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Toward a digital twin of a robot workcell: standards and methods

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Abstract

Digital twins are poised to improve the engineering, operation, and management of manufacturing facilities. However, implementing digital twins has been a challenge primarily due to a lack of resources and the absence of standardized digital twin frameworks and methods. This paper describes creating a digital twin of a robot workcell using available standards, tools, and methods. The workcell comprises collaborative robot arms, a computer numeric control (CNC) machine tool, and a coordinate measuring machine (CMM). The ISO 23247 standard provides a guideline for building the digital twin. Data are collected from physical devices and the MTConnect standard provides a format for communicating the data between the physical equipment and their digital counterparts. The machine components in the workcell are represented as models in the virtual world. This research shows that the above standards and methods support building a digital twin of a robot workcell. The data collected and communicated can be used to improve workcell functions such as quality management and predictive maintenance.

Keywords

Digital twin, methods, standards, data streaming, robot workcell

1. Introduction

Smart manufacturing requires the ability to model a system, analyze its data, and evaluate it under different operational conditions in the virtual world. A digital twin provides not only these functions but also monitors, diagnoses, predicts, and prescribes a course of action for a system, in real-time, during operation. The ISO 23247 standard defines a digital twin as a ''fit-for-purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization.'' Building a digital twin requires representing a system in a virtual environment and connecting and synchronizing it with its digital counterpart.[1] Digital twins involve highly complex functional subsystems and activities, including data collection, processing, communication, modeling, analytics, visualization, simulation, and optimization and control.

Some digital twin models are developed from the first principles of the system. The digital twins developed with this approach are called physics-based digital twins and require a high level of knowledge of the science behind the system. However, data-driven digital twins are built predominantly on data collected from the system. Many digital twin developers use simulation tools to represent the physical system. Simulation combines the science of the system as well as its data. Kutscher et al.[2] describe how a digital twin can be developed using simulation techniques. Some digital twins incorporate three-dimensional (3D) virtual reality animations. Recently, augmented reality has been applied in the digital twin to enhance simulation graphics and provide visualizations that are more illustrative and user-friendly.[3] Simulation supports testing out new ideas and approaches as well as prediction. The digital twin simulates a system during operation, using data that changes dynamically with time, and the results can improve digital twin services. For example, a digital twin simulation and predictive analytics increase the efficiency of scheduling activities such as maintenance. The prediction accuracy increases as more data are collected to update the prediction model.

Building a digital twin requires a framework that can be instantiated for case-specific implementations of digital

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twins. However, digital twin developers have used disparate approaches.[4,5] In general, the details of any digital twin depend on the physical object or process and the intended purpose of the digital twin. Shao and Helu[6] discussed different perspectives on the digital twin to identify critical characteristics that must be understood when creating a digital twin for a specific application. These perspectives are (1) application (intended use), (2) viewpoint (product, process, or system), and (3) context, including temporal integration issues—whether real-time exchange is necessary or not and the level of importance of data visualization. The objectives and scope determine the type of information and detail to include in the digital twin. Furthermore, different digital twins can be developed for the same system, with each twin serving a different purpose. Manufacturing digital twins, for example, have been developed for purposes such as factory design, production scheduling, predictive maintenance, risk analysis, product quality, and constraint analysis.

Despite its many benefits, implementing a digital twin is still challenging, especially for small- and medium-sized manufacturers (SMM), because of a lack of expertise and resources, lack of cost-benefit analyses, and insufficient information on technologies and standards.[1,7] There is also a lack of a universal definition, implementation framework, and protocol. This paper shows how a digital twin for manufacturing applications is built using existing tools, standards, and tools. The procedure is illustrated with a robot workcell.

A digital twin needs credibility regarding Verification, Validation, and Uncertainty Quantification (VVUQ), and testing. It has been observed that for the digital models to be truly representative of the actual system during operation, revolutionary approaches to verification and validation of the models, simulations, and systems are needed.[8] To ensure that the developed digital twins are helpful, the results generated by the digital twins must be trustworthy for real manufacturing needs.[9] The VVUQ activities, however, are not included in the current series of the ISO 23247 standard nor in any of the existing digital twin standards. Techniques involving model-in-loop, software-in-the-loop, controller-in-the-loop, and hardware-in-the-loop can be explored for digital twin assurance.[10–12] VVUQ needs to have a life cycle approach because the conditions under which real systems operate may not all be foreseen during system development. In addition, it is also necessary to verify and validate digital twin data acquisition systems, configurations, analytical algorithms, and scenarios.

It is observed that many industrialists rely on digital twin solution providers such as PTC, Oracle, Microsoft, and IBM to build and maintain their digital twins, which is a costly investment. The implementation details of digital twins are also often not publicly available, making it difficult to understand their components or assess their effectiveness, share lessons, and collectively advance and benefit from digital twin technology.[13] Current digital twin literature is dominated by technical approaches, analysis methodologies, and challenges of data collection and integration of the digital twin components.[14] Moreover, the number of case studies decreases with the increasing level of integration between the physical system and the digital counterpart.[15] The motivation for this paper is to provide an approach based on available simulation tools and interface standards that manufacturers can leverage to implement digital twins. This research of this paper identifies and demonstrates available technologies, methods, standards, and tools that support digital twin development for manufacturing while highlighting challenges and providing recommendations for standards and testing. The methods and tools for this digital twin provides an affordable alternative compared with engaging solution providers. The size of the workcell makes our approach suitable for SMM adoption, but the tools and procedures are relevant for large industrial-scale machines.

This paper would be useful to industrialists planning to implement digital twins in the manufacturing systems, digital twin solution providers, and digital twin researchers. These stakeholders will benefit from this research by broadening their awareness of research gaps, modeling methods and tools, and especially the role and selection of interface standards for a digital twin in a manufacturing environment. This paper especially provides a guide to SMM who aspire to integrate digital twins in their operations. The rest of the paper is organized as follows: Section 2 provides a background to the research, Section 3 offers relevant work for building a digital twin while highlighting the framework standards and methods, Section 4 is an overview of the workcell with the equipment, peripherals, and its configuration, Section 5 describes the digital twin modeling process and how data are extracted from the physical workcell and communicated to the digital counterpart, and Section 6 presents discussion and the way forward.

2. Background

Several publications provide theoretical definitions, foundations, and justifications for a digital twin. However, real-life implementations in industry have not caught up with the increasing literature.[13] One of the main reasons is the difficulty and lack of methods and established guidelines for implementing a digital twin. Moreover, few implementation details are publicly available even with the successfully implemented cases. Practitioners seeking digital twins, especially SMMs, need cases from which lessons can be drawn for their benefit. To this end, a digital twin laboratory comprising a small-scale robot workcell is being established at the National Institute of Standards and Technology (NIST). The workcell acts as a testbed to

identify and develop use-case scenarios representing common manufacturing processes and challenges faced in industry. Digital twins built for these use cases will result in publicly available digital twin development guidelines, methods, procedures, and processes. In addition, relevant standards, technologies, and methodologies for the digital twin will be tested, and the findings will result in new contributions to digital twin standards for manufacturing.

