A Digital Twin framework for Industry 4.0/5.0 technologies

Mansur Asranov[1,2][0000-0002-3144-9711], Khurshid Aliev[1,2][0000-0001-9551-4925],
Paolo Chiabert[1,2][0000-0002-4740-9896] and Jamshid Inoyatkhodjaev[2][0000-0001-8782-9740]

[1]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
[2]Turin Polytechnic University in Tashkent, Kichik Halqa Yuli 17, 100095 Tashkent
mansur.asranov@polito.it, khurshid.aliev@polito.it,
paolo.chiabert@polito.it, jamshid.inoyatkhodjaev@polito.uz

Abstract. Industry 4.0 Paradigm unleashed tremendous opportunities to boost economical and societal transitions for the business and improved living standards of society, while Industry 5.0 is extending previous technological breakthrough in steering transformation, stimulating industry and society to be human-centric, sustainable, resilient, and green. Digital Twins, in turn, play a key role as enabler in such transformation. Heterogeneity of manufacturing technologies imposes specific challenges in developing and adopting Digital Twins. The main goal of this paper is to propose, assess and justify a robust and open framework of Digital Twins for manufacturing technologies, such as collaborative and mobile robots, as well as subtractive manufacturing machines. A framework eventually can be used by SME, while also in Educational and Research Institutions.

Keywords: Industry 4.0/5.0, Digital Twins, Industrial Internet of Things, Robotics.

1 Introduction

A Digital Twin (DT) framework is an emerging concept that is becoming increasingly popular in the context of Industry 4.0 and Industry 5.0. The idea is to create a digital replica of a physical asset or system, such as a factory or a product, which can be used to simulate and optimize its performance [1]. This approach can help organizations to better understand the behavior of their assets and make more informed decisions about how to manage and optimize them.

In the context of Industry 4.0, a Digital Twin framework can be used to improve the efficiency and productivity of manufacturing processes. By creating a digital replica of a factory or production line, organizations can simulate different scenarios and identify opportunities to optimize processes and reduce waste. This can help to increase throughput, reduce costs, and improve quality [2].

In the context of Industry 5.0, a Digital Twin framework can be used to improve the design and performance of products. By creating a digital replica of a product, organizations can simulate its behavior under different conditions and identify opportunities to improve its design and functionality. This can help to create more innovative products that better meet the needs of customers [3].

A Digital Twin framework typically involves the integration of various technologies, including the Internet of Things (IoT), artificial intelligence (AI), advanced robotics, and big data analytics. By leveraging these technologies, organizations can collect data from sensors and other sources, analyze it in real-time, and use it to improve the performance of their assets and systems [4].

A Digital Twin framework has some benefits that could be included for Industry 4.0/5.0 technologies [5]:

- Data Acquisition: The first step in creating a Digital Twin is to acquire the necessary data from physical systems. This includes sensor data, machine logs, and other relevant data sources. The framework should provide guidelines on how to collect and manage this data.
- Modeling: Once the data has been collected, it must be used to create a virtual model of the physical system. The framework should define best practices for creating accurate and reliable models.
- Integration: The Digital Twin should be integrated with other systems and platforms, such as Enterprise Resource Planning (ERP) systems, Manufacturing Execution Systems (MES), and other Industry 4.0/5.0 technologies. The framework should provide guidelines for how to accomplish this integration effectively.
- Analytics: The Digital Twin generates vast amounts of data, which can be analyzed to gain insights into the performance of the physical system. The framework should define best practices for analyzing this data to identify patterns, trends, and opportunities for optimization.
- Visualization: The Digital Twin can be used to create visual representations of the physical system, such as 3D models or Augmented Reality (AR) displays. The framework should provide guidelines for how to create effective visualizations that support decision-making.
- Maintenance: The Digital Twin should be maintained over time to ensure that it remains an accurate representation of the physical system. The framework should provide guidelines for how to update and maintain the Digital Twin effectively.

The objective of this article is to introduce a Digital Twin framework concept that can be utilized in manufacturing scenarios, concentrating on collaborative and mobile robots. Furthermore, the article outlines the process of Digital Twin implementation and how communication and services take place between physical, simulation, and digital assets. The results section provides information on the framework's application layer, which is intended to be beneficial to small and medium-sized businesses, as well as educational and research establishments.

2 Related works

The concept of Digital Twins has gained significant attention in recent years, becoming a key aspect of Industry 4.0/5.0 and enabling companies to optimize their operations, reduce costs, and improve performance across a wide range of industries and applications. This literature review explores the origins and evolution of the Digital Twin concept, its key components and applications, and the current state of research and development in this field.

