



**NIST Advanced Manufacturing Series  
NIST AMS 100-68**

# **Digital Twin Lab: Supporting Research and Development for Standards and Implementations**

Rishabh Venketesh  
Deogratias Kibira  
Guodong Shao  
Matthew J. Triebe

This publication is available free of charge from:  
<https://doi.org/10.6028/NIST.AMS.100-68>

**NIST Advanced Manufacturing Series  
NIST AMS 100-68**

# **Digital Twin Lab: Supporting Research and Development for Standards and Implementations**

Rishabh Venketesh  
Deogratias Kibira  
Guodong Shao  
Matthew J. Triebe  
*Systems Integration Division  
Engineering Laboratory  
US Department of Commerce  
National Institute of Standards and Technology*

This publication is available free of charge from:  
<https://doi.org/10.6028/NIST.AMS.100-68>

August 2025



U.S. Department of Commerce  
*Howard Lutnick, Secretary*

National Institute of Standards and Technology  
*Craig Burkhardt, Acting Under Secretary of Commerce for Standards and Technology and Acting NIST Director*

NIST AMS 100-68  
August 2025

Certain equipment, instruments, software, or materials, commercial or non-commercial, are identified in this paper in order to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement of any product or service by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

**NIST Technical Series Policies**

[Copyright, Use, and Licensing Statements](#)

[NIST Technical Series Publication Identifier Syntax](#)

**Publication History**

Approved by the NIST Editorial Review Board on 2025-04-09

**How to Cite this NIST Technical Series Publication**

Venketesh, R., Kibira, D., Shao, G. and Triebe, M.J., (2025) Digital Twin Lab: Supporting Research and Development for Standards and Implementations. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Advanced Manufacturing Series (AMS) NIST AMS 100-68. <https://doi.org/10.6028/NIST.AMS.100-68>

**Author ORCID iDs**

Rishabh Venketesh: 0009-0000-7521-0895

Deoqratis Kibira: 0009-0002-7796-2518

Guodong Shao: 0000-0001-8856-3622

Matthew J. Triebe: 0000-0002-5964-1078

**Contact Information**

[rishabh.venketesh@nist.gov](mailto:rishabh.venketesh@nist.gov)

## **Abstract**

Digitalization in manufacturing is a concept that, while having existed for some time, can now be realized because of advancements in IIoT (Industrial Internet of Things) enabling technologies and data standardization. Digital twins are at the forefront of this trend and are being implemented by many manufacturers worldwide. To further encourage the adoption of digital twins by United States (U.S.) manufacturing enterprises, the Systems Integration Division (SID) at the National Institute of Standards and Technology (NIST) has established a Digital Twin Laboratory (DTL). In this report, we outline the vision and objectives of the DTL and provide fundamental information on digital twins within the context of manufacturing. We provide a detailed description of the DTL setup and case studies implemented in the lab. Additionally, the relevant standards implemented in the DTL are listed and their contexts in digital twins for manufacturing are briefly summarized. Lastly, we explore possible research areas that can be supported by the DTL and identify future efforts to accomplish research objectives.

## **Keywords**

data pipeline; digital twins; digital twin standards; manufacturing cell; MTConnect; small and medium-sized enterprises; smart manufacturing

## Table of Contents

<b>1. Introduction</b>	<b>1</b>
1.1. Lab Vision	2
1.2. Lab Purpose and Objectives	2
1.2.1. Testing and Developing Relevant Standards	2
1.2.2. Prototyping Digital Twin Systems and Components	2
1.2.3. Testing Enabling Technologies	3
1.2.4. Providing Demonstrations and Enabling Collaborations on Digital Twins	3
1.2.5. Developing Tools for Digital Twin Prototypes	4
<b>2. Digital Twin Lab Operating Environment and Equipment</b>	<b>4</b>
2.1. Manufacturing Work Cell and Communication Network	4
2.1.1. Manufacturing Work Cell Layout and Material Flow	4
2.1.2. Communication Network	5
2.2. Computerized Numerical Control (CNC) Machine Tool	6
2.2.1. PocketNC	6
2.2.2. Automated Fixturing Solution	7
2.3. Collaborative Robots	8
2.4. Coordinate Measuring Machine	8
<b>3. Digital Twin Lab Data Infrastructure</b>	<b>9</b>
3.1. MTConnect Implementation	9
3.1.1. Data Collection from Equipment	10
3.1.2. Data Aggregation	10
3.2. Data Streaming	10
3.2.1. Data Streaming Requirements	11
3.2.2. Technical Implementation	11
3.3. Data Storage	11
3.3.1. Data Storage Requirements	11
3.3.2. Technical Implementation	12
<b>4. Relevant Standards and Implementation</b>	<b>12</b>
<b>5. Research and Development Efforts</b>	<b>13</b>
5.1. Part Design to Support Prototype Demonstration	13
5.2. Equipment Digital Twins	14
5.2.1. Collaborative Robot Digital Twin	14
5.2.2. CNC Machine Tool Digital Twin	15
5.3. Augmented Reality (AR) and Virtual Reality (VR)	15

<b>6. Conclusion and Future Work.....</b>	<b>16</b>
<b>References.....</b>	<b>17</b>
<b>Appendix A. MTConnect Device Configuration File .....</b>	<b>19</b>
<b>Appendix B. MTConnect Agent Configuration File .....</b>	<b>29</b>