This paper enhances the previous publication by Kibira et al.,[16] who identified and demonstrated technologies, methods, standards, and tools supporting manufacturing digital twin development. The research is still a work in progress, and the scope is limited to collecting data from the physical domain and streaming it into its digital counterpart in real time. A taxonomy in a publication by Kritzinger et al.[15] classified different levels of integration or interactions between the physical object and the digital counterpart to understand digital twins. These classifications are digital model, digital shadow, and digital twin. This paper is at a level of the digital shadow as the research progresses toward a digital twin. A discussion of the procedure to do the same for the CNC machine tool and the CMM is also provided.

The flow of activities in this paper provides an affordable starting point toward realizing the digital twin involving bidirectional data flow between the physical and its digital counterpart. The work is ongoing, but the successful completion will result in understanding the procedure, methods, and best practices for a digital twin of a manufacturing application. It will also inform the relevant standards. In furthering the work of this paper, the workcell will be integrated using the open-source software, ROS, to control robot arms and other equipment during operation. These will provide the closed loop needed for the digital twin.

3. Related work

This section reviews several related issues, including frameworks, interfaces, tools, and procedures for implementing digital twins. The original definition of the digital twin emphasized the three major components: the physical world, the digital world, and interconnections of data and information flow between the physical world and the digital world.[17] As the applications and services of the digital twin expanded, new requirements to meet these applications emerged. The result was new components (digital twin dimensions), that is, data and services. Based on the identified new dimensions, the enabling technologies and tools for the digital twin were identified in the publication. These were classified from the perspective of cognizing and controlling the physical world, modeling the physical world, digital twin data management, digital twin services, and connections within the digital twin. These expanding dimensions call for frameworks to support building a digital twin. Autiosalo et al.[18] analyzed the digital twin models regarding the application field, hierarchy, discipline, dimension, universality, and functionality. Cimino et al.[19] provided an overall vision of the digital twin in manufacturing, emphasizing identifying the different levels of detail of digital twin applications, including production systems, manufacturing cells, workstations, equipment, or products. The discrepancies between the literature and implementations were reviewed. Thelen et al.[20] reviewed digital twin-enabling technologies emphasizing technologies that facilitate physical-to-virtual and virtual-to-physical, based on the direction where data flows. Lehner et al.[21] analyzed digital twin platforms for manufacturing to understand the extent to which they fulfill requirements such as synchronization, interoperability, and real-time behavior specified in the ISO 23247 standard. It was found that only some of these requirements were considered during the development of the software. Avenues for future improvements were identified.

There are also several frameworks for a digital twin. Examples of digital twin frameworks at a high level are provided in Lu et al.[22] and Onaji et al.[23] Such frameworks, developed for high-level resolution, offer little utility for a digital twin of a small workcell. However, Galli et al.[24] recognized the availability of several digital twin frameworks and set out to find similarities between them. The focus was on the structure of the frameworks to find correlations in terms of form and conceptualization. The available architectures were identified as traditional, service-oriented, and fractal. Despite these efforts, no universal definition, implementation framework, and protocol are available. There is also a lack of comprehensive and in-depth analysis of digital twins from the perspective of concepts, technologies, and industrial applications research.[25]

In response to the high expense of digital twin solutions, Shah et al.[26] investigated the approach to using open-source software to develop a digital twin. The objective was to improve accessibility, affordability, and reusability by building a digital twin entirely on open-source software tools and standards. The physical system was represented by a mathematical model suitable for systems like a portable temperature-controlled chamber, which was used as a case study for that research. Using a mathematical model would be very difficult or impossible for a complex manufacturing system. The research of this paper uses simulation modeling software tools to model a manufacturing system and available interface standards to exchange data between the physical world and the digital world. The standard-based approach provided as an example in this paper relies on a universal definition, implementation framework, and protocol.

4. Workcell description and configuration

The workcell consists of small collaborative robot arms for material handling and machine tending, a CNC

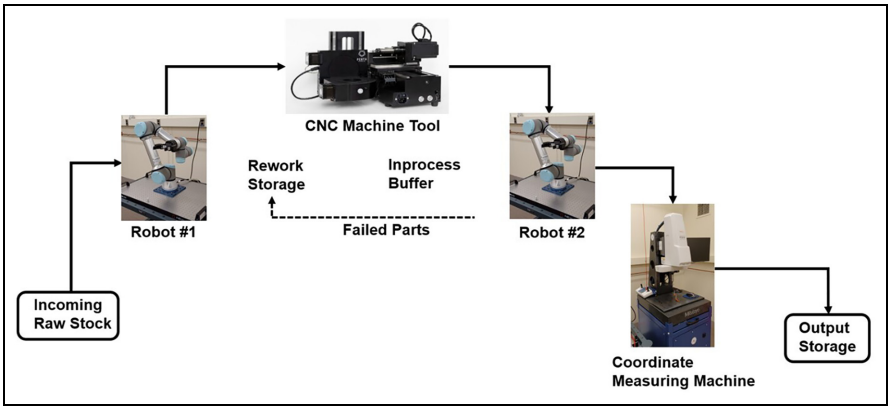

Figure 1. Workflow through machines and equipment in the robot workcell.

machine tool for producing a part, and a CMM for product geometry measurements and quality control. The inspection process provides product information that verifies and validates selected parameters used in the quality control. This is accomplished by comparing measurements with the nominal model (CAD model of the workpiece). Dimensional data from the geometries of interest is collected and analyzed through a computer-aided inspection system to determine geometrical dimensioning and tolerancing errors. The results of that analysis are used to determine feedback to the process. The general workflow in the workcell is shown in Figure 1. Typical operational tasks include receiving parts, loading parts to the CNC, machining the parts, unloading parts from the CNC, loading parts to the CMM, inspecting the parts, and unloading parts from the CMM. Any parts that do not conform to specifications are reworked. There is a single input buffer and a single output buffer.

The workcell is reconfigurable to different scenarios, for which a different digital twin can be developed. In one configuration, ROBOT #1 can be dedicated to picking a workpiece from the input buffer, loading it into the CNC machine tool upon request, offloading the finished part, and placing it into the in-process buffer. ROBOT #2 picks the part from the in-process buffer, loads it to the CMM machine, and offloads it when the inspection is completed. Both robots could share all tasks in a different configuration if their work envelopes can be appropriately designed to minimize or eliminate possible collisions.