An overview of Digital Twins and how they can be used to improve manufacturing systems which includes a discussion of key elements of a Digital Twin framework is provided by authors [6]. Another research paper discusses the challenges and opportunities of creating Digital Twins for Industry 4.0. It provides a framework for developing Digital Twins and describes how they can be used to support various industrial processes [7]. Another study demonstrated the potential of digital twin technology by simulating a UR3 collaborative robot in the V-REP environment and utilizing the Modbus communication protocol [8]. A book by Alasdair Gilchrist provides a comprehensive introduction to Industry 4.0 and its key technologies, including the Internet of Things, cyber-physical systems, and cloud computing [9]. A systematic approach of implementing a digital twin, driven by information from various lifecycle stages is proposed by researchers. This approach uses a digital thread as linker between the different type of information to the digital twin applications [10].

Other literatures provide a comprehensive overview of Digital Twins and their application in Industry 4.0 that includes examples of Digital Twin implementations in various industries and a discussion of key applications, such as predictive maintenance, quality control, and supply chain optimization [11] [12].

A different article investigates the development of Industry 5.0 and its fundamental traits, including a focus on humans, sustainability, and resilience. It suggests a three-dimensional framework for implementing Industry 5.0, analyzes significant drivers, potential applications, and challenges. The paper concludes by emphasizing the importance of a comprehensive Industry 5.0 system and by suggesting future research directions. The primary aim of this paper is to encourage discussion and cooperation in the Industry 5.0 sector [13].

Nahavandi et. al. provides an overview of Industry 5.0 and its key features, including the integration of human skills and the use of advanced technologies like AI and robotics. It also discusses the role of Digital Twins in supporting Industry 5.0 [14].

Above mentioned literatures provide concepts of the Digital Twin but does not present a solution with a case study applications. Therefore, this paper aims to provide steps to develop a Digital Twin from the Physical assets using proposed framework concept.

3 Digital Twin framework concept

The proposed framework supports conceptual overview of technology stack used for building a DT. Higher level abstraction of the framework incorporates functional planes and interfaces. The Figure 1 illustrates the structure of the framework.

Fig. 1. The Digital Twin framework structure abstraction.

As can be seen from the Figure 1, the framework consists of the following planes and interfaces:

- *Physical Plane.* Physical assets that include shop floor technologies, such as, collaborative and industrial robotic systems, additive and subtractive manufacturing systems, and mobile robotic systems reside at this plane.
- *Southbound Interfaces.* This plane represents interfaces that support communication and plays a key role in providing necessary communication services for monitoring and control data exchange between Physical and the other functional planes.
- *Data Plane.* This plane is responsible for supporting data acquisition, processing, storage, and management services for other functional planes of the framework.
- *Control plane.* The plane represents services for enforcement of control functions on physical plane assets, as well as their digital replicas in the Visualization plane.
- *Northbound interfaces.* These interfaces support communication services between the digital assets of Visualization plane and Data, Control planes of the framework.
- *Visualization plane.* Digital counterparts of the physical assets are concentrated at this plane. Moreover, this plane provides access to HMI interfaces of the physical and digital assets, therefore giving opportunity of extended control and visualization for end-users.

4 Digital Twin implementation

In the case study, implementation of the Digital Twin relies on the framework abstraction described in above section. In the following sections, items of the technology stack are described in more detail starting from Physical plane up to Digital Twins, finally being concluded with process flow between physical assets and their digital counterparts. The implementation relies on a physical laboratory for additive and subtractive manufacturing processes integrating robots, cobots and mobots.

4.1 Physical Twin description

The physical twins of the framework are represented by heterogenous manufacturing technologies available in the lab and can be subdivided into two categories:

- *Fixed Robotic Systems.* This subcategory represents collaborative and industrial robotic systems, which are statically fixed in a cell and implement manipulation function in a manufacturing process. In the case study, collaborative robots from Universal Robots: UR10e, UR3e, as well as ABB IRB 4400 industrial robot, are used as the Fixed Robotic Systems.

- *Mobile Robotic Systems.* Mobile robots, typically performing transportation services for supporting internal logistics of the manufacturing process, are represented in this category. The case study focuses on a mobile robot with extended manipulation capabilities. Specifically, mobile robot-manipulator is based on UR3 manipulator, fixed on the frame on top of Mobile Industrial Robot MiR100. This robot supports execution of mixed tasks, such as pick-and-place and transportation of the workpieces in different manufacturing scenarios.

4.2 Communication and services infrastructure

The communication and services infrastructure described in this section, allows for building a robust bridge between physical and digital world.