### List of Figures

<b>Fig. 1. Material Flow of the DTL Manufacturing Work Cell .....</b>	<b>5</b>
<b>Fig. 2. Material Flow of the DTL Manufacturing Work Cell .....</b>	<b>6</b>
<b>Fig. 3. Axes of the Pocket NC .....</b>	<b>7</b>
<b>Fig. 4. Expanded CAD model of zero-point fixturing solution for Pocket NC machine tool .....</b>	<b>8</b>
<b>Fig. 5. Data pipeline diagram .....</b>	<b>9</b>
<b>Fig. 6. Part design to be cut on the CNC, handled by the robots, and inspected by the CMM .....</b>	<b>13</b>
<b>Fig. 7. In progress robot digital twin for model validation and improvement.....</b>	<b>14</b>
<b>Fig. 8. Altair simulation of CNC machine tool .....</b>	<b>15</b>

## **Acknowledgments**

We greatly acknowledge Yehoshua Halle, Eric Charlery, William Stiller, Aubrey Simonson, and Laetitia Monnier for their work in developing digital twins and digital threads for the lab, Michael Chen for his work in setting up the data infrastructure, and Simon Frechette and Josh Lubell for their support on the hazard review of the lab.

## 1. Introduction

In the United States (U.S.), most, if not all, large manufacturing companies have made digital manufacturing a priority and started to implement digital twins in their facilities and supply chains. Although the relevant technologies for digital twins originated in the 1960's with the push for space exploration, the term was not coined until 2002 by Michael Greaves – an expert in product lifecycle management [1]. In this report, we focus on digital twins for manufacturing. The role of digital twins in modern manufacturing is so well recognized that the most recent U.S. *National Strategy for Advanced Manufacturing* calls for efforts to

*“Enable the application of advanced sensing control technologies and machine learning across the manufacturing sector. Advance smart manufacturing by pursuing digital twins. Develop standards for data compatibility to enable seamless integration of smart manufacturing.”* [2].

In response, the National Institute of Standards and Technology (NIST) established a Digital Twin Laboratory (DTL) to advance the development and adoption of standards to support the use of digital twin technology for manufacturing.

A barrier to advancing digital twin technology in manufacturing is the need for commonly accepted definitions for the concept and relevant terms. Aspects of digital twins such as accuracy, synchronization, and bidirectional communication with real systems and their significance are all debated topics that make defining digital twins a not-so-simple task. This report adopts the terminology and structure defined in the ISO 23247 (Digital Twin Framework for Manufacturing) standard to provide a reference framework for digital twins in manufacturing. This framework includes the following definitions of manufacturing digital twins and relevant terms [3].

- manufacturing digital twin - “a fit-for-purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation”
- observable manufacturing element - “an item that has an observable physical presence or operation in manufacturing”
- digital representation - “a data element representing a set of properties of an observable manufacturing element”

This report discusses the vision and objectives of the DTL (Section 1), describes the hardware and relevant setups of the DTL work cell, and provides information on the data pipeline implemented in the DTL (Sections 2 and 3 respectively). In addition, it describes ongoing standards work and research efforts that leverage the DTL (Sections 4 and 5).

## **1.1. Lab Vision**

The vision of the DTL is to enable innovation by advancing measurement science, standards, and technology in the field of digital twins for manufacturing. The DTL utilizes critical technologies to test and promote the use of relevant standards for U.S. manufacturers to successfully implement digital twins in their operations.

## **1.2. Lab Purpose and Objectives**

The purpose of the DTL is to serve as a testbed to support research areas pertaining to digital twins in manufacturing. The DTL supports five primary objectives.

- Testing and Developing Relevant Standards
- Prototyping Digital Twin Systems and Components
- Testing Enabling Technologies
- Providing Demonstrations and Enabling Collaborations on Digital Twins
- Developing Tools for Digital Twin Prototypes

This section discusses these objectives and how the DTL supports each one.

### **1.2.1. Testing and Developing Relevant Standards**

To promote the adoption of digital twin technologies, identifying and developing relevant standards is necessary. Standards allow for interoperability between enabling technologies (e.g., IIoT, smart sensors, communication protocols, modeling tools, and visualization applications) and various manufacturing tools in today's market. Additionally, by providing common language, standards support industry partners in communicating and sharing their perspectives on digital twins for manufacturing. The DTL provides a platform to implement standards such as ISO 23247 and MTConnect [4] [5] [6] [7] [8]. Through implementation, collaborators can demonstrate the advantages of leveraging existing standards, identify areas of improvement in said standards, and provide feedback to the relevant standards organizations.

One example of leveraging the DTL to test standards is the implementation of ISO 23247 in the lab. This standard outlines the requirements of the digital twin framework for manufacturing. Section 5.2 provides concrete examples of how the framework is implemented and tested. Another example is the use of the MTConnect Standard in the DTL data pipeline (see Section 3). Through collaboration with the MTConnect Institute, the lab supports the testing and development of their latest revision for the MTConnect standard. More information on relevant standards can be found in Section 4.

### **1.2.2. Prototyping Digital Twin Systems and Components**

At their core, digital twins are complex systems comprised of multiple components, e.g., data

collection, data modeling, and user interfaces. The hardware and software infrastructure of the DTL facilitates the prototyping of individual digital twin components and integrating them to form complete digital twins. Key digital twin components that can be developed through prototyping in the DTL include components for (a) data collection and communication and (b) data management. For the former, the DTL supports the implementation of multiple industrial communication protocols such as Modbus TCP/IP in combination with semantic standards for manufacturing data such as MTConnect. For the latter, the DTL supports the implementation of data management solutions, such as MongoDB (a No-SQL database product) to store and query historical datasets. Prototyping digital twin systems and components allows for the testing of standards and exploring scenarios where digital twin components can be reused for different use cases.

