BUILDING A DIGITAL TWIN OF AN AUTOMATED ROBOT WORKCELL

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ABSTRACT

A digital twin of a manufacturing system can positively impact its performance with respect to productivity, energy consumption, product quality, and cost. However, leveraging available methods and tools to build a digital twin is a challenge for many manufacturers, especially small and medium-sized manufacturers. The result is that despite a significant number of research publications on the subject, the uptake of digital twins has been more limited than anticipated. This paper describes a method of instantiating the ISO 23247 framework for building a digital twin. A case study comprised of robot arms, a CNC machine tool, and a coordinate measuring machine (CMM) identifies the modeling tools and computational environment for the digital twin. The MTConnect standard is implemented to collect data from a robot arm to update the digital twin. Integration of workcell components and communication between workcell equipment and their digital counterparts are described. This research will result in implementation guidelines for industries seeking to build digital twins for their manufacturing systems and form the basis for developing test and validation methodologies for digital twins.

Keywords: digital twin, methods, MTConnect, implementation, robot workcell.

1 INTRODUCTION

1.1 Background and Research Plan

A digital twin is an integrated virtual representation of a system that connects and synchronizes a system with its digital counterpart and is enabled by both historical and real-time data (Shao et al. 2018). Operating a digital twin for a manufacturing system or manufactured products leads to benefits such as reduced time to market (Lo et al. 2021), better prognostics and health management (Errandonea et al. 2020), and improved product quality (Detzner et al. 2018). Several approaches published in the literature support a system engineer in building a digital twin (Abbasi et al. 2021; Zheng et al. 2019). Wang et al. (2022) and Liu et al. (2021) have reviewed technologies and standards that support building a digital twin. Manufacturers are also increasing the adoption of automation for manufacturing processes, which can be leveraged to support digital twin implementations, especially sensing for data collection, analysis, and control (Sjödin, et al. 2018).

However, implementing a digital twin, especially for small and medium-sized manufacturers (SMM), is still challenging because of lack of expertise and resources, inadequate understanding of the benefits of digital twins, and insufficient information on technologies and standards (Shao et al. 2018, Wärmefjord et al. 2020). In addition, most digital twins developed today are asset specific, purposed for objectives such as production optimization or predictive maintenance (Bécue et al. 2020). The main interest of these efforts is to collect equipment data throughout the life cycle to optimize the manufacturing process or improve equipment design. Therefore, the experience from building these digital twins cannot readily be applied to new use case scenarios such as production monitoring or efficient energy utilization.

This research identifies and demonstrates available technologies, methods, standards, and tools that support digital twin development for manufacturing with the goal of highlighting challenges and providing recommendations for standards and testing. 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 will act 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.

1.2 Integration requirements for a robot workcell digital twin

Building a digital twin requires connections and communication between the real-world and the digital world, collecting data, and modeling the real-world entities. Some requirements are supported by modern manufacturing equipment and processes. For example, robot arms are often integrated with other shop floor equipment such as computer numerical control (CNC) machine tools and software applications. The integration supports collection and analysis of data that can be used to determine the production rate, health status, and fault prediction. However, data from different machines and applications are often available in different formats that may present problems for a manufacturer attempting to integrate these data from different types of equipment (Lynn et al. 2017).

As such, the communication and integration of data between the real-world entities and their digital models can be a challenge to manufacturers. Furthermore, during the execution of tasks, messages and commands need to be exchanged among robot arms and other production assets. For example, robot arms load CNC machine tools with workpieces and then unload the machined parts. Communication between the robot arm and the machine tool can be managed either through the robot arm or an external controller. If the robot is managing the process, it can, for example, notify the machine that the workpiece has been loaded and the machine door can be closed, and machining process can be started. For integration of data from different machines and effective networking within the plant, manufacturing equipment should communicate using a common protocol.

The MTConnect Standard provides interfaces by extracting data from equipment and making it available in a standard format and is based on eXtensible Markup Language (XML). MTConnect Standard is an open-source protocol that enables data transmission from manufacturing equipment and allows communication from machine to machine and machine to operator. 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 these data for developing and updating a digital twin. Moreover, the MTConnect Standard supports one-way (read only) communication and cannot change the state of a piece of equipment or cause an action to occur (MTConnect 2022a; Han et al. 2021). Previous work at NIST built a Smart Manufacturing System (SMS) testbed and demonstrated application of the open-source Robot Operating System (ROS) to control robot arms and other equipment during operation (Robinson, 2019). A ROS/MTConnect solution is devised to offer logical connections where REQUEST and RESPONSE types of messages are implemented (Helu et al. 2020). 'REQUEST' refers to one equipment requesting for a part or service from another equipment and 'RESPONSE' refers to the latter equipment's reply. We plan to use the same open standards and technologies for communicating information from the digital twin.