The infrastructure that supports the communication and provision of the necessary services for the workflows of DT is described using extended version of the previously introduced conceptual framework. Specifically, each functional plane and interface include corresponding enabling technology that provides necessary services for DT. The following part of this section describes and discusses each enabling technology in detail, focusing on their specific role in completing overall workflow.

The figure 2 depicts a detailed technology stack of the DT framework.

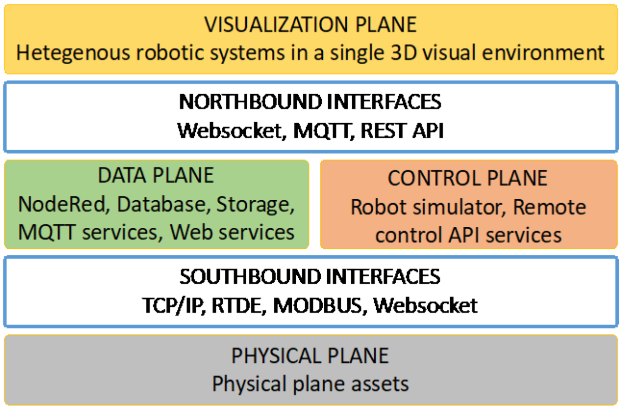

Fig. 2. Technology stack in extended DT framework

As can be seen from the Figure 2, each plane and interface contain specific enabling technologies that support the services:

- *Visualization Plane.* Digital replicas of heterogenous Robotic Systems, previously introduced in Physical twin description section, reside at this plane. The visual behavior of digital replicas relies on the data received from Data and Control planes, through the appropriate Northbound Interfaces.
- *Northbound Interfaces.* Heterogeneity imposes specific challenges in integration of robotic systems from different vendors. Therefore, careful adoption of different interfaces and Application Programming Interfaces (API), provided by vendors, are required. For this reason, Websocket, MQTT and REST API are included in the

framework as the Northbound Interfaces for the case study. As mentioned before, these interfaces provide communication services between Data, Control and Visualization planes.

- *Data Plane.* The Data Plane comprehends a set of services, focused on horizontal and vertical data flow support, which is necessary to drive overall DT framework. This plane represents NodeRed service for data acquisition and management, while Database service records time series data related to hardware health status of the physical twins. Additionally, MQTT service facilitates data transmission procedures, while the Storage is responsible for provision of file system service, necessary for storing digital assets, configurations, robotic programs, and related data. Finally, Web services provide engine for running the unified Web Applications Environment discussed in section 4.4.
- *Control Plane.* This plane provides access to the simulators and remote-control API services, therefore, allowing for extended control of the Robotic Systems in both Physical and Visualization planes. The Control plane relies on the Data plane in terms of exchange of control information, and relies on Southbound Interfaces for enforcing control functions
- *Southbound Interfaces.* A boundary between physical and digital parts of the framework are represented by these interfaces. Similarly, as Northbound interfaces, realizations of communication at this plane relies on accurate decisions about selecting appropriate interfaces. In the case study, TCP/IP, RTDE, MODBUS and Websocket interfaces are selected. These interfaces are used for acquisition of raw hardware status data in upstream direction, while in downstream direction, they support communication for the control functions enforcement, originated by the Control Plane.
- *Physical Plane* is presented in this section to complete the logical sequence of discussion, but it has been already described in detail in the section 4.1.

The assets and services in Data, Control and Visualization Planes are organized as microservices (Figure 3).

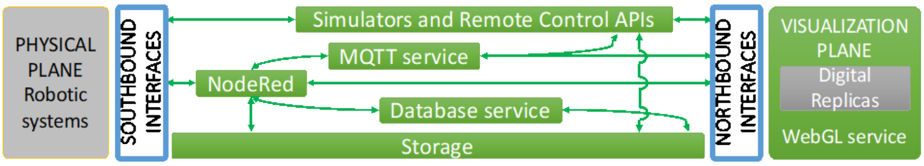

Fig. 3. Microservice architecture for supporting DT framework.

Arrows between microservices represent horizontal and vertical data exchange during interaction between the enablers from various planes of the DT framework, as discussed previously. Each microservice is enclosed in a container (green boxes) and performs the desired functions. The containers for microservices are developed using Docker software, and they include necessary runtime environment (middleware libraries and binaries) to run the services.

4.3 Digital Twin description

The Visualization Plane, hosting the digital replicas of Robotic Systems, gives a unified access for end-users to monitor, control and manage the DT. In a web application terminology, it can be considered as front-end system, which stays near to end-users, while the other microservices reside in a back-end, supporting overall workflow of DT.