### **1.2.3. Testing Enabling Technologies**

A driving force behind the rise of digital twins in manufacturing is the advancement of enabling technologies. These technologies include, but are not limited to, sensors, automation technologies, modeling and visualization tools, extended reality (XR) [5], simulation tools, and up-to-date data management solutions. Since digital twins operate at the intersection of these technologies, testing and validating these technologies is critical to success. Not only does the testing instill confidence in stakeholders looking to digitalize their shop floor, but it also helps them apply relevant standards (see Section 4), develop frameworks, and implement use case scenarios. Due to its reconfigurability and flexibility, the DTL provides an opportunity to deploy various enabling technologies. An example of leveraging enabling technologies to enhance a work cell is an automated material fixturing solution being implemented on the Pocket NC as described in Section 2.2.2 to support research in automated workflows for manufacturing cells.

### **1.2.4. Providing Demonstrations and Enabling Collaborations on Digital Twins**

As a managed source of data and a testbed supporting different work cell configurations, the DTL offers opportunities for both internal and external collaborations. These opportunities include (a) working with machine-tool vendors to implement capabilities supported by digital twin standards and development (e.g. implementing MTConnect Part 5 - Interfaces on a Mitutoyo Coordinate Measuring Machine), (b) optimizing manufacturing processes to reduce waste and maximize productivity (e.g. exploring the intersection of digital twins and LEAN manufacturing principles), and (c) working with Standard Development Organizations (SDOs) such as the MTConnect Institute to test revisions to standards. In addition to collaboration and research, the DTL demonstrates how digital twins for manufacturing applications can be developed and deployed. Furthermore, digital twin use cases give both internal researchers and external stakeholders an understanding of the capabilities of digital twin technology when paired with appropriate data visualization tools.

### **1.2.5. Developing Tools for Digital Twin Prototypes**

The set of software tools available in the lab range in capabilities such as collecting and transforming raw data from equipment, aggregating data from multiple equipment and certain stages of a product’s lifecycle (design, manufacturing, and inspection), converting between multiple data standards, and interfacing with client-side applications (e.g. simulation modeling tools, database solutions, augmented reality, virtual reality, etc.) [4] [5]. While some of these tools are publicly available many of the tools were developed in-house as part of research in the DTL. Stakeholders can use our library of tools to replicate the setup in the DTL or adapt to similar use-cases.

## **2. Digital Twin Lab Operating Environment and Equipment**

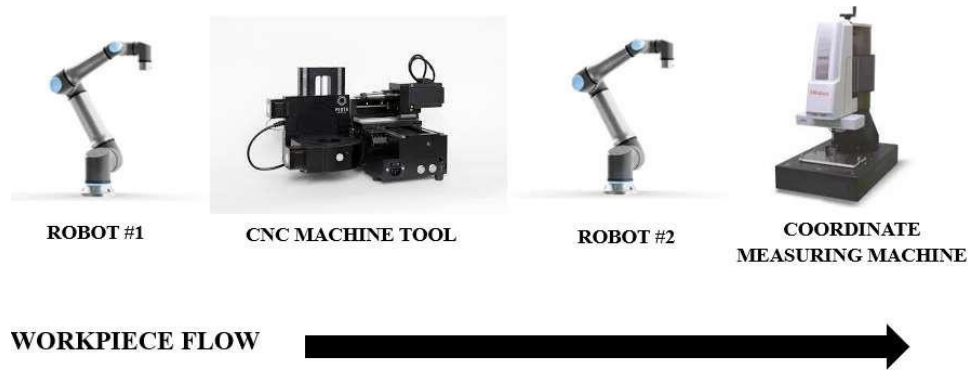
The DTL contains equipment and hardware, including collaborative robots, a machine tool, inspection equipment, and computing hardware. All equipment is connected centrally to support the data infrastructure described in Section 3. This section (a) describes the hardware and software setups of the DTL and how the current lab configuration supports the flow of data from machines to client-side applications (i.e. data pipeline), and (b) explains the capabilities of each piece of hardware and respective setups.

### **2.1. Manufacturing Work Cell and Communication Network**

Cellular manufacturing is a “lean method of producing similar products using cells” to optimize operations and more efficiently utilize resources [9]. Some advantages of cellular manufacturing include work-in-progress (WIP) reduction, space utilization optimization, lead time reduction, increased productivity, and greater flexibility [10]. To remain competitive, U.S. manufacturing enterprises often adopt this style of manufacturing. However, challenges such as balancing cost, efficiency, and flexibility still exist. The DTL aims to support research in cellular manufacturing through a small-scale manufacturing work cell that supports digital twinning with full automation for various use cases.

#### **2.1.1. Manufacturing Work Cell Layout and Material Flow**

Cellular manufacturing is a “lean method of producing similar products using cells” to optimize operations and more efficiently utilize resources [9]. Some advantages of cellular manufacturing include work-in-progress (WIP) reduction, space utilization optimization, lead time reduction, increased productivity, and greater flexibility [10]. To remain competitive, U.S. manufacturing enterprises often adopt this style of manufacturing. However, challenges such as balancing cost, efficiency, and flexibility still exist. The DTL aims to support research in cellular manufacturing through a small-scale manufacturing work cell that supports digital twinning with full automation for various use cases.



**Fig. 1. Material Flow of the DTL Manufacturing Work Cell**

While Fig. 1 describes the current setup of the manufacturing cell, the DTL is reconfigurable, thus supporting the implementation of multiple material flow and layouts.

