE CASE STUDY

A proof of concept of the software infrastructure to synchronize a real robot with its DT was implemented in the Flexible Manufacturing Systems (FMS), Robotics Demo Centre and ProtoLab of TalTech. The latter includes the Industrial Robotics' section, which consists of two heavy load robots. One is Yaskawa Motoman GP8 with a changeable tool for picking and placing tasks. The herein proposed infrastructure was built focusing on this robot. In this regard, its virtual model was created through the Unity3D game engine platform. The visualization of this model requires using standard VR equipment (e.g., head-mounted display units, such as Oculus Rift/HTC Vive).

For the re-creation of a real Industrial Robot, a cell was created with the aid of 3D modelling software, producing a virtual representation of the laboratory with all its assets (Fig. 1). The more precise process of creation of digital model is described in previous research papers of the authors with all aspects of the technical side [9]. A short list of most essential aspects, which should be considered while digitalizing manufacturing equipment, using own 3D models based on drawings or imported from the libraries of equipment manufacturer, is the following:

- rigging of the model – the central pivot points for movable objects should be defined appropriately;
- rendering time – the 3D objects, geometry should be simplified to improve the performance of the visual simulation, the mesh should be correct;
- re-checking and keeping one-to-one scale for the accuracy;
- proper kinematics of portable equipment.

If the aspects of this list are not taken into consideration, the accuracy of a DT will not be efficient for the experiments.

Figure 2 shows five different components of the software infrastructure:

(a) *RobotController*, which controls the robot through a specific API;
(b) *DigitalTwinController*, which manages the DT model;
(c) a publish-subscribe middleware as introduced in the previous section;
(d) *RobotCommunicator*, which handles the communication for the real component;
(e) *DigitalTwinCommunicator*, which handles the communication for the virtual component.

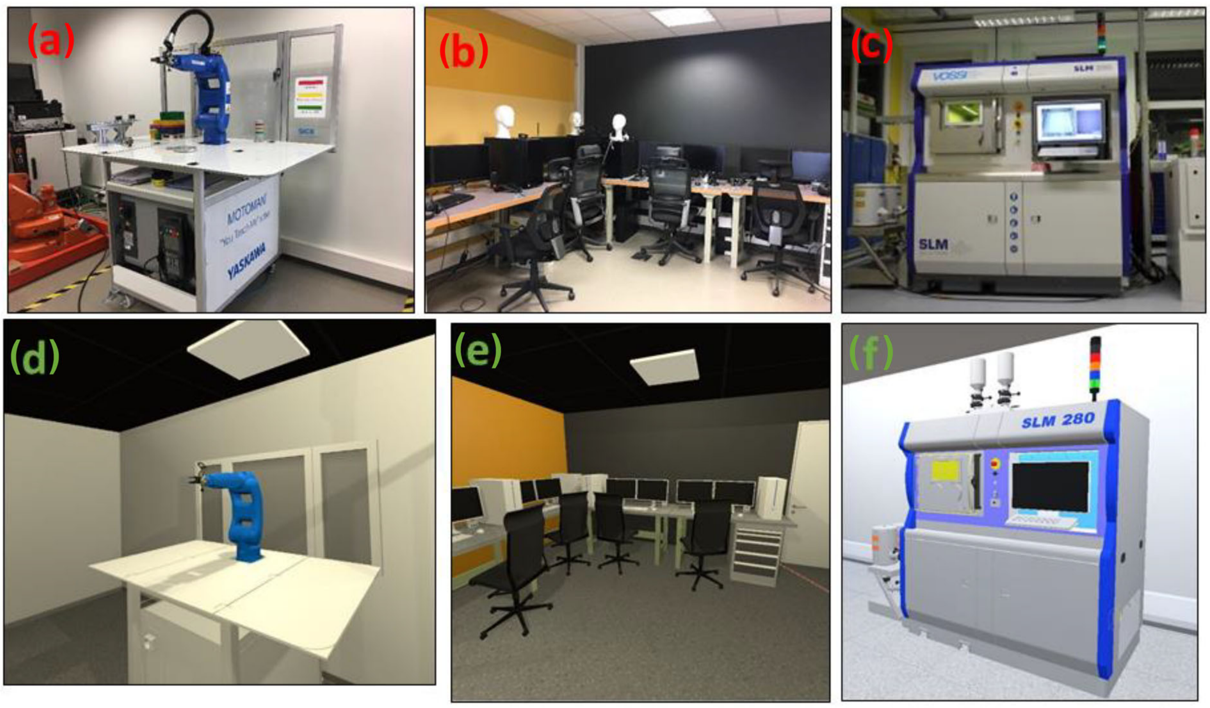

Fig. 1. Digitalized laboratories – Flexible Manufacturing Systems, Robotics Demo Centre, and ProtoLab (a, b, c – real; d, e, f – replica).