1.3 Scope and organization of the paper

This paper describes the method for building a digital twin of a robot workcell using standards and open-source software for collecting data and multibody modeling simulation of machine tools and robots. This work contributes to the identification of the hardware, software, and task elements to realize a digital twin of a workcell that includes robot arms, a CNC machine tool, and a coordinate measuring machine (CMM). The size of the workcell makes it suitable for SMMs adoption but the methods and procedures employed are also suitable for large industrial-scale machines. The paper also shows the extraction of data from a physical robot arm using the MTConnect protocol, creating a digital representation of the robot arm, and updating it with the collected data. The robot arm then replicates the activities of the physical counterpart. The flow of activities for the work of this paper provides an affordable starting point toward a more complete realization of the smart factory paradigm through the digital twin. The rest of the paper is organized as follows: Section 2 is an overview of the workcell with the equipment, peripherals, workcell configuration, and examples of use case scenarios, Section 3 introduces the digital twin framework for manufacturing, Section 4 describes how data are extracted from the physical system and describes the digital twin modeling process, and Section 5 presents discussion and way forward.

2 WORKCELL DESCRIPTION AND CONFIGURATION

The workcell consists of small collaborative robot arms for material handling and machine tending, a CNC machine tool for cutting a part, and a CMM for product geometry measurements and quality control. 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 offloading parts from the CMM. Any parts that do not conform to specifications are sent to the rework buffer. The cell has a single input location and a single output location.

The workcell is reconfigurable to support a wide range of prototypes of digital twins for various scenarios with different objectives. In one configuration, ROBOT #1 can be dedicated to picking workpieces from input storage to loading the CNC machine tool upon request, offloading the finished part, and placing it into the in-process buffer. As such, ROBOT #1 is dedicated to tending the CNC machine tool. ROBOT #2 picks parts from the in-process buffer, loads them to the CMM machine and offloads them when completed. In a different configuration, ROBOT #2 could also be set to offload the CNC machine tool thereby sharing tending to this machine with ROBOT #1.

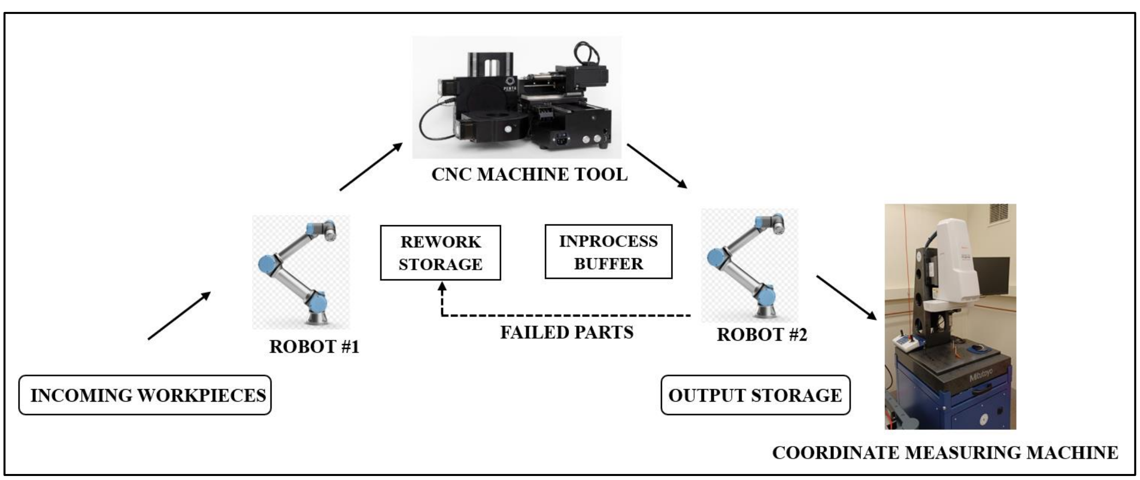


Figure 1: Workflow through machines and equipment in the robot workcell.

2.1 The workcell components specifications

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

- *Robot arms*

The robot arms are universal UR5e robots with six degrees of freedom. They are designed for a payload capacity of 5 kg and a reach of 0.85 m. Programming the robots can be carried out by either coding a program (URScript at the script level) or by using a teach pendant.

- *End effector*

The robot arm end effector is the 2F-85 Gripper (see Figure 2). It is electrically actuated and is grip force and/or position controllable. This allows the gripper to be used in both time-based control and event-based control schemes. The gripper can be controlled though the robot controller or the Programmable Logic Controller (PLC).

- *CNC Machine tool*

The machine tool is the Pocket NC V2-50 5 Axis Desktop CNC mill. It executes standard G code so that the results can be scaled up to any machine tools. 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.

- *Coordinate Measuring Machine*

The CMM is a lightweight type to measure dimensions of a part and compare with the part CAD models. This CMM can be integrated with other equipment on the shop floor such as the CNC machine tool and robot arms. Integrating the CMM to provide real-time feedback is essential for effective process monitoring and control as opposed to mere inspection as would be the case in standalone mode.