To be reconfigurable, the available floor space plays a significant role in determining the layout of the workcell. The elements in the workcell can be relocated for efficient material flow management. However, this paper focuses on demonstrating how existing tools and standards can be leveraged to support digital twin development. The activities associated with acquiring necessary hardware and software to support reconfiguration are not considered. In addition, specific issues of the workcell equipment, such as robot singularity, are resolved during the development of the robot instruction program. Hence, a description of how the digital twin will support these endeavors is beyond the scope of this current work.

4.1. The workcell components specifications

The workcell consists of primary components and some miscellaneous items as follows.

4.1.1. Robot arms and end effector. The robot arms are universal UR5e robots with 6 degrees of freedom. They are designed for a payload capacity of 5 kg and a reach of 0.85 m. Programming the robot is done by coding a program (URScript) or using a direct human–machine interface. A teach pendant, a handheld device used to instruct a robot, provides the human–machine interface. This device is available. The end effector or tool mounted at the robot's end is the 2F-85 Gripper (see Figure 2). The gripper is used in both time-based control and event-based control schemes. The gripper is controlled through the robot controller or the Programmable Logic Controller (PLC).

4.1.2. CNC machine tool. The machine tool is a five-axis Pocket NC V2-50 Desktop CNC mill. It executes standard G codes. The Pocket NC machine tool can be programmed either manually or by obtaining the tool path from a Computer-Aided Manufacturing (CAM) software and transferring it to the machine tool. The Pocket NC operates with the most common CAM software.

4.1.3. Coordinate measuring machine. A coordinate measuring machine is a tool that measures the dimensions of a part using coordinate technology. The purposes of a CMM are to (1) assess the quality of the product regarding conformance to specifications and geometric dimensioning and tolerancing (GD&T) and (2) provide feedback to improve the process and the products manufactured. This

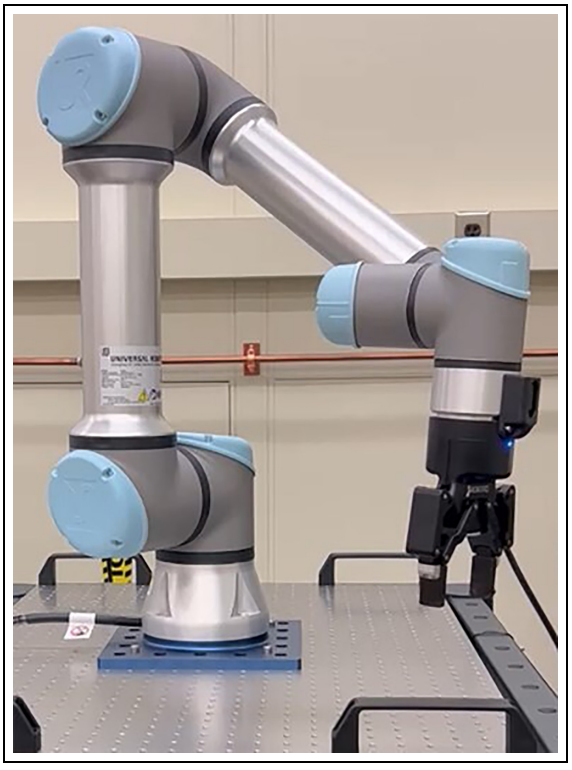

Figure 2. The UR5e robot arm with the attached 2 F-85 Gripper.

CMM will be integrated with other equipment to provide real-time feedback for effective process monitoring and control instead of just inspection, as would be the case in the standalone mode.

4.1.4. Other workcell elements. Other workshop elements include the optical tables, human–machine interfaces (teach pendant), and part fixtures. Stacked lights and alarm systems will be installed to alert anyone when the workcell is in operation to ensure safe operations.

5. Digital twin development process

This section describes the procedure for modeling to represent the real/physical elements in the digital world, data collection from the real system, and data streaming to update the state of the digital world. There is also a section on monitoring the physical system in the digital world based on the data. This process has been completed for the robot arm, for which detailed descriptions are provided. Modeling plans for the Pocket NC and CMM are described.

5.1. Framework and standards

Currently, the digital twin and its benefits in industry are widely published in the literature. However, there is no single, agreed-upon approach to developing digital twins.[27] However, researchers have developed frameworks to guide building a digital twin. These frameworks have considered how the major components, such as the physical system, digital model, and data collection and communication, would work together in a digital twin. These have been reviewed in related work.

5.1.1. The ISO 23247. ISO 23247 is a standard for building a digital twin for manufacturing applications.[28] This standard is chosen because (1) it provides a repeatable procedure that other industries can adopt, and (2) it has sufficient instructions for a user to follow. The ISO TC184/SC4 committee developed the standard to standardize a digital twin architecture framework for manufacturing applications in the context of Industry 4.0. The framework provides a guide on how to build a digital twin for manufacturing, specifying how systems can interoperate and how data from different sources can be integrated. Shao et al.[29] provide an analysis of the strengths, the applications, and the interdependence across the different layers of the standard. Analyzing this interdependence leads to understanding how the standard contributes to the digital twin and smart manufacturing. The standard is at a high to medium level of specification with a structure that enables it to be applied to areas besides manufacturing. In recent research, the standard has been applied to the aerospace industry, where the objective is to develop a collision avoidance system by detecting small objects in space and taking corrective action in time.[30] However, its specifications at a medium-level guide building digital twins and are now increasingly being applied.

The framework is composed of four domains represented by four different application layers. The first layer deals with the domain of observable manufacturing entities (OMEs): the devices, sensors, machines, materials, products, and other shop floor elements we are interested in monitoring and controlling. The second layer represents the data collection domain and device control that support monitoring and collecting data from the OME domain. The third layer is responsible for management, modeling, and optimization of the system. OMEs are modeled and synchronized within this domain to provide services such as monitoring, analyzing, predicting, and optimizing the system. This domain is the core of the digital twin. The provision of services falls within the core of the digital twin. These services include activities such as simulation, analysis of data from the OMEs, production scheduling, and reporting of actions such as production and order status. Finally, there is the user domain, where entities such as human users, devices, or other systems that use the services provided by the digital twin core domain.