In the case study, this front-end system is accessed by the end-users using web browsers, and incorporates all the necessary digital assets and tools to support interaction between end-users and DT:

- Digital replicas – 3D models of Robotic Systems: ABB IRB 4400 industrial robot equipped with high-speed spindle, Universal Robots UR10e collaborative robot, mobile robotic manipulator system based on Universal Robots UR3 collaborative robot and Mobile Industrial Robot MiR100.
- Dashboard services – these services give the access to NodeRed dashboard user interface, which contains performance real time and historical data. Such data are based on the readings from different sensors of Robotics System and managed using NodeRed flow design capabilities.
- Control services – this capability is supported by virtual instances of Universal Robots Simulation software (URSim), running in containers, as well as control interfaces on the physical counterparts. To provide seamless end-user access to these control services in the same browser, open-source RPORT software is utilized. The RPORT software is also packed into a container and added to the set of containerized microservices.

Obviously, the 3D models are designed in CAD and 3D modelling software. The workflow that integrates digital replicas of different robotic systems, monitoring and control tools, kinematic models and allows for their visualization in a browser, is represented in Figure 4:

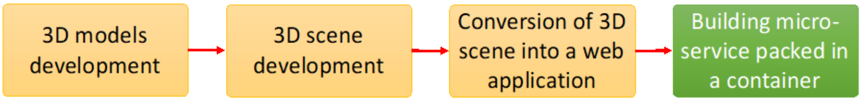

Fig. 4. Digital replicas web application microservice development workflow.

The workflow illustrated in Figure 4 in composed of the following four phases:

- *3D models development.* 3D models are developed using CAD/3D modelling software (SolidWorks). Important decisions are made regarding solid components. The modeling of robots' joints has a relevant impact on the replication of robot movements in the digital environment with respect to the true motion the robot carries out in the physical environment. Finally, 3D models are converted into appropriate file format and passed to the next phase of 3D scene development.
- *3D scene development.* This phase requires complex development and configuration process, where 3D models and their kinematics are synchronized with their physical counterparts, along with integration of monitoring and control tools in a single 3D

environment. Therefore, 3D game development software is used (Unity3D), which provides comprehensive toolbox for 3D scene design. 3D models are imported into the 3D scene, necessary kinematics behavior of robots is configured, and important monitoring and control tools are integrated using C# and Python APIs of the Unity3D software. As discussed before, Robots' behavior, monitoring and control tools rely on the communication provided by Northbound and Southbound interfaces, as well as on appropriate data provision supported by NodeRed and MQTT services.

- *Conversion of 3D scene into a web application.* Developed and properly configured 3D scene is converted into a web application using built-in tool of Unity3D software. Unity3D software generates a web application files package, which is then passed to the next phase. Unity3D software utilizes WebGL framework for converting 3D applications into a web applications (Figure 3).
- *Building microservice packed in a container.* Finally, the web application files package, the output from previous phase, is packed into a container, along with necessary runtime environment (software libraries and binaries), and added into the microservice architecture, as described in Figure 3.

4.4 Process flow between Digital and Physical systems

The process flow that supports interaction between the Digital and Physical systems, relies on the unified Web Application Environment. This environment aggregates different activity modes, assets and microservices in a single workspace (a web browser). The figure 5 illustrates that process flow, which incorporates previously described elements of the DT framework along with an end user, another actor of the process.

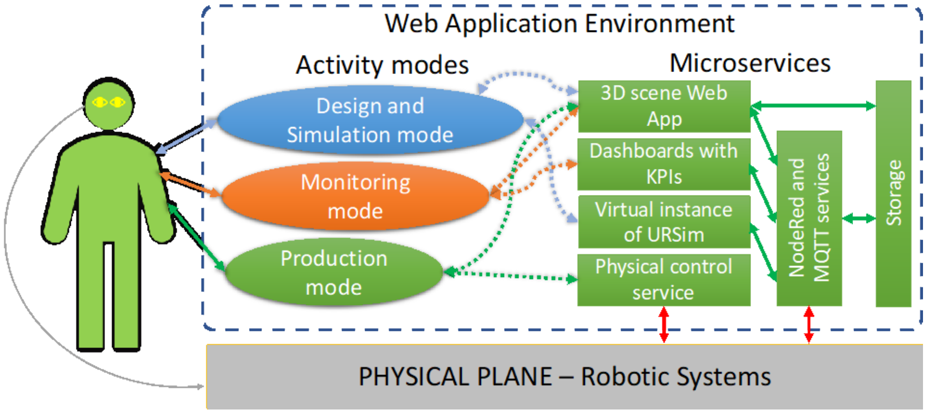

Fig. 5. Process flow of the DT framework.