- *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.

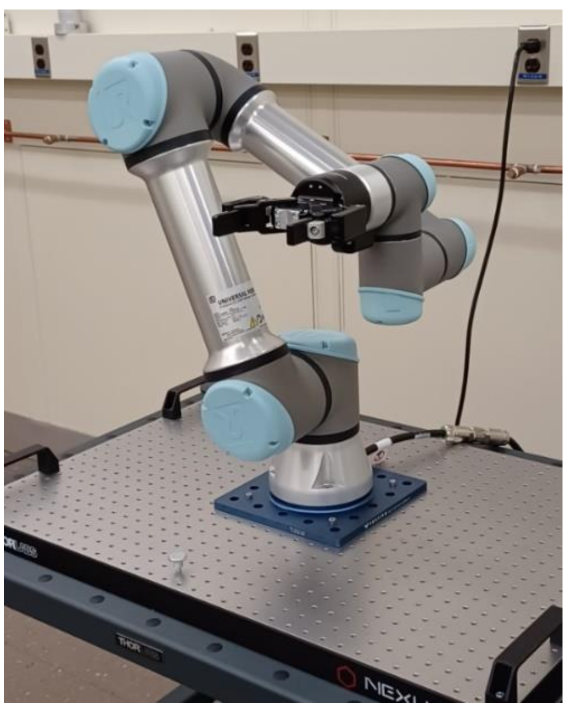


Figure 2: 2F-85 Gripper mounted on the UR5e robot arm in the laboratory.

2.2 Potential use cases

The typical configuration provided earlier in this section describes tasks that are performed by each component of the workcell. A digital twin of such a configuration can be purposed for different objectives each resulting in different use case scenarios from equipment status monitoring, fault diagnosis, and performance prediction to optimization and control. Some decision-making objectives that the digital twin can be targeted to improve include the following:

- *Optimize the manufacturing process through improved scheduling*

Production scheduling is difficult because of dynamic changing conditions on the shop floor. One of the functions of real-time scheduling and control is task allocation. When two robots are assigned to machine tending and material handling activities, a digital twin can be used to monitor machine utilization, waiting time, blocked time, etc. The digital twin combines real and simulated data to determine optimal allocation of the tasks to the robot arms in the workcell (Zhang et al. 2021).

- *Support real-time monitoring and quality control*

The CMM in the workcell measures and verifies the dimensions of the machined part. The quality data together with process data and equipment/tool condition data provide real-time feedback on any drift in the process (Detzner et al. 2018). The digital twin uses data from both the process and CMM to detect and recognize eventual quality issues on the parts and the results can be used to enhance the quality and efficiency of the production process.

- *Support prognostics and health management (PHM)*

Diagnostics and failure prediction often rely on previously collected data representing both the health status and failure states of a machine or robot (Errandonea et al. 2020). Analytics are performed on this data to compare with data collected during operation to understand the state of the system. However, unhealthy state data are not usually available. If failure states of equipment can be virtually represented in the digital twin, failure progression of the robot arm can be predicted to optimally determine maintenance timing.

- *Test and evaluate reconfigurations of the workcell*

During operation, each robot arm is assigned to perform a set of tasks. However, as requirements for production change, such as in volume and part design or as equipment performance change due to degradation, flexibility is needed. The digital twin can evaluate in real-time the changes in the tasks performed by the robot arms and the CNC to support near real-time response.

3 DIGITAL TWIN FRAMEWORK FOR MANUFACTURING

A new ISO standard, ISO 23247 - Digital twin Manufacturing Framework, has recently been published to facilitate the implementation of digital twins in manufacturing. The standard provides guidelines for analyzing modeling requirements, defining scope and objectives, and promoting the use of common terminology and generic reference architecture. The reference architecture includes a reference model with domains and entities. There are four domains, and each has a logical group of tasks and functions, which are performed by functional entities. Figure 3 shows the entity-based reference model and an illustration of the four domains and their interactions (ISO 2020). Each domain is briefed as follows.

- observable manufacturing domain: contains the Observable Manufacturing Elements (OMEs), including personnel, which are the physical elements that provide an environment for digital twins.
- device communication domain: links OMEs to their digital twins for synchronization by monitoring and collecting data from sensor devices in the observable manufacturing domain, and controls and actuates OMEs.
- digital twin domain: responsible for overall operation and management of digital twins, hosts applications and services such as data analytics, simulation, and optimization to enable provisioning, monitoring, modeling, and synchronization. It also interacts with other digital twin entities.
- user domain: a user can be a human, a device, an application, or a system that uses applications and services provided by the digital twin domain.