Figure 3 is an instantiation of the entity-based reference model for the robot workcell elements. The first layer of

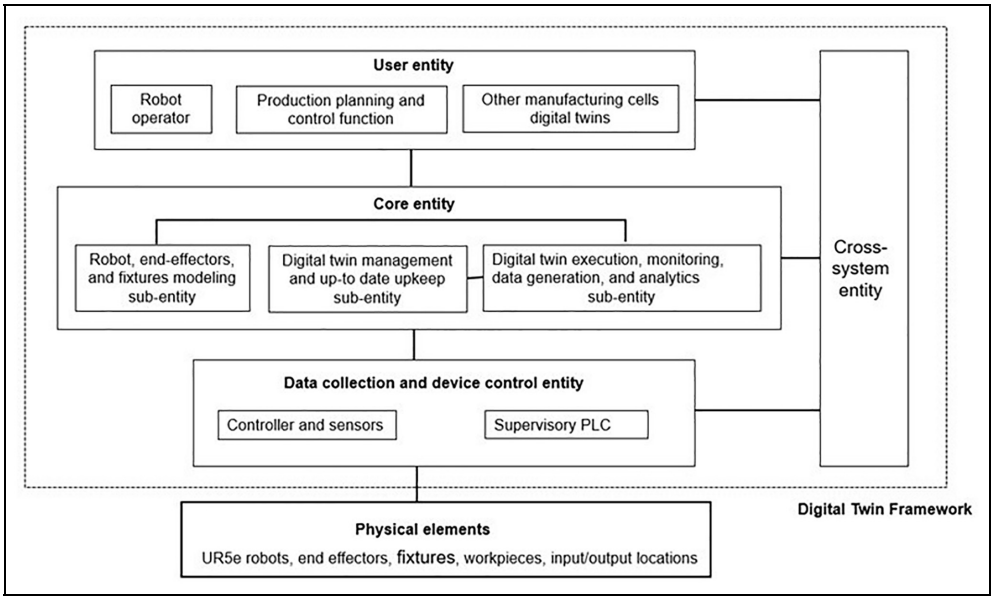

Figure 3. Instantiation of the ISO 23247 standard for the robot workcell.

the OMEs, looking from the bottom up in the figure, corresponds to the manufacturing elements where the robots, Pocket NC machine tool, and other equipment are located. It is from these OMEs that data are collected. These machines require adapters for data to be collected. We created MTConnect adapters to run as Python scripts on the robot arms and the Pocket NC controllers. The data transmitted are the basis for the digital twin. The second layer, higher in the hierarchy of the architecture, shows the data collection and device control entity. These are the controller, sensors, and PLCs. To further assist in data collection, a Raspberry microprocessor Pi has been incorporated into the robot system, and it is one that has the adapter installed. The third layer constitutes the core entity or the nucleus of the developed system. This is the aggregation of the elements that comprise the manufacturing system and those that perform the basic activities of the digital twin. The services provided by the digital twin in this work are monitoring the equipment performance with two-dimensional (2D) visualization. It should be noted that there are many potential functionalities of greater complexity that require a higher degree of maturity of the digital twin in its development than the version of this paper. The last is the user entity, who are those interested in consuming the services provided by the digital twin. These may be people or systems within the manufacturing plant. The user entity can be extended to external users of companies in the industrial sector that require monitoring services and 3D simulation of CNC machine tools.

5.1.2. MTConnect. Data from different machines and applications is often available in different formats that may present problems regarding integration.[31] Neutral formats are required. The MTConnect Standard is an open-source and royalty-free protocol that enables data transmission to be used by web clients via Transmission Control, Protocol Internet Protocol (TCP/IP). The MTConnect standard avails data in a neutral format and is based on eXtensible Markup Language (XML). This protocol and associated interfaces enable data transmission from a physical machine to its digital counterpart. While MTConnect has been used to collect data from a machine tool for status monitoring and analysis, not much work has been performed on the use of this data for updating a digital twin. However, MTConnect supports one-way (read-only) communication and cannot change the state of a piece of equipment or cause an action to occur.[32,33] A ROS/MTConnect solution will be explored to offer logical connections where REQUEST and RESPONSE types of messages are implemented.[34] This solution will offer the ability to transmit messages to equipment based on analysis from the digital twin.

MTConnect is a model of a device and the data that it helps collect. Everything about the standard is from the point of view of the device. The workpiece and components of the machine from which data is to be collected are defined. The standard enables modeling all things involved in the manufacturing process, such as cutting tools, raw materials, files, and inspection reports. It describes the device's capabilities, kinematics, and geometry. There are more than 230 top-level observation types.

5.1.3. STEP. The ''Standard for the Exchange of Product Model Data'' (STEP), formally known as ISO 10303,

supports the exchange of product manufacturing information.[35] This standard has supported the development of digital models through the export and import of real system Computer-Aided Design (CAD) models (machines and parts) into the modeling tools environment.

5.2. Digital twin modeling

Each piece of equipment on the shop floor is an OME from which data are collected. Wu et al.[36] emphasize complete mapping between the physical space and digital space by modeling the physical space from multiple dimensions such as geometry, physics, behavior, and rules. The mapping supports coevolution of elements in both the physical and digital spaces. Modeling and simulation are some of the technologies enabling the digital twin.[37] In the digital twin, this simulation is continually updated to different states of the system using various sensors and algorithms to mirror changes in the physical system. In addition to modeling the physical system in a virtual world, simulation often offers visualization capabilities, which support verification and validation, system understanding, and decision-making.

Modeling the physical system requires selecting a modeling and simulation method. Physical modeling was selected for this project because it can simulate the types of data collected from real workcells. These data represent the behavior of the physical system in the digital environment. Such data are also the type that enables determining when to perform activities such as predictive maintenance. Physical modeling requires the presence of 3D CAD models of the components of the machines and equipment. These components for a robot arm, for example, are the robot base, links, joints, end effector, and workpiece. The machine components are modeled as ''blocks'' provided in the physical modeling software. At a more detailed level, devices such as motors, gearboxes, and bearings can also be modeled, and data collected from them.

Physical modeling does not require sophisticated programming. Therefore, minimum effort is needed for model development, as well as for operation and maintenance. It enables visualization of system operation, generates kinematic and dynamic data, and can be easily transferred to industry. The robot simulation tool is Simscape, which is an integrated package within MATLAB's Simulink toolbox. Most modeling tasks are carried out in the Simscape Multibody environment and linked with Simscape networks. Simscape networks enable the modeling of more system detail when needed. Data are collected by modeling sensors attached to the elements. The Pocket NC is modeled using Altair's Inspire, another tool that provides physical modeling.

5.3. Digital twin for the UR5e robot

The activities for building a digital twin are representing the physical workcell in the digital space, acquiring and communicating data, analyzing the system through the digital twin, and creating a feedback loop from the digital twin to the physical workcell. Figure 4 is an illustration of the procedure.