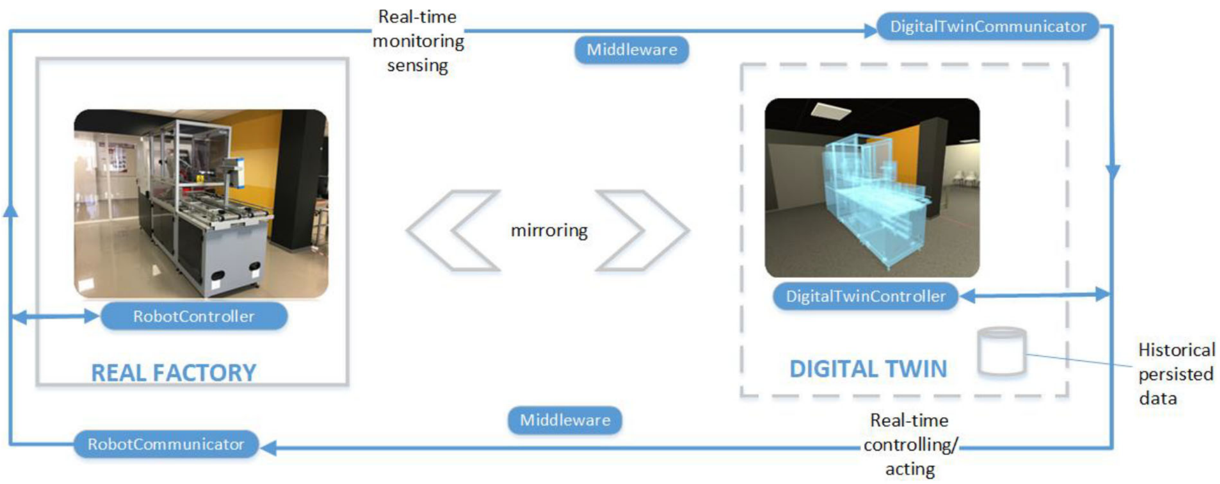

Fig. 2. Synchronization process through the proposed software infrastructure.

Also, Fig. 1 represents how these components are linked to enable the synchronization process, which in particular, is enabled by the middleware and two of its clients (*RobotCommunicator* and *DigitalTwinCommunicator*). The role of middleware is in turn played by Message Queuing Telemetry Transport (MQTT) publisher/subscriber protocol, which is standardized by ISO [15] and known for being a lightweight and fast solution for IoT applications.

Another potential option for middleware could have been Kafka platform [16], which allows greater scalability and data persistence. However, MQTT was adopted for its ease of implementation and shorter setup time, while also providing the needed features for the considered case study. Also, current MQTT implementations provide countermeasures against various failures or error situations by offering features, which make middleware more resilient.

All messages published by the MQTT clients are sent to the MQTT broker, which then forwards the messages to other clients subscribed to the same messaging topic (the two *Monitors* are at the same time data publisher and consumer). The presented solution utilizes six message topic pairs, which correspond to the control inputs and monitoring outputs of the *RobotListener* (i.e., setting and monitoring of the robot position). The MQTT broker was hosted on a public IP server, managed by Digital Ocean [17], and located in Frankfurt, Germany. The real robot can be managed by running *DigitalTwinCommunicator* script, which allows the robot to be connected using MQTT.

Another challenge was related to Unity. Indeed, since it does not have MQTT integration out of the box, it was necessary to implement a custom solution, which would allow starting MQTT client scripts directly from Unity runtime. However, MQTT protocol is universal, and the clients were already implementing it in many programming languages, including C# used by Unity. The final solution for this demo was based on .NET MQTT client implementation by Eclipse [18] and existing test Unity project available on GitHub [19].

An important reason for choosing a Unity3D game engine for development, was possibility to build both, VR-supported and classic desktop versions of the application. Though both versions feature the same DT control interface, VR version was also complemented with user avatar networking, allowing researchers to test the robot online while being together in the same virtual environment (Fig. 3). This feature allows demonstrating an important aspect of the factories connected in the future – the ability to monitor equipment and collaborate in real-time, even from remote locations.