### **2.1.2. Communication Network**

An important consideration when configuring the hardware in the lab is to support the development of a flexible data pipeline that allows data to be collected from each stage of the manufacturing process from production to inspection. Figure 2 shows the network diagram that describes the manufacturing equipment layout and computing resources. The collaborative robots, the CMM, and the CNC are directly wired to an ethernet switch. This switch then connects directly to the lab's wireless router. A Linux computer that hosts the MTConnect Agent (see Section 3.1) connects to the router as well. This enables a local subnet in which all the manufacturing equipment communicates with both a central data aggregator and each other. Database services are also deployed on a Linux computer. Lastly, a Windows computer wirelessly connects to the router to pull data from the MTConnect Agent. The Windows computer has simulation modeling tools (e.g. Altair and MATLAB Simulink) that researchers can use for digital twin research and demonstrations.

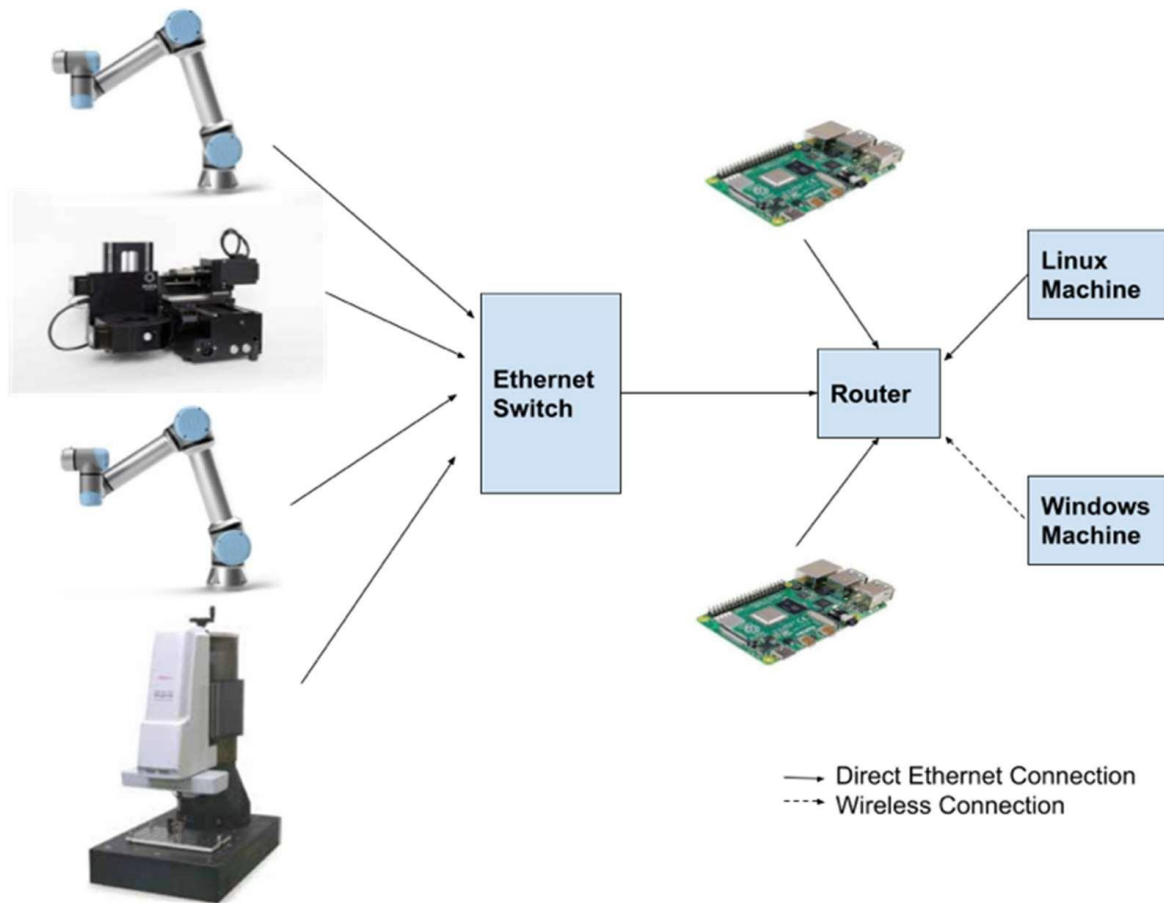


Fig. 2. Material Flow of the DTL Manufacturing Work Cell

## 2.2. Computerized Numerical Control (CNC) Machine Tool

The CNC machine tool used in the lab is a manufacturing technology that utilizes subtractive manufacturing to produce designed parts and is the core of our work cell. Additionally, the CNC machine tool provides numerous data items that include operational data, machine status data, and data for setups and tool path data. This section briefly describes the CNC machine tool used in the lab and the extra hardware deployed.

### 2.2.1. PocketNC

The work cell uses a Pocket NC V2-10, a 5-axis desktop milling machine. With 5-axis milling capabilities, the lab can simulate the operations of larger industry counterparts for subtractive manufacturing. This mill has a 50,000 RPM spindle and travels 115.5mm (X), 128.3 mm (Y), and 90.1mm (Z). The table rotates from  $-25^{\circ}$  to  $135^{\circ}$  in the A direction while the table can continuously rotate in the B direction ( $-9999^{\circ}$  to  $9999^{\circ}$ ). These axes can be seen in Fig. 3.

The Pocket NC operates with most CAM software. The machine accepts standard G-code, which enables the results to be scaled up to large workshop-size machine tools. Desktop-scale manufacturing equipment makes it practical to provide researchers with accessible equipment

whose results are comparable to those of workshop counterparts.