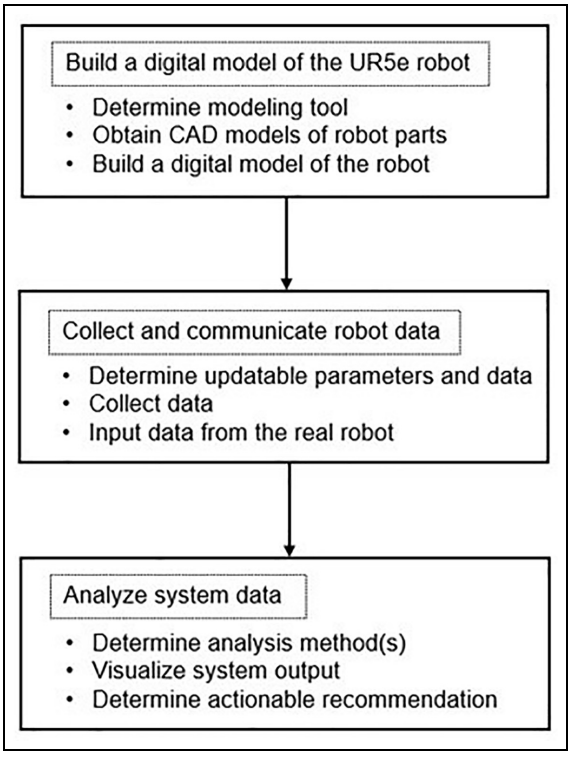

Figure 4. Procedure for building a digital twin for the robot.

5.3.1. Digital model of the robot arm. The digital twin requires the following data.

5.3.1.1. Robot arm CAD models. The CAD models that describe the geometry of the parts of the robot are imported into the Simscape environment and ''assembled'' to create a physical model of the UR5e robot arm. The gripper's CAD models are also ''assembled'' at the joints into the end effector in the AutoCAD Inventor environment. The resulting assembly is exported as an XML file to the digital twin environment using the multibody add-on and ''attached'' to the robot arm model. Figure 5 shows the model of the robot arm and attached end effector.

5.3.1.2. Robot arm link parameters and inertial properties. Developing kinematic and dynamic models of a robot arm requires knowledge of Denavit–Hartenberg (DH) parameters and the inertial properties. DH parameters enable the building of a robot model by defining the position and orientation of each link with respect to another in the robot kinematic chain. Inertial properties

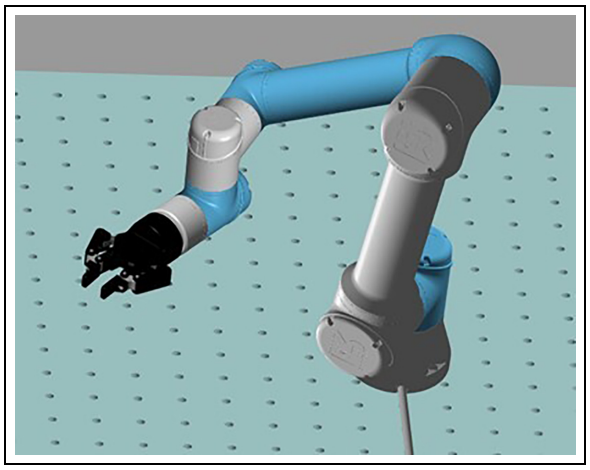

Figure 5. The UR5e robot arm in the digital twin environment with a gripper attached.

are a description of the mass, center of mass, and moments of inertia of each link.

5.3.2. Data collection and communication. The process of acquiring data and building a scalable data pipeline has multiple components: (1) collecting physical data from the workcell, (2) leveraging the MTConnect standard and interface to integrate physical data coming from disparate sources within the workcell, and (3) developing a set of tools to enable client-side use of the MTConnect agent. We utilized the Universal Robot's Real-Time Data Exchange (UR-RTDE) interface that has Application Programming Interfaces (API) for both C + + and Python. The Python API is used to collect a set of predetermined data items.

The two elements in an MTConnect implementation are the adapter and the agent. The adapter serves as a data collection element from the equipment while the agent collects data from the adapter. Most CNC machine tools are supplied with a preinstalled adapter that supports collecting and sending machine tool data to an agent. The adapter packages data into a format that is readable by the agent. The agent provides an interface for applications to retrieve the MTConnect data gathered from the adapter. The agent also acts as a data aggregator in case data originates from more than one device. Figure 6 shows the flow of data from a physical device (UR5e) to the digital twin. A semantic structure was provided for the data generated by the UR5e robot arm through MTConnect. This structure includes data tags and units as outlined in the MTConnect Standard.[38] The full list of data items available through the UR-RTDE interface are provided by the vendor. The adapter was installed on a Raspberry Pi connected to the robot arm. An instance of the MTConnect agent then consumes the data and serves it in a machine-readable format.

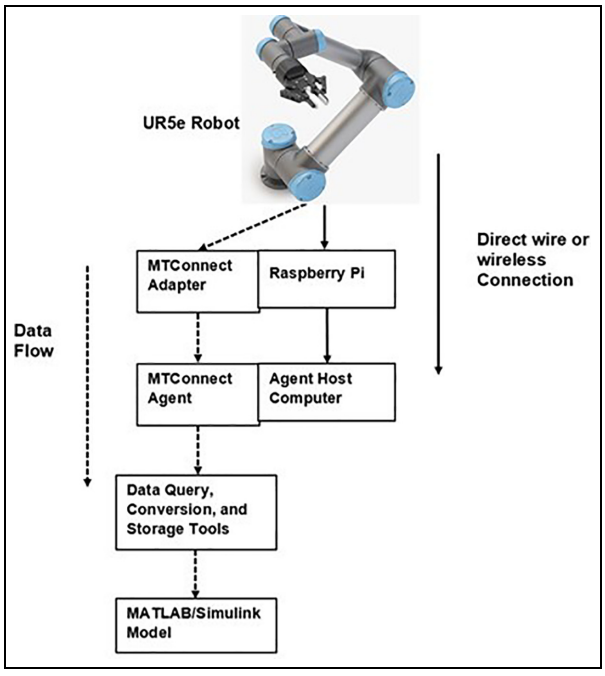

Figure 6. MTConnect data flow from robot arm to the digital model.

5.3.3. Client-side integration. The MTConnect agent is implemented in C + + and displays data in XML format on a Hypertext Transfer Protocol (HTTP) server. Data streaming is implemented by installing the Simulink Desktop Real-Time to input data in real-time in the robot model. A program has been written in Java to make HTTP requests for the data from the agent and pass it to the robot. We sample blocks of data from the agent rather than obtaining individual data points to eliminate the possibility of data loss. Figure 7 shows a section of the streamed data in the XML format.