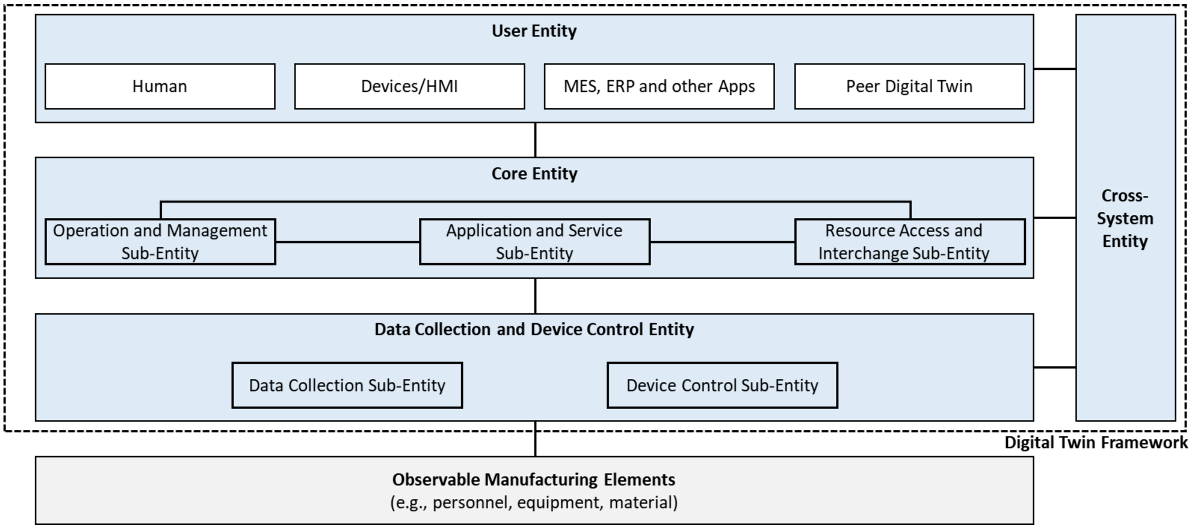


Figure 3: Functional view of the digital twin reference model for manufacturing.

In Figure 3, the digital twins can be created based on the Digital Twin Framework depicted within the dotted line. The framework supports the applications of IoT infrastructure for data collection, communication protocols for data transmission, and information flows between entities of different domains, i.e., OMEs, Data Collection and Device Control, Digital Twin Core, and User layers. To identify requirements for digital twin development, these various aspects need to be considered and followed.

4 DIGITAL TWIN DEVELOPMENT FOR THE WORKCELL ROBOT ARM

Based on the digital twin framework introduced in Section 3, each piece of equipment in the Lab can be regarded as an OME, for which data need to be collected, and digital twins for various scenarios need to be developed. In this section, we take one robot arm in the workcell as a focus to showcase the method of digital twin development. Each functional layer is discussed in more detail.

After introducing the method for the digital twin development, we instantiate the ISO framework for the UR5e robot arm (a component of the workcell) while performing picking and loading a workpiece to a CNC machine tool. Figure 4 is an illustration of the instantiation of the framework for the robot arm.

The most prominent activities from the illustration are data acquisition from the physical system, modeling the physical system, and updating the model with the collected data. Data are acquired by using a combination of hardware and software. The protocol used was developed to acquire data from shop floor equipment to be available for software to carry out analysis and monitoring. These data are to be preprocessed and made available to update a digital twin. Modeling the physical system requires selecting a modeling method and environment. The method of physical modeling requires knowledge of the three-dimensional geometry of the robot arm components including robot base, links, joints, end effector, and workpiece. The robot components are modeled as ‘blocks’ available in the physical modeling software. In summary, the activities for building a digital twin will involve data acquisition, representing the physical workcell in the digital world, building analytical models in the digital world, integrating the physical with the digital world, and creating a feedback loop from the digital world to the physical workcell. In this paper, the robot arm in the physical world has been represented in the digital world and data have been acquired from the robot and transformed into a neutral format (XML). These data have been input into the digital robot. The details of the accomplished activities are described in this section.