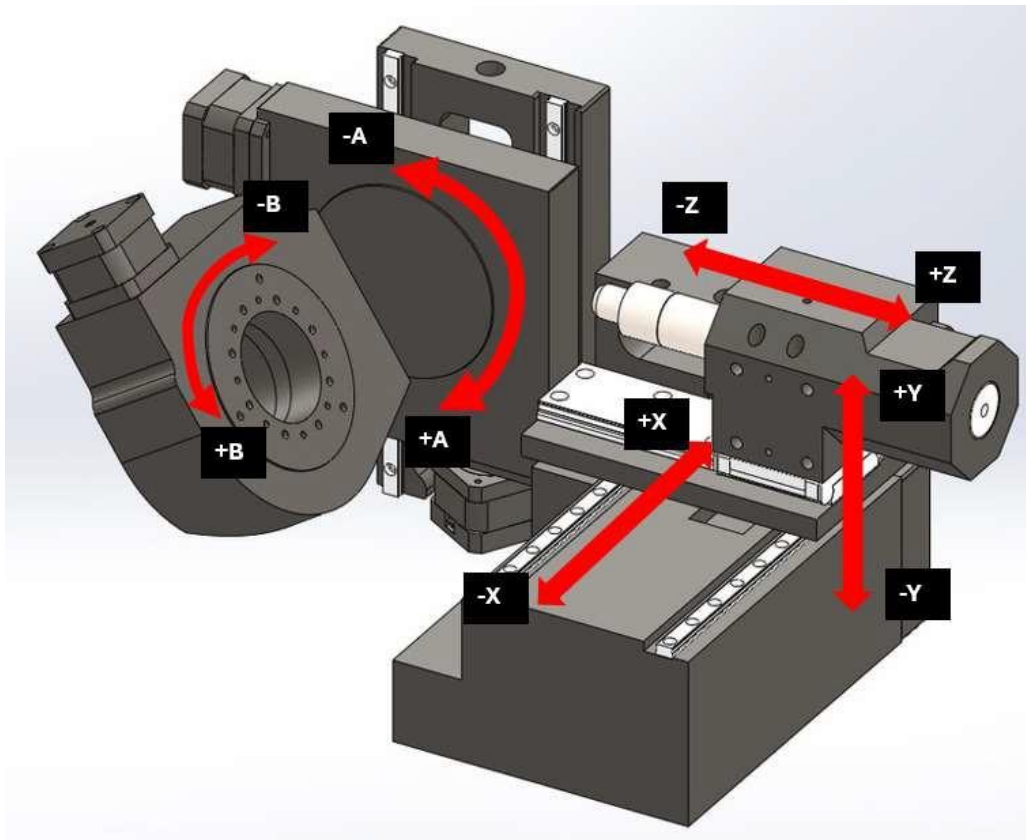


Fig. 3. Axes of the Pocket NC

### 2.2.2. Automated Fixturing Solution

An automated material fixturing solution for the Pocket NC supports full automation of the work cell. While multiple automated material fixturing, solutions are available for traditional shop floor machine tools, the small size of the Pocket NC necessitates a custom solution for the machine tool. A zero-point fixture (a fixturing system that uses pre-defined reference points) solution ensures there is only one possible point to fixture parts, allowing for higher repeatability. This is especially important for work cell automation, as even the slightest deviation in the material fixture can lead to significant discrepancies in part quality.

Figure 4 shows an expanded CAD model of the zero-point fixturing system. A custom-built adapter connects the clamping module to the Pocket NC's B-Table (see Section 2.2.1). The adapter serves as a connector between the clamp and the machine tool, and it also features air hose fittings to power the air-actuated clamping module. While not shown in Fig. 4, the fixturing system requires the installation of a push-to-connect swivel connector on the base of the adapter for the air hose. Schunk's Vero-S module serves as the air-actuated clamping module. It requires at least six bars (600 kPa) of actuating air pressure to be supplied to release the clamping mechanisms. Lastly, to attach a workpiece to the clamping system, two steps must be completed to prepare stock material prior to clamping. The first is installing a clamping pin

to each piece of stock. The clamping pin clamps onto the Vero-S module, and the pins are tailor-made for the Vero-S module. The second step is to machine a notch in the stock material so that the workpiece is rotationally locked with the clamping module, as shown in Fig. 4.

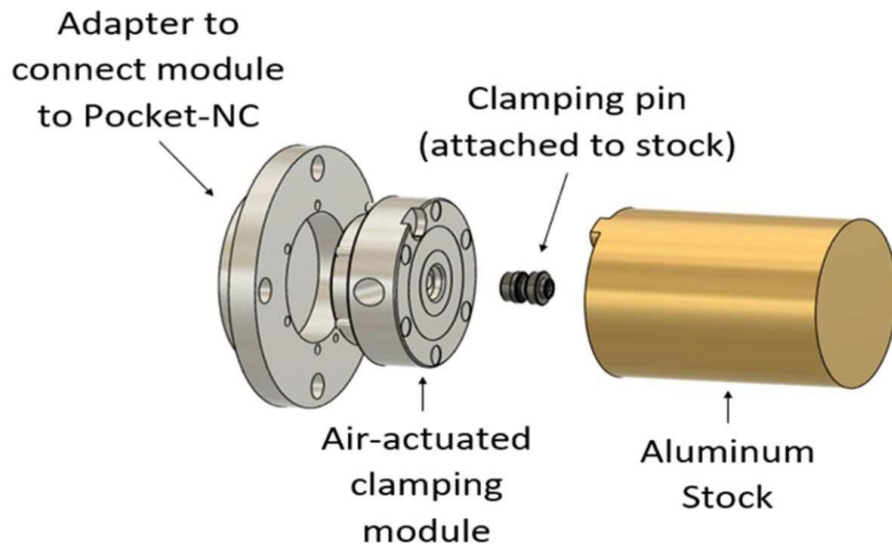


Fig. 4. Expanded CAD model of zero-point fixturing solution for Pocket NC machine tool

### 2.3. Collaborative Robots

The DTL uses UR5e robots that are lightweight (20.6 kg) and maneuver with six degrees of freedom. They have a maximum payload of 5 kg, a reach of 0.85 m, and a repeatability of  $\pm 0.03\text{mm}$ . The UR5e robots are used for material handling activities in the work cell: picking parts from the input storage, loading onto the Pocket NC, offloading the Pocket NC, loading the CMM, and offloading the CMM to the output storage. These robots are programmed by either writing a program in URScript and loading it to the controller or using a teach pendant.