5.3.4. Monitoring the system using the digital twin. Monitoring the shop floor is the process of continuously acquiring data on the status and flow of materials, equipment, and personnel in the production process to help make decisions related to controlling the operation of the shop floor.[34,35] In this paper, joint position data from the physical robot are collected. The error data, that is, the difference between the commanded and measured data, are plotted. The real position data are monitored in the digital twin. Figure 8 shows the plot of error data for the tool center point (distance) and tool center point (angle) for UR5e robot. Monitoring through visualization of the operation of the robot in the digital world contributes to its description and model verification. Prospects for system monitoring would depend on the focus of the user entity, as described in Section 5.1. Examples are the flow of materials, the status of production orders and equipment, and personnel in

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      <Angle dataItemId="angle_j1" name="angle_j1" sequence="685439" subType="ACTUAL" timestamp="2022-12-14T17:46:31.679966Z">-
      85.7676589371779</Angle>
      <Torque dataItemId="tor_j1" name="tor_j1" sequence="587172" timestamp="2022-12-14T17:41:20.961607Z">2.7674225954537</Torque>
      <Torque dataItemId="tor_j1" name="tor_j1" sequence="587201" timestamp="2022-12-14T17:41:21.065352Z">2.76601123289404</Torque>
      <Torque dataItemId="tor_j1" name="tor_j1" sequence="587235" timestamp="2022-12-14T17:41:21.167239Z">-1.17088080932207</Torque>
      <AngularVelocity dataItemId="vel_j1" name="vel_j1" sequence="565569" subType="ACTUAL" timestamp="2022-12-
      14T17:40:12.84661Z">22.3137618580208</AngularVelocity>
      <AngularVelocity dataItemId="vel_j1" name="vel_j1" sequence="565604" subType="ACTUAL" timestamp="2022-12-14T17:40:12.947363Z">-
      21.6889054168968</AngularVelocity>
      <AngularVelocity dataItemId="vel_j1" name="vel_j1" sequence="565638" subType="ACTUAL" timestamp="2022-12-14T17:40:13.048013Z">-
      21.2718865095744</AngularVelocity>
      ="vel_j3" sequence="580790" subType="ACTUAL" timestamp="2022-12-14T17:41:00.911546Z">0.266901808092707</AngularVelocity>
```


Figure 7. Section of the XML file of the streamed data.

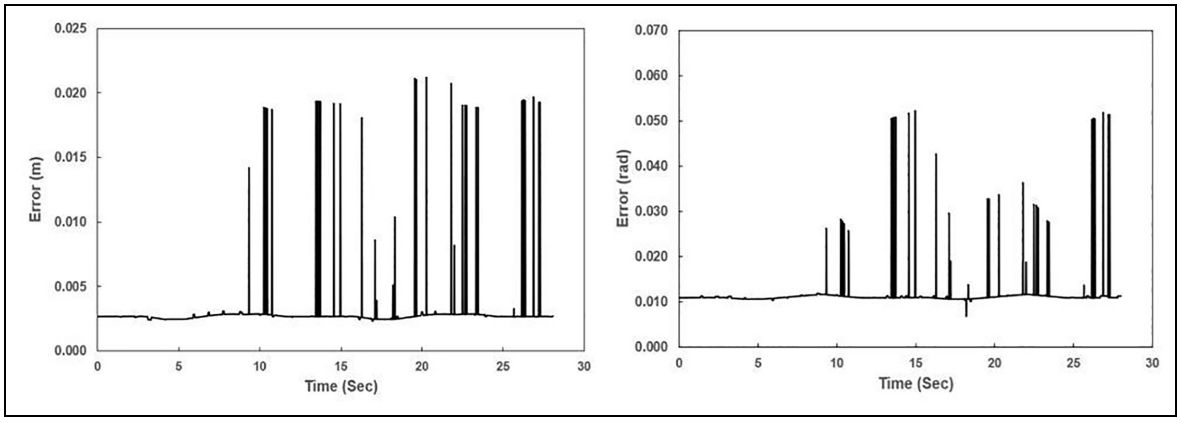

Figure 8. Plot of tool center point error data for distance (left) and angle (right).

the production process. For the CMM, monitoring informs of the state and any changes in the quality of the machined product in addition to determining product features that are gradually deteriorating. The results of monitoring support decisions related to controlling the operation of the shop-floor.[39] Details of the margins of error during monitoring are to be resolved in further work when an analysis of the data is carried out. This is out of the scope of this paper.

The causes of differences could be kinematic model errors due to manufacturing tolerances of the robot elements and the assembly process. In addition, the changing working environmental conditions such as temperature and the effects of tear and wear. This means that the model of the manipulator in the controller should be a precise representation of the mechanisms and allow the system to achieve the desired robot pose. Because of these errors, corrective action may be needed to reduce these errors. Currently, a human is in the loop and adjusts inputs in the teach pendant.

5.4. Toward a digital twin of the pocket NC

This research uses data obtained from a five-axis Pocket NC desktop milling machine. There are five moving parts of the Pocket NC that are controlled to execute machining activities. These are

1. Carriage: holds the spindle and controls tool motion in the x-direction.
2. Vertical saddle: holds the A table and controls workpiece motion in the y-direction.
3. Spindle: holds the tool while rotating on an axis (moves along the z-axis).

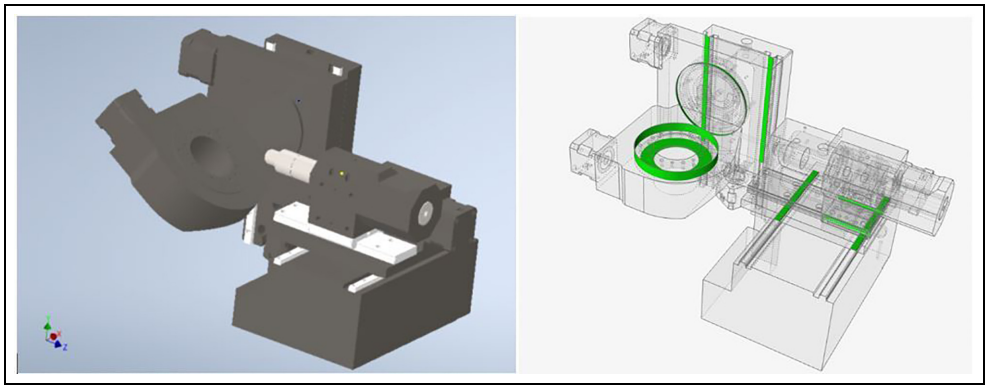

Figure 9. Pocket NC CAD model (left) and Altair Inspire model (right), indicating the active joints.

4. A Table: the work area on the machine (rotates about its center).
5. B Table: holds the vise that clamps a workpiece when being worked on (rotates about its center).

The modeling tool for the pocket NC is the Altair Inspire, which is software used in various engineering areas of design. Altair MotionSolve performs 3-dimensional multibody simulations to predict the dynamic response of a system. The workflow for digital twin development in Altair Inspire is the same as that of Simscape. The first step is to obtain CAD models of the machine, environment, and part design. The second step is to import the models into the Altair design environment. Figure 10 shows such a Pocket NC digital twin model. Altair Inspire accepts data in comma-separated values (CSV) format. Software that parses the XML output from the MTConnect Agent populates a 2D array and stores the array in a CSV file has been developed. It is not data-dependent and can be applied to any data pipeline with MTConnect capabilities. The multiple data items received over a time interval are recorded and synced up to their respective timestamps (UTC format). Streaming options are investigated for building the digital twin. Figure 9 shows the Pocket NC CAD model and the model after importing into Inspire.

5.5. Toward a digital twin of the coordinate measuring machine

The inspection process using the CMM provides product information that allows verification and validation of product data based on parameters that are used in quality control. This is accomplished by comparing CMM measurements against the nominal model (CAD model of workpiece). When the part measurement is performed by a CMM, dimensional data from the part are collected and analyzed through a computer-aided inspection system to determine errors related to GD&T. Results of that analysis are used to determine the required feedback to improve the manufacturing process.