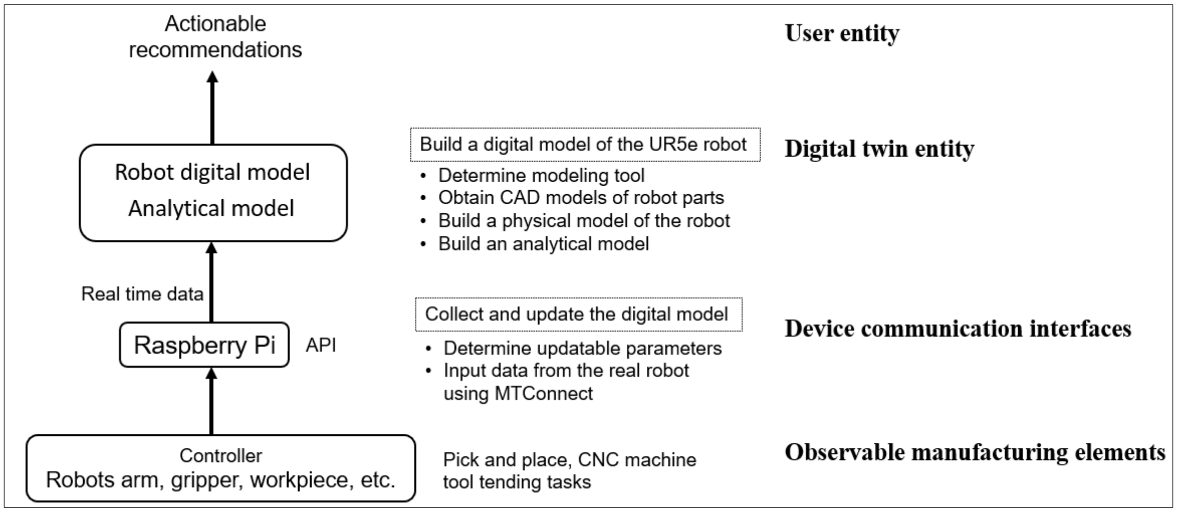


Figure 4: Implementation method of building a digital twin for the robot based on ISO 23247.

4.1 System and manufacturing process data acquisition

The process of data acquisition and building a scalable data pipeline for the workcell has multiple components: (i) collecting physical data from the workcell, (ii) leveraging the MTConnect standard and interface to integrate physical data coming from disparate sources within the workcell, and (iii) developing a set of tools to enable client-side use of the MTConnect agent. The data acquisition process for the robot arm is detailed in the following subsections. The data are saved, and the model is executed on a high-speed personal computer. Additionally, incorporating disparate data sources into the data pipeline is discussed.

4.1.1 Operational data of the Workcell

To collect the operational data from the UR5e robot arm, we utilized the Universal Robot's Real-Time Data Exchange (UR-RTDE) interface that has Application Programming Interfaces (API) for both C++ and Python. This interface is provided by the vendor and enables data collection such as angular position, velocity, acceleration, torque, current, and temperature for each of the six joints of the robot arm. The Python API is used to collect a set of predetermined data items.

4.1.2 MTConnect interface

The two crucial elements in an MTConnect implementation are the adapter and the agent. The adapter serves as a data collection element from the equipment controller or sensors 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 that are gathered from the adapter. The agent also acts as a data aggregator in case data are collected from more than one machine. Figure 5 shows the flow of data from a physical device (UR5e) to the digital twin.

A semantic structure was provided for the physical data generated by the UR5e robot arm through MTConnect. This semantic structure includes data tags and units as outlined in the MTConnect 2.0 Standard (MTConnect 2022b). Universal Robots (2019) shows the data items (and the corresponding units) that are offered by the vendor through the UR-RTDE interface that can be mapped to MTConnect data tags. Using the Python UR-RTDE API, a socket-based adapter that sends MTConnect compliant data to the agent was developed. The adapter was installed on a Raspberry Pi connected to the robot arm. An instance of the MTConnect 2.0 agent then consumes the data and serves it in a machine-readable format. As more machines and data sources are set up in the workcell, the agent also serves as a data aggregator prior to serving data.

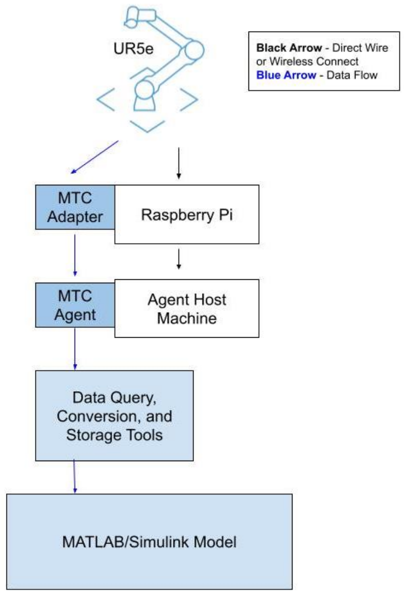
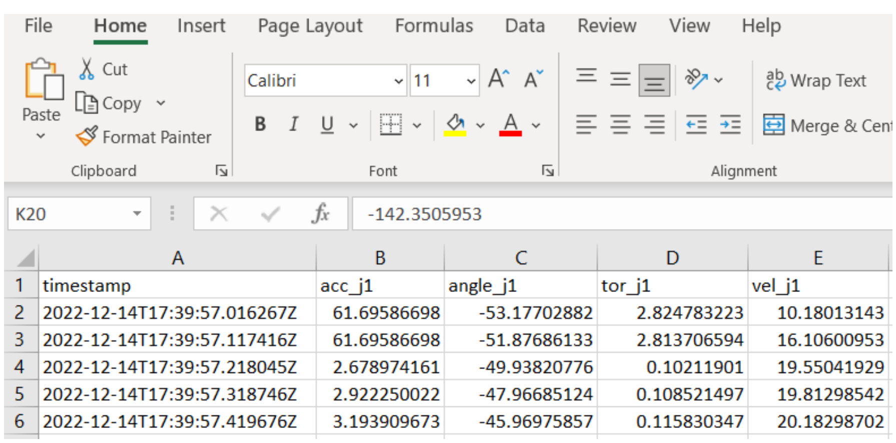


Figure 5: MTConnect data flow from robot arm to the digital model.