The robot end effector is the 2F-85 Gripper and is designed for material handling operations. The gripper has two articulated fingers with two joints for each finger. These features enable it to handle parts of various geometries required for pick and place, machine tending, assembly, and quality testing. The gripper can be used in both time-based control and event-based control schemes. Like the UR5e robots, the gripper can be programmed by either writing a program and loading it to the controller or using a teach pendant.

### 2.4. Coordinate Measuring Machine

A CMM is used to measure the geometrical features of a physical object by touching the surfaces of the object with a probe to measure discrete points. The CMM supports product quality conformance by validating that the product matches the design. When a part is measured by a CMM, data regarding the dimensions of the part geometries are collected and analyzed to determine if there are any nonconformities. The results of this analysis provide feedback to the manufacturing system or process [12]. Excessive geometric variation in the finished product can then be avoided.

The CMM in the DTL is a Mitutoyo Ko-ga-me that can characterize and inspect parts manually or automatically with a part program. This CMM can be integrated with other equipment in the work cell, such as the CNC machine tool and robot arms. This integration provides real-time feedback is essential for effective process monitoring and quality control, as opposed to mere inspection in a standalone mode.

### 3. Digital Twin Lab Data Infrastructure

The DTL provides a wealth of data ranging from operational/status data from machines and metrology data from product inspection. This section describes the data infrastructure of the DTL. Additionally, this section discusses relevant standards and tools to provide background on the data pipeline's setup and implementation.

#### 3.1. MTConnect Implementation

This section briefly overviews the MTConnect standard and explains how the standard provides a foundation for the DTL data infrastructure. Figure 5 shows the flow of data in the data pipeline. Each aspect of the data pipeline is discussed below.

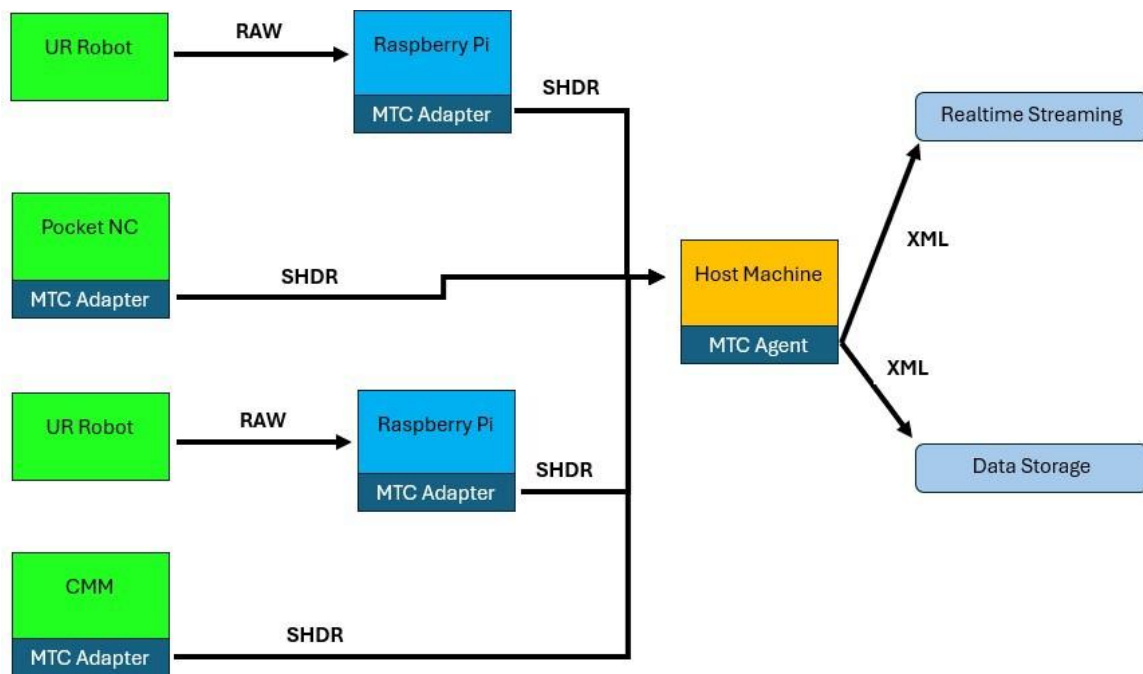


Fig. 5. Data pipeline diagram

The MTConnect standard provides a semantic vocabulary for manufacturing data that defines structure and context. The standard serves to facilitate interoperability between data coming from various machine types and different vendors. In addition to the semantic vocabulary offered by the MTConnect standard, the MTConnect Institute provides a set of tools that allow the collection of raw data from machines, the transformation of the data to an MTConnect-

compliant data format, the aggregation of data from multiple machine tools and sensors, and the supply of data for client-side/third-party applications. For more information on the MTConnect standard and how the available tools operate, please refer to the NIST Advanced Manufacturing Series Report for “Connecting, Deploying, and Using the Smart Manufacturing Systems Test Bed” (NIST AMS 200-2) [13] and the MTConnect standard documentation [14][17].

### **3.1.1. Data Collection from Equipment**

All the DTL equipment (UR5e robot arms, Pocket NC, and Mitutoyo Ko-ga-me CMM) can generate operational and condition data. In addition, the CMM provides inspection data.