The digital twin planned for the CMM will support part measurements and analyses. The twin allows the inspection machine operator to visualize the impact of geometric variations. The development of the CMM digital twin includes obtaining the 3-D CAD models of the machine and fixtures, workpiece, and work environment. The inspection strategy with the digital twin consists of selecting and extracting inspection and process data from the produced parts. The data are then served to the digital twin in real-time. In the digital twin, the part measurement data are compared with the original part design. Analysis of the collected data leads to knowledge and insights that inform adjustments of the production process to optimize geometrical quality. Figure 10 shows the CMM for measuring parts after machining with the Pocket NC machine tool.

6. Discussion and future research

This paper has described how to build a digital twin of a robot workcell using available standards, technologies, and methods. The workcell comprises two robot arms, a desktop CNC machine tool, and a CMM. Physical modeling is selected for building the digital twin of a robot arm and the CNC machine tool. Real-time data are collected and communicated using the MTConnect standard. The ISO 23247 standard provided the modeling framework. The standard provides definitions of terms, concepts, and reference models. The standard is generic but has been instantiated to the robot workcell. Standards applications in this work have included interface standards for acquiring and communicating data as well as model development using the STEP standard for exchanging models between different applications. Commercial tools for simulation are used for building the dynamic models. Currently, data are collected from the physical elements and used to update the states of their digital counterpart in real-time.

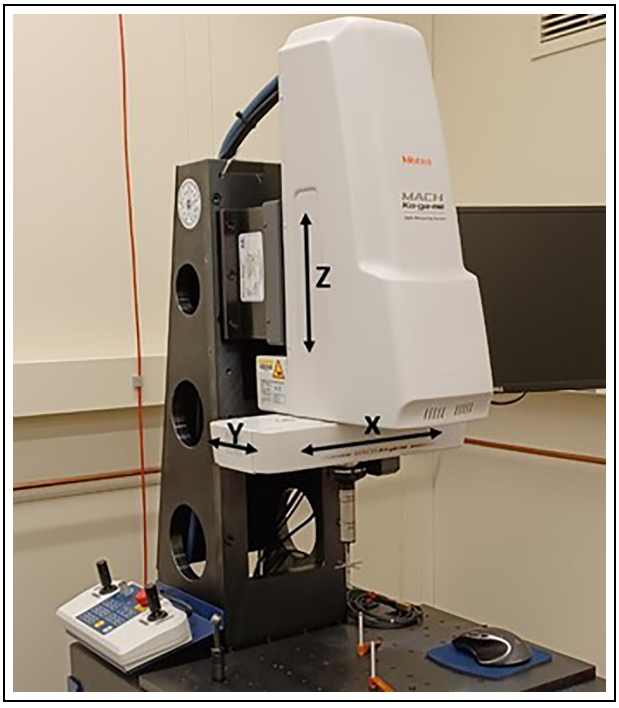

Figure 10. The CMM showing the three axes of motion.

This work was motivated after observing that the literature lacks sufficient information to successfully build a digital twin using available software and open standards. Even with the implementations available, few digital twin development process details are published. More examples of implementations of digital twins are needed for SMMs to leverage for their benefit. In addition, modeling and simulating physical elements with real components of the machine is easy to train manufacturing personnel since it does not involve sophisticated programming. Moreover, this modeling and simulation approach enables the building of a digital twin where different machine components are represented at different levels of resolution if desired. The work is ongoing to develop a feedback loop from the digital world to the physical element. The experience from these activities will inform standards and guidelines for building digital twins.

The use cases for digital twins include optimizing the efficiency of operations through production scheduling. One of the activities of the scheduling function is the real-time allocation of production tasks to the manufacturing resources. Scheduling algorithms can be validated through the digital twin. There is also a use case of real-time monitoring and control of product quality. CMM measurements can be analyzed in the digital twin to provide real-time feedback on the drift in the process. Another potential use case is prognostics and health management. Data are collected from the process representing healthy and unhealthy states and used to build a prediction model. Where such data is not available, a digital twin with artificially introduced faults can be used to generate the fault state data. Updatable parameters that define the health state of a machine can be identified. These parameters are used to synchronize the real system with the digital twin degradation model.

In future work, an automated feedback loop to improve activities in the real world based on analysis by the digital twin will be developed. Furthermore, industry-driven use cases will be developed driving additional standards and tools to support companies to easily implement their own digital twins. The use cases will be prioritized based on relevance to applications of digital twins by manufacturers deploying robot workcells. Data will be collected for these specific use cases. The manufacturing community would benefit from measurement science, that is, the development of performance metrics, development methodology, standards, test methods, and reference datasets. VVUQ will be embedded in the building of digital twins by testing the digital twin model and the services that are provided. VVUQ of the digital twin provides confidence in the services of the digital twin such as prediction and prescription. Techniques such as software-in-the-loop, controller-in-the-loop, and hardware-in-the-loop that have been mentioned in the introduction Section can enhance the VVUQ of the digital twin by providing a complete network that supports interactions between the physical machines and their digital counterparts. Software-in-the-loop helps to validate the digital twin before being fully connected to streaming data. In the same way, the controller can be validated on the virtual machine. These techniques are relevant to many aspects of digital twin development including real-time monitoring and optimization of products and production systems. Another area of the standard for future discussion is the relationship between the digital twin and the Metaverse.

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References

1. Shao G and Kibira D. Digital manufacturing: requirements and challenges for implementing digital surrogates. In: *Proceedings of the 2018 winter simulation conference* (eds Rabe M, Juan AA, Mustafee N, et al.), Gothenburg, 9–12 December 2018, pp. 1226–1237. Piscataway, NJ: Institute of Electrical and Electronics Engineers.
2. Kutscher V, Anokhin O and Anderl R. Enhancing digital twin performance through simulation of computerized numerical control firmware. *Proc Manuf* 2020; 49: 69–74.
3. Zhu Z, Liu C and Xu X. Visualization of the digital twin data in manufacturing by using augmented reality. *Procedia CIRP* 2019; 81: 898–903.
4. Abbasi R, Yanes AR, Villanuera EM, et al. Real-time implementation of digital twin for robot based production line. In: *Proceedings of the 2021 Conference on Learning Factories (CLF)*, 2011, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3860500