4.1.3 Client-Side integration

The MTConnect agent is implemented in C++ and displays data in XML format on a Hypertext Transfer Protocol (HTTP) server. XML is a machine-readable format. Depending on the use case, client-side applications have specific data requirements from the perspective of integration. The tool used in this research for modeling the robot workcell is the Simulink/Simscape, which can input either comma-separated values (CSV) or spreadsheet values where multiple data items over a time interval are recorded and synced up to their respective timestamps (UTC format). Figure 6 shows a section of the data in the spreadsheet file. The software tools that are used to parse the XML output from the MTConnect Agent, populate a 2-Dimensional array, and store the array in a CSV file have been developed. These tools are not data-dependent and can be applied to any data pipeline with MTConnect capabilities.



	A	B	C	D	E
1	timestamp	acc_j1	angle_j1	tor_j1	vel_j1
2	2022-12-14T17:39:57.016267Z	61.69586698	-53.17702882	2.824783223	10.18013143
3	2022-12-14T17:39:57.117416Z	61.69586698	-51.87686133	2.813706594	16.10600953
4	2022-12-14T17:39:57.218045Z	2.678974161	-49.93820776	0.10211901	19.55041929
5	2022-12-14T17:39:57.318746Z	2.922250022	-47.96685124	0.108521497	19.81298542
6	2022-12-14T17:39:57.419676Z	3.193909673	-45.96975857	0.115830347	20.18298702

Figure 6: Section of the data showing timestamp and data for joint 1 of UR5e.

4.2 Methods and tools for the digital twin

Modeling dynamic behavior of a robot arm includes the modeling of physical properties, such as mass of robot links, centers of mass, link and joint inertia, and mass distribution into the model of the digital twin. In this case, we used physical modeling, where a model consists of the real physical components of the system. Physical modeling does not require sophisticated programming, it enables visualization of system operation, generates kinematic and dynamic data, and can be easily transferred to industry. The digital twin environment for the physical modeling is Simscape, which is an integrated package within the MATLAB's Simulink toolbox. Most modeling tasks will be carried out in the Simscape Multibody environment and linked with Simscape networks. Simscape networks enable the modeling of more detail of the system, when needed. Data are collected by modeling sensors attached to the elements.

4.2.1 Robot arm CAD models

To develop a physical model of a robot arm, CAD models of its components are fundamental. These models are the description of geometry of the parts and how they are connected or assembled to result into the robot arm. The robot's CAD models are provided by the robot manufacturer. These CAD models can be imported into the digital twin environment to create a physical model of the UR5e robot arm. The CAD models for the gripper are "assembled" at the joints into the end effector in the AutoCAD Inventor environment. The resulting assembly is exported into the digital twin environment using the multibody add-on as XML files. They are then imported as an assembly module and "attached" to the robot arm model. Figure 7 shows the model of the robot arm and attached end effector.

4.2.2 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. Some of these data are provided by the manufacturer (Universal Robots, 2020). These properties 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, on the other hand, are a description of the mass, center of mass, and moments of inertia of each link.

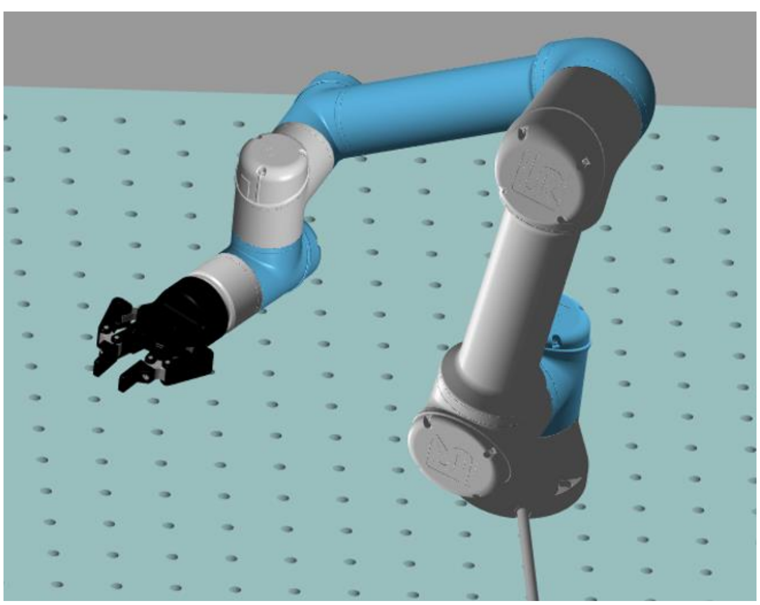


Figure 7: The UR5e robot arm in the digital twin environment with a gripper attached.