Appendix A shows the device configuration file for the data items from each machine while relating proprietary data tags to MTConnect data tags. For a list of MTConnect Data Tags with their respective contextual information, refer to Part 2.0 of the MTConnect Standard – the Device Information Model [14]. For each machine, software adapters transform raw data into a MTConnect-compliant data format. The universal robot controllers do not support the installation of third-party software. Therefore, Raspberry Pi’s collect raw data from the UR5e’s via ethernet and have the adapters installed on them. The MTConnect-compliant data format is known as SHDR, which is a pipe-delimited text format structured as follows:

*YYYY-MM-DDTHH:MM:SS.SSSZ|DataTag|DataValue.*

The SHDR format associates a data tag and data value with a timestamp in UTC (Coordinated Universal Time). Also, of note, a Quality Information Framework (QIF) document, for which MTConnect provides a wrapper in native eXtensible Markup Language (XML) format, is used to aggregate and organize inspection data from the CMM.

### **3.1.2. Data Aggregation**

For data aggregation purposes, the MTConnect C++ Agent (v 2.1) is hosted on the Linux computer, referred to in section 2.1.2. Upon transforming raw machine data to SHDR, the adapters for each machine send the SHDR data to the Linux host via socket-to-socket programming. Upon receiving data from the adapters, the Agent validates the data to ensure that the data coming in adheres to the MTConnect standard. The redacted agent configuration file with local network information can be found in Appendix B.

## **3.2. Data Streaming**

The DTL offers different data streaming capabilities via a data pipeline. The data pipeline lays out how to manage a constant flow of data from disparate sources and supports leveraging the DTL for different use cases. The MTConnect Agent is a software tool that collects and organizes MTConnect data and allows us to implement the standard in our data pipeline.

### **3.2.1. Data Streaming Requirements**

The requirements for data streaming are as follows:

- a. the data stream should be readily available to internal researchers for integration with client-side applications
- b. the data should have context associated with it so that other stakeholders can better understand the dataset
- c. the data stream should support addition of more manufacturing elements (machine tools, sensors, etc.)

researchers should have the ability to query based on specific components, devices, and time intervals.

### **3.2.2. Technical Implementation**

The MTConnect Agent is a software application provided by the MTConnect Institute that collects machine data, organizes the data, and provides the data in a MTConnect-compliant format. The Agent also receives and processes data requests from client-side applications. The MTConnect Agent, upon aggregating and validating data from the machine adapters, serves up the data in a machine-readable format – namely XML. Users can query the agent based on device name, component name, and sample size using the Hypertext Transfer Protocol (HTTP) requests. (As of this publication, the Agent is only available internally at NIST.) Upon querying the data, researchers obtain an XML document with their dataset that can be parsed and used for third-party applications. It is important to note that the Agent has a max buffer size of 131,072 samples, thus making it unsuitable for storing historical data over significant intervals of time. Therefore, a data storage strategy is in place as described in section 3.3.

## **3.3. Data Storage**

Application use cases in the DTL may require the use of historical datasets, and a data storage strategy enables the DTL to serve as a managed source of data for various use cases. The data storage strategy is driven by the requirements of our setup and use cases but can be modified for similar digital twin implementations.

### **3.3.1. Data Storage Requirements**

The requirements for data storage are as follows:

- a. the managed data should be readily available to internal researchers for integration with client-side applications
- b. users should have ease of access to datasets without technical knowledge of the data storage implementation

- c. the data storage solution should have the sufficient capacity and ability to archive historical data sets

researchers should have the ability to query based on specific components, devices, and time intervals.

### **3.3.2. Technical Implementation**

A MongoDB implementation handles the data storage in the DTL. MongoDB is an open-source No-SQL Database solution. No-SQL (Structured Query Language) solutions are non-relational databases. Compared to relational databases (SQL), non-relational databases prioritize rapid development and accommodate the addition of various data attributes throughout their usage.

The implemented methodology is as follows. The MTConnect Agent is routinely sampled (~1 Hz) using HTTP requests that result in XML documents containing data from all the machines over the sampling period. These XML documents are then parsed, and the data are restructured to be added to the MongoDB instance. Additionally, for user convenience, a Graphical User Interface (GUI) helps users generate MongoDB queries.

## **4. Relevant Standards and Implementation**

Digital twin standards, such as architectural frameworks, can provide implementation guidelines for the development of digital twins. Specific standards support digital twin functionalities such as data collection, communication, information modeling, systems integration, system abstraction/modeling, automation, and control. The set of standards currently being implemented in various digital twin components in the DTL are described below. New applicable standards will be continuously added to the list in future versions of this report.

- ISO 23247, Digital Twin Framework for Manufacturing, provides a generic guideline, a reference architecture, and a framework for case-specific digital twin implementations. The standard supports the composability of models and interoperability among digital twin modules. It also provides examples of data collection, data communication, integration, modeling, and applications of relevant standards [15]. ISO 23247 provides the framework for all the digital twin development in the DTL (see Section 5) and the concepts and definitions from ISO 23247 are adapted to this paper.
- ISO 10303, Automation Systems and Integration – Product Data Representation and Exchange, also known as Standard for the Exchange of Product (STEP) model data, supports the exchange of product manufacturing information [16]. We implement ISO 10303 during the product design process (see Section 5.1) and when modeling lab equipment for digital twin visualization (see Section 5.2).
- The American National Standards Institute (ANSI) MTConnect supports interoperability by providing a vocabulary for manufacturing equipment, making

possible structured contextualized data, and avoiding proprietary formats. Data sources of MTConnect in production include equipment, sensor packages, and other factory-floor hardware [17]. MTConnect is the foundation for the DTL's data pipeline (see Section 3) and the MTConnect Agent implemented in the pipeline is a software tool provided by the MTConnect Institute.