The aspects that can affect the success for such a real-time, multi-user, internet-based collaborative VR systems, are the latency, i.e., the time needed to synchronize the virtual world with the real one and vice versa, the scalability and user experience. These aspects depend in turn on the number of the connected IIoT devices, the throughput of the information shared between the devices and the size of the 3D scene (nodes, geometries, assets). Thus, after the implementation, the solution was evaluated according to the following three criteria:

(a) latency (the aim of the test is to measure it and demonstrate that it is under a fixed threshold);
(b) capability to measure according to the throughput, which can be increased by changing the status update frequency of the robot;
(c) capability to control DT from remote locations.

To perform the above mentioned experiment, a test was performed by changing two parameters: robot send

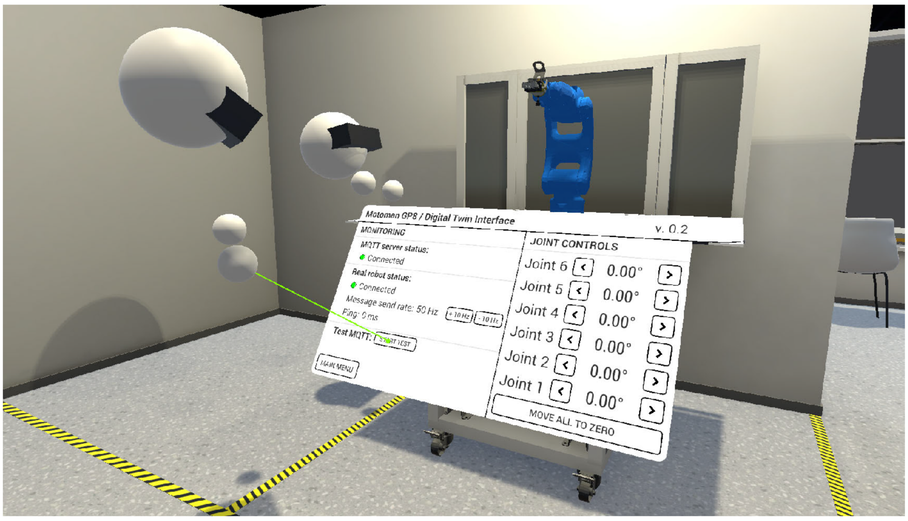

Fig. 3. Researchers' avatars controlling the robot in VR.

rate (how often *RobotListener* sends updates about the robot's position to the broker) and MQTT Quality of Service (QoS) level (it determines how reliably the messages are delivered by the MQTT protocol). Send rate values were taken in the range from 10–100 Hz, with a step of 10 Hz, while QoS level can take values of 0, 1, or 2. Greater values require more computation time to process messages. Finally, the time required for sending messages from *DigitalTwinCommunicator* to *RobotCommunicator* and back (ping), was taken as a metric of connection speed. For each combination of parameters, the robot was sent 50 movement commands and ping was continuously sampled, to calculate the average for each experiment. The test was run in two different places at premises of STIIMA-CNR (Bari, Italy) and of TalTech Industrial Virtual and Augmented Reality Laboratory (IVAR Lab), which is part of Flexible Manufacturing Systems and Robotics Demo Centre. Data collected after running tests in these two locations can be seen in Fig. 4.

A significant result obtained from the experiment is the fact that different values of the send rate used in the experiment do not affect the time of synchronization. The only parameter affecting the communication speed is QoS – rising level to 2 results in longer ping times (as the message processing time increases), while level 0 and 1 provide approximately equal results. This proves that it is possible to maintain a fast and reliable connection even with high send rate and an acceptable QoS level.

4. BENEFITS OF THE PROPOSED SOLUTION AND FUTURE DEVELOPMENTS

A list of benefits deriving from the exploitation of the proposed infrastructure is the following:

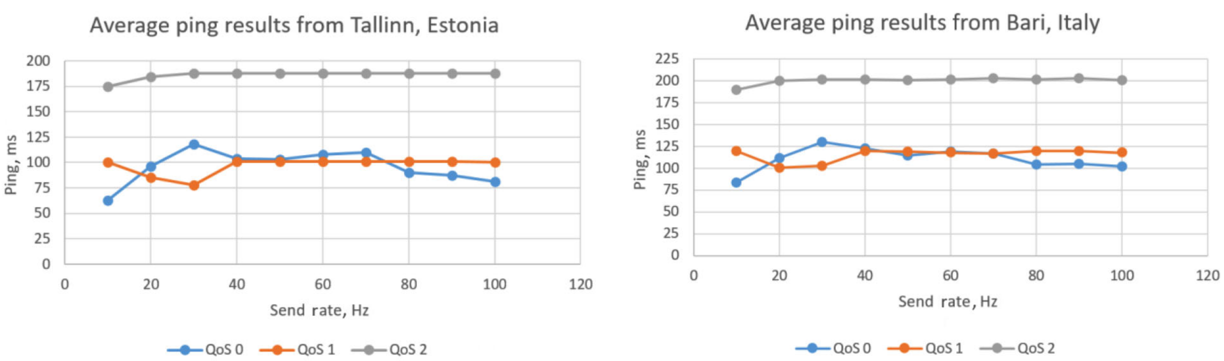

Fig. 4. Experiment results.

- it is possible to work with the system remotely in real time, eliminating the need to be in close contact with dangerous equipment or hazardous environments.
- support of multiplayer mode and remote collaboration. IIoT-enabled devices can efficiently share their work with many clients, allowing them to create a single networked virtual environment where workers can directly communicate while managing the connected equipment. DT can support training with the equipment virtually as training in reality may not be feasible (e.g., too expensive, etc.).
- possibility to create simulations, which allow to "rewind" the state of the virtual system to an arbitrary point of time to identify failures or analyse system's actions, exploiting both, real data coming from the robot and historical data previously collected; and then persisted on the database (a feature to be implemented). Moreover, these capabilities can allow creating virtual sensors, which can send commands to the real machines in order to evaluate performance and track possible collisions with personnel or solid bodies.
- DT brings production efficiency to a new level. Indeed, instead of taking down the manufacturing line to apply some changes, everything can be tested and verified on the virtual clone, and then safely put into production. Human-robot interactions can be tested in the virtual environment in offline mode. In addition, industrial equipment does not need to be stopped while re-programming, which leads to time-saving.

In the future, speed optimization has to be developed to synchronize and integrate other assets of different new and existing labs with the middleware. In addition, the potential of Kafka in the role of middleware has to be investigated. Moreover, the DT will be paired with the database to maintain the history of robot's positions, which can then be used to replay past robot movements (See Fig. 1) [20]. Finally, the overall infrastructure will be tested in other fields also different from manufacturing (e.g., telemedicine).

5. CONCLUSIONS

Results of this work describe implementation of IIoT middleware, which supports full dual-way synchronization between a real robot and its virtual counterpart. An experimental application showed efficient connectivity, and the researchers from STIIMA-CNR (Bari, Italy) were able to control and manage industrial robot situated in TalTech IVAR Lab (Tallinn, Estonia). Moreover, the work gave the opportunity to make an international collaboration, creating the basis for the integration of different laboratories and factory environments into a digital network.

ACKNOWLEDGEMENTS

This research was supported by the project AR16077 Smart Industry Centre (SmartIC) No. 2014-2020.4.01.16-0183, supported by the EU Regional Development Fund. The authors are also grateful to the Computer and Systems Engineering student of the Tallinn University of Technology – Ninel Dudnyk, for her help in the experiments with laboratory digitalization. The publication costs of this article were covered by the Estonian Academy of Sciences.

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Füüsiline tehas ja selle digitaalse kaksiku sünkroonimine tööstusliku nutistu vahevara kaudu: juhtumi uuring

Vladimir Kuts, Gianfranco E. Modoni, Tauno Otto, Marco Sacco, Toivo Tähemaa, Yevhen Bondarenko ja Ruxin Wang

Digitaalne kaksik (DT) on tehase või tehnoloogiaseadme virtuaalne kloon, mis võimaldab erineva detailsusega ka selle staatilisi ja dünaamilisi vaateid (näiteks protsessidest, süsteemidest, toodetest jne). Olulisemate väljakutsete hulgas tootmisettevõttele digitaalse kaksiku metoodika rakendamisel on nutika tootmise taristu väljaarendamine, mis võimaldaks füüsilist tehast digitaalse kaksikuga sünkroonida. Digitaalseid kaksikuid võib seejuures kasutada tootmis-operatsioonide simuleerimiseks ja tehase jõudluse hindamiseks. Selle hõlbustamiseks on artiklis pakutud tööstusliku nutistu vahevaral põhinev lahendus, mis võimaldab kahesuunalist sünkroonimist reaalsete ja virtuaalsete maailmade vahel. Lisaks on analüüsitud lahenduse rakendusvõimalusi reaalse juhtumiuuringu raames, mis viidi läbi TalTechi paindtootmise ja robootika demokeskuses.