In Figure 5, the end-user interacts with the Web application environment that engages digital resources and communicates with the physical Robotics Systems.

Digital resources are grouped into two categories:

- *Activity modes* – elements of this category, represent capabilities that can be leveraged by utilizing each corresponding mode;
- *Microservices* – repository of previously introduced microservices and assets, which support capabilities, provided by the Activity modes.

Activity modes includes the following:

- *Design and simulation mode* – a web page, which allows for designing and simulating the manufacturing processes (blue solid arrow). Corresponding microservices are retrieved (blue dashed arrows) from the Microservices repository to support the capability. Manufacturing process can be designed and simulated using virtual instance of URSim software. The activities are immediately visualized in the 3D scene Web application.
- *Monitoring mode* – a web page, which supports observation of KPIs of Physical Robotics Systems and overall manufacturing process (orange solid arrow). This activity mode relies on 3D scene Web application along with Dashboards and KPIs services (orange dashed arrows).
- *Production mode* – at this web page, the end-user is provided with capability to interact with the Robotic Systems of Physical Plane (green solid arrow). The robotic programs, simulated and verified in the Design and Simulation mode, can now be tested in physical Robotic Systems, using Physical control service. This service gives direct access to the control interfaces of the Robotics systems in the same browser, the end-user utilizing, and the results of such interaction can be visually inspected in the 3D scene web application (green dashed arrows), as well as in a physical workspace (grey solid arrow).

Finally, the services, supporting the Activity modes, exchange real time monitoring and control information with NodeRed and MQTT broker services. They also store and retrieve the time series hardware health, configuration, and 3D assets data, provided by the Storage service (green solid arrows).

Additionally, Physical control, NodeRed and MQTT services can communicate with physical robotics systems to acquire real time status data, while also enforce control actions on the physical Robotics Systems (red solid arrows).

The figure 6 shows the implementation of the proposed DT framework, using the

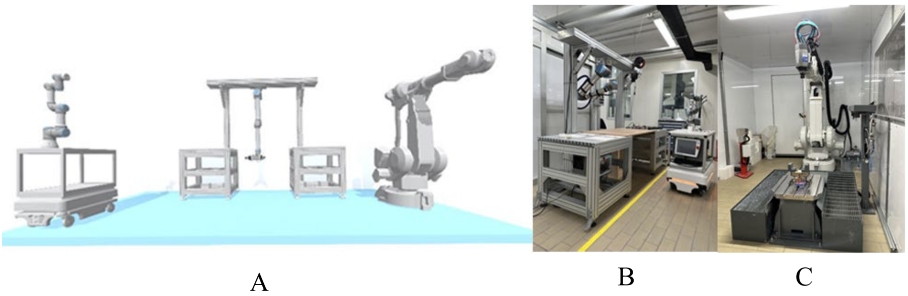

Fig. 6. Implementation of DT framework

available assets in the lab of the department. As can be seen from the figure DT counterparts of physical robotic systems are combined in a single 3D environment. Figure 6.A depicts the Digital Twins of the robotic systems, while Figure 6.B and Figure 6.C show their physical counterparts. Interaction of the assets is supported by the proposed framework. The work on building manufacturing scenario using the assets and supporting DT framework is undergoing.

5 Results, discussion and conclusions

Nowadays, web applications, being popular in a digital services domain, relies on existence of appropriate browser and web server to deliver a digital service. This, in turn, attracts end-users since it requires minimum efforts to consume the service. Therefore, in the case study, in order ensure the best user experience, Web application approach has been selected for supporting interaction between end-users and DT framework. However, such approach is still needing an assessment in terms of cognitive load, which may impact the overall user experience and quality of service.

Microservices approach provides flexibility, scalability, portability, and robustness of the DT framework. This approach is well adopted by IT professionals. Thank to such adoption, the proposed DT framework can be easily deployed and maintained in both industrial companies and research communities. Moreover, the containerization allows for deployment of DT framework in any container orchestration platform: starting from Docker Desktop on a standalone PCs, to advanced and highly scalable enterprise orchestration engines, such as Kubernetes, Mesos, Docker Swarm, OpenShift etc.

The configuration of containers in the current state of the DT framework is performed manually and requires relevant effort for adding new manufacturing technologies into the Physical plane. Therefore, there is a room for improvement to add automation of container configurations procedures, to provide flexibility of DT framework to different changes of manufacturing scenarios.

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