QIF is a framework standard for computer-aided quality QIF systems. QIF enables the capture, use, and re-use of metrology-related information throughout the Product Lifecycle Management (PLM) and Product Data Management (PDM) domains. It supports the creation of digital threads. It applies to product design, manufacturing, and quality inspection. It relies on the XML standard and contains a library of XML schemas. It supports data integrity and interoperability in implementing model-based enterprise and IoT [18]. QIF is used to structure and report metrology information as parts are inspected by the DTL's CMM.

## 5. Research and Development Efforts

Research within the DTL is conducted over a simplified product lifecycle (i.e., design, manufacture, and inspection stages). Product design in the lab is set up to use Autodesk Inventor and the designed product is manufactured using the equipment in the lab. Lastly, inspection of the manufactured part is completed using the CMM. The following sections describe the current ongoing research efforts that leverage the DTL.

### 5.1. Part Design to Support Prototype Demonstration

To fully leverage the work cell in the DTL, a part is designed to be cut on the CNC machine tool, handled by the robots, and inspected by the CMM. This part is designed using Autodesk Inventor. It is envisioned that future designs will be constructed using Inventor on the desktop computer in the lab, and toolpaths will be generated using the same software. The part design (shown in Fig. 6) is designed to be cut from wax stock.

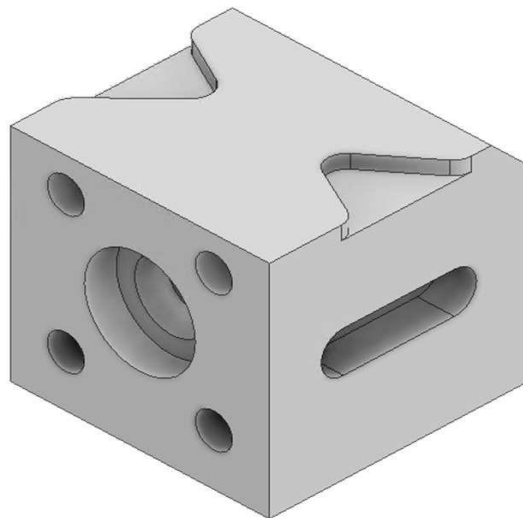


Fig. 6. Part design to be cut on the CNC, handled by the robots, and inspected by the CMM

## 5.2. Equipment Digital Twins

This section discusses digital twins developed for individual devices and identifies specific ongoing work. Individual device digital twins are under development for the collaborative robots (see Section 2.3) and the CNC machine tool (see Section 2.4). Each of the device digital twins are developed using the ISO 23247 standard and serve to test the standard as well.

### 5.2.1. Collaborative Robot Digital Twin

The DTL work cell includes two collaborative robots. As mentioned in Section 2.3, the robots have six degrees of freedom and are designed for industrial manufacturing settings. Collaborative robots, in the context of manufacturing, are primarily used for material handling and machine tending. Universal Robots has an extensive list of data items that can be collected through the UR-RTDE (Universal Robot Real Time Data Exchange) interface. This interface allows third party developers to read real time data from the robots and send commands to the robots. Using the UR-RTDE, MTConnect adapters collect each robot joint's position, velocity, and acceleration for digital twin development. The orientation of the tool-center-position (TCP), as well as data on the movement of the robot's adaptive gripper attachment, are also collected by the MTConnect adapter. All these data items are provided by the built-in sensors installed by the vendor on the robots.

Figure 7 shows a deployed digital twin of one of our collaborative robots. To the left in the figure is the physical robot looping through a basic drag-and-drop operation. On the top right is the visualization of the robot's motion based on simulated data produced by the model of the robot (see Appendix C). On the bottom right is a visualization produced in MATLAB of the error between the data from the simulated robot and the physical system.

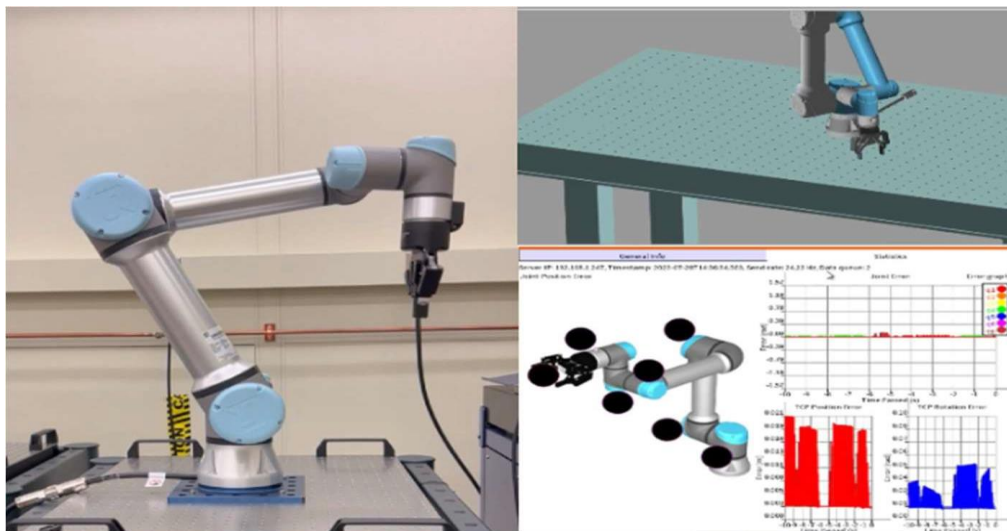