5. Zheng Y, Yang S and Cheng H. An application framework of digital twin and its case study. *J Ambient Intel Human Comput* 2019; 10: 1141–1153.
6. Shao G and Helu M. Framework for a digital twin in manufacturing: scope and requirements. *Manuf Lett* 2020; 24: 105–107.
7. Wärmefjord K, Söderberg R, Schleich B, et al. Digital twin for variation management: a general framework and identification of industrial challenges related to the implementation. *Appl Sci* 2020; 10: 3342.
8. Glaessgen E and Stargel D. The digital twin paradigm for future NASA and US air force vehicles. In: *53Rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference; 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA P*, Honolulu, HI, 26–28 April 2012.
9. Shao G, Hightower J and Schindel W. Credibility consideration for digital twins in manufacturing. *Manuf Lett* 2023; 35: 24–28.
10. Guerreiro GMG, Martin F, Dreyer T, et al. Advancements on grid compliance in wind power: component & subsystem testing, software-/hardware-in-the-loop and digital twins. *IEEE Access* 2024; 12: 25949–25966.
11. Mihoubi B, Bouzouia B, Tebani K, et al. Hardware in the loop simulation for product driven control of a cyber-physical manufacturing system. *Product Eng* 2020; 14: 329–343.
12. Ugarte M, Etxeberria L, Unamuno G, et al. Twin-based virtual commissioning in machine tool manufacturing. *Proced Comput Sci* 2022; 200: 527–536.
13. Sharma A, Kosasih E, Zhang J, et al. Digital twins: state of the art theory and practice, challenges and open research questions. *J Ind Inform Integr* 2022; 30: 100383.
14. VanDerHorn E, Wang Z and Mahadevan S. Towards a digital twin approach for vessel-specific fatigue damage monitoring and prognosis. *Reliab Eng Syst Safe* 2022; 219: 108222.
15. Kritzinger W, Karner M, Traar G, et al. Digital twin in manufacturing: a categorical literature review and classification. *IFAC-PapersOnLine* 2018; 51: 1016–1022.
16. Kibira D, Shao G and Venketesh R. Building a digital twin of an automated robot workcell. In: *2023 annual modeling and simulation conference (ANNSIM)*, Mohawk College, ON, 23–26 May 2023, pp. 196–207. Piscataway, NJ: Institute of Electrical and Electronics Engineers.
17. Qi Q, Hu T, Anwer N, et al. Enabling technologies and tools for digital twin. *J Manuf Syst* 2021; 58: 3–21.
18. Autiosalo J, Siegel J and Tammi K. Twinbase: open-source server software for the digital twin web. *IEEE Access* 2021; 9: 140779–140798.
19. Cimino C, Negri E and Fumagalli L. Review of digital twin applications in manufacturing. *Comput Ind* 2019; 113: 103130.
20. Thelen A, Zhang X, Fink O, et al. A comprehensive review of digital twin—part 1: modeling and twinning enabling technologies. *Struct Multidiscip Optim* 2022; 65: 354.
21. Lehner D, Pfeiffer J, Tinsel E-F, et al. Digital twin platforms: requirements, capabilities and future prospects. *IEEE Softw* 2021; 39: 53–61.
22. Lu Y, Liu C, Kevin I, et al. Digital twin-driven smart manufacturing: connotation, reference model, applications and research issues. *Robot Comput Integr Manuf* 2020; 61: 101837.
23. Onaji I, Tiwari D, Soulatiantork P, et al. Digital twin in manufacturing: conceptual framework and case studies. *Int J Comput Integr Manuf* 2020; 35: 831–858.
24. Galli E, Fani V, Bandinelli R, et al. Literature review and comparison of digital twin frameworks in manufacturing. *Proc Europ Council Model Simul* 2023; 2023: 428–434.
25. Liu M, Fang S, Dong H, et al. Review of digital twin about concepts, technologies and industrial applications. *J Manuf Syst* 2021; 58: 346–361.
26. Shah K, Prabhakar TV, Sarweshkumar CR, et al. Construction of a digital twin framework using free and open-source software programs. *IEEE Intern Comput* 2022; 26: 50–59.
27. D'Amico RD, Addepalli S and Erkoyuncu JA. Industrial insights on digital twins in manufacturing: application landscape, current practices and future needs. *Big Data Cognit Comput* 2023; 7: 126.
28. ISO 23247-1: 2021. Automation systems and integration—digital twin framework for manufacturing—Part 1: overview and general principles.
29. Shao G, Frechette S and Srinivasan V. An analysis of the new ISO 23247 series of standards on digital twin framework for manufacturing. *International Manufacturing Science and Engineering Conference*, 2023, https://www.nist.gov/publications/analysis-new-iso-23247-series-standards-digital-twin-framework-manufacturing
30. Shtofenmakher A and Shao G. Adaptation of ISO 23247 to aerospace digital twin applications-on-orbit collision avoidance and space-based debris detection. In *AIAA SCITECH 2024-0275*, https://arc.aiaa.org/doi/10.2514/6.2024-0275
31. Lynn R, Louhichi W, Parto M, et al. Rapidly deployable MTConnect-based machine tool monitoring systems. In: *Proceedings of the ASME 2017 12th international manufacturing science and engineering conference MSEC2017*, Los Angeles, CA, 4–8 June 2017. New York: ASME.
32. MTConnect Institute. MTConnect R© Standard part 2.0—device information model. *Advanced Manufacturing Technology*. Available at: https://www.mtconnect.org (accessed 7 August 2023).

33. Han SH, Park AJ, Park AR, et al. Automated DNA extraction monitoring system based on MTConnect technology. *Appl Sci* 2021; 11: 684.
34. Robinson M. Cost effective coordinated and cooperative robotics enabled by open technologies. *NIST Final Technical Status*, Report CFDA Number: 11.609, 16 January 2019. Washington, DC: NIST, Department of Commerce.
35. ISO 10303: 2021. Industrial automation systems and integration—product data representation and exchange.
36. Wu Y, Zhang K and Zhang Y. Digital twin networks: a survey. *IEEE IoT J* 2021; 8: 13789–13804.
37. Ebni M, Bamakan SMH and Qu Q. Digital twin based smart manufacturing; from design to simulation and optimization schema. *Proced Comput Sci* 2023; 221: 1216–1225.
38. MTConnect Institute. MTConnect R© Standard Part 50—Interfaces interaction model. *Advanced Manufacturing Technology*. Available at: https://www.mtconnect.org (accessed 7 September 2023).
39. Zhuang C, Miao T, Liu J, et al. The connotation of digital twin and the construction and application method of shop-floor digital twin. *Robot Comput Integr Manuf* 2021; 68: 102075.

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