4.2.3 Integration of component digital twins

Digital twins are built for individual components (robot arms, CNC, and CMM) of the workcell. These component digital twins need to be integrated to obtain a digital twin of the workcell. The activities of the components in the real world are to be coordinated by messages and commands through interfaces. In the digital twin, each component will be updated with data from its physical counterpart. MTConnect, and the open-source Robot Operating System (ROS) Industrial are to be used to enable interoperability between robots and machine-cell devices (Robinson et al. 2019).

4.3 Digital twin validation

The digital twin needs to be validated because the quality of information fed back to the physical counterpart depends on the accuracy of the digital twin in representing the real system. Emphasis will be put on both similarity and fidelity. Different components of the physical workcell will be modeled to different levels of fidelity, depending on the focus and granularity of data collection and analysis. Zhang et al. (2021) discuss verification and validation methods for the digital twin, which are categorized into qualitative methods, quantitative methods, and integrated methods. Both qualitative and quantitative methods require metrics for digital twin validation. These metrics include credibility/fidelity, complexity, standardization, and capability maturity of model construction.

Hua et al. (2022) summarized general strategies to validate a digital twin. These include visual inspection of the twin for correctness using established standards, testing properties of the digital twin, model-based testing using methods such as input-output conformance testing, and machine learning or artificial intelligence-based testing. Kibira et al. (2022) used a model-based approach to validate the digital twin model of a robot arm. Joint position and orientation data, velocity data, and acceleration data were collected from the physical twin. These data were input into the digital twin model and the torque required to execute a given tool center point trajectory was computed by the digital twin. These torque data were then compared with that of the physical system. Concurrency of results indicated a valid model.

5 DISCUSSION AND FUTURE RESEARCH

This paper introduced a method for using available standards, technologies, methods, and tools to build a digital twin of a robot workcell comprising two robot arms, a desktop CNC machine tool, and a CMM. Physical modeling is selected for building an initial digital twin of a robot arm to simulate the action of picking parts and loading parts onto a CNC machine. Real-time data are collected using the MTConnect standard. In the work that will follow, digital twins for the remaining equipment will be built using a similar approach. The digital twins will be connected to each other to function as an integrated digital twin of the workcell. All digital twin models will be executed and updated using real-time data that are collected from its physical counterpart. This ensures that the digital twins of all equipment, and the information and commands exchanged, will be synchronized, and integrated with the activities of the physical workcell. No previous digital twin has been demonstrated for different equipment using this approach. Further, working with industry will help to identify additional standards and tools that industry can easily implement.

Once the digital twin is built, the efforts will proceed to perform study for various use cases. Relevant data will be collected for these specific use cases with specific objectives. A few examples of potential use cases are discussed in section 2. The level of fidelity of the digital twins will be determined based on the scope and objectives of the use case. For example, if we consider PHM as a use case, the common types of degradations of the equipment will be identified as well as the level of detail in the digital twin to capture data related to those failures. Degradations may manifest themselves in performance such as reduction in accuracy when placing a part or an increase in energy consumption. However, the cause(s) can be identified by analyzing the data from the manufacturing process. Analytical models will be developed from both physical and simulated data in the digital twin. These models will be verified and validated using physically collected and virtually generated data. Multiple scenarios representing different digital twin objectives are being planned. Digital twins will be built for each scenario using available tools and following established standards. The experience from these activities will result in methods and guidelines for building digital twins and hence, wider adoption of the digital twin.

DISCLAIMER

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REFERENCES

Abbasi, R., A. R. Yanes, E. M. Villanuera, and R. Ahmad. 2021. "Real-Time Implementation of Digital Twin for Robot Based Production Line". In *Proceedings of the Conference on Learning Factories* (CLF), Online, 1–2 July 2021.

Bécue, A., E. Maia, L. Feeken, P. Borchers. and I. Praça. 2020. "A New Concept of Digital Twin Supporting Optimization and Resilience of Factories of the Future". *Applied Sciences*, vol. 10, p. 4482.

Detzner, A. and M. Eigner. 2018. "A Digital Twin for Root Cause Analysis and Product Quality Monitoring". In *Proceedings of the Design 2018 15th International Design Conference*, pp. 1547–1558, University of Zagreb.

Errandonea, I., S. Beltrán, and S. Arrizabalaga. 2020. "Digital Twin for Maintenance: A Literature Review". *Computers in Industry*, vol. 123, p. 103316.

Han, S. H., A. J. Park, A. R. Park, and M. H. Ryu. 2021. "Automated DNA Extraction Monitoring System Based on MTConnect Technology". *Applied Science*, vol. 11, 684.

Helu M. and T. Hedberg, Jr. 2020. "Connecting, Deploying, and Using the Smart Manufacturing Systems Testbed". *NIST Internal Report*, AMS 200-2. https://doi.org/10.6028/NIST.AMS.200-2. Accessed on Jan. 15, 2023.

Hua, E.Y., S. Lazarova-Molnar, and D. P. Francis. 2022. "Validation of Digital Twins: Challenges and Opportunities". In *Proceedings of the 2022 Winter Simulation Conference*, pp. 2900–2911, IEEE.

ISO. 2020. *ISO (DIS) 23247-2: Automation Systems and Integration - Digital Twin Framework for Manufacturing - Part 2: Reference Architecture.* ISO/TC 184/SC4/WG15

Kibira, D., and B. A. Weiss. 2022. "Towards a Digital Twin of a Robot Workcell to Support Prognostics and Health Management". In *Proceedings of the 2022 Winter Simulation Conference*, pp. 2968–2979, IEEE.

Lo, C. K., C.H. Chen, and R. Y. Zhong 2021. A Review of Digital Twin in Product Design and Development". *Advanced Engineering Informatics*, vol. 48, 101297.

Lu, Y., C. Liu, I., Kevin, K. Wang, H. Huang, and X. Xu. 2020. "Digital Twin-driven Smart Manufacturing: Connotation, Reference Model, Applications and Research Issues". *Robotics and Computer-Integrated Manufacturing*, 61, p.101837.

Lynn R, W. Louhichi, M. Parto, E. Wescoat, and T. Kurfess. 2017. "Rapidly Deployable MTConnect-Based Machine Tool Monitoring Systems". In *Proceedings of the ASME 2017 12th International Manufacturing Science and Engineering Conference MSEC2017*, pp. 1–10. ASME.

MathWorks, *Simscape: Model and Simulate Multidomain Physical Systems* https://www.mathworks.com/products/simscape.html. Accessed on Jan. 15, 2023.

Mengnan, L., S. Fang, H. Dong, C. Xu. 2021. "Review of Digital Twin about Concepts, Technologies, and Industrial Applications". *Journal of Manufacturing Systems*, vol. 58, Part B, pp. 346–361.

MTConnect. 2022a. *MTConnect R© Standard Part 2.0 – Device Information Model*, Version 2.0.0.

MTConnect. 2022b. *MTConnect R© Standard Part 5.0 – Interfaces Interaction Model,* Version 2.0.0.

Özgüra, E. and Y. Mezouarb. 2016. "Kinematic Modeling and Control of a Robot Arm Using Unit Dual Quaternions". *Robotics and Autonomous Systems*, vol. 77, 66–73.

Pérez, L., S. Rodríguez-Jiménez, N. Rodríguez, R. Usamentiaga, and D. F. García. 2020. "Digital Twin and Virtual Reality-Based Methodology for Multi-Robot Manufacturing Cell Commissioning". *Applied Sciences*, vol. 10, p. 3633.

Robinson, M. 2019. "Cost Effective Coordinated and Cooperative Robotics Enabled by Open Technologies". *NIST Final Technical Status Report,* CFDA Number: 11.609.

Shao, G. and D. Kibira. 2018. "Digital Manufacturing: Requirements and Challenges for Implementing Digital Surrogates". In *Proc. of the 2018 Winter Simulation Conference*, IEEE.

Sjödin, D. R., V. Parida, M. Leksell, and A. Petrovic. 2018. "Smart Factory Implementation and Process Innovation". *Research-Technology Management*, vol. 61, pp. 22–31.

Universal Robots. 2019. *Real-Time Data Exchange (RTDE) Guide*, https://www.universal-robots.com/articles/ur/interface-communication/real-time-data-exchange-rtde-guide/ Accessed on Jan. 20, 2023.

Universal Robots: *Robot Step File UR5e* https://www.universal-robots.com/download/mechanical-e-series/ur5e/robot-step-file-ur5e-e-series/ Accessed on March 14, 2023.

Wang K., Y. Wang, and Y. Li. 2022. "A Review of the Technology Standards for Enabling Digital Twin". *Digital Twin,* 2:4 https://doi.org/10.12688/digitaltwin.17549.2 Accessed on Jan. 23, 2023.

Wärmefjord, K., R. Söderberg, B. Schleich, and H. Wang. 2020. "Digital Twin for Variation Management: A General Framework and Identification of Industrial Challenges Related to the Implementation". *Applied Science,* vol. 10, pp. 1–16, 3342.

Zhang, M., Tao, F., and A. Y. C. Nee. 2021. "Digital Twin Enhanced Dynamic Job-Shop Scheduling". *Journal of Manufacturing Systems*, vol. 58, pp. 146–16156.

Zhang, L., L. Zhou, and B. K. Horn. 2021. "Building a Right Digital Twin with Model Engineering". *Journal of Manufacturing Systems*, vol. 59, pp.151–164.

Zheng, Y., S. Yang, and H. Cheng. 2019. "An Application Framework of Digital Twin and its Case Study". *Journal of Ambient Intelligence and Humanized Computing*, vol. 10, pp.1141–1153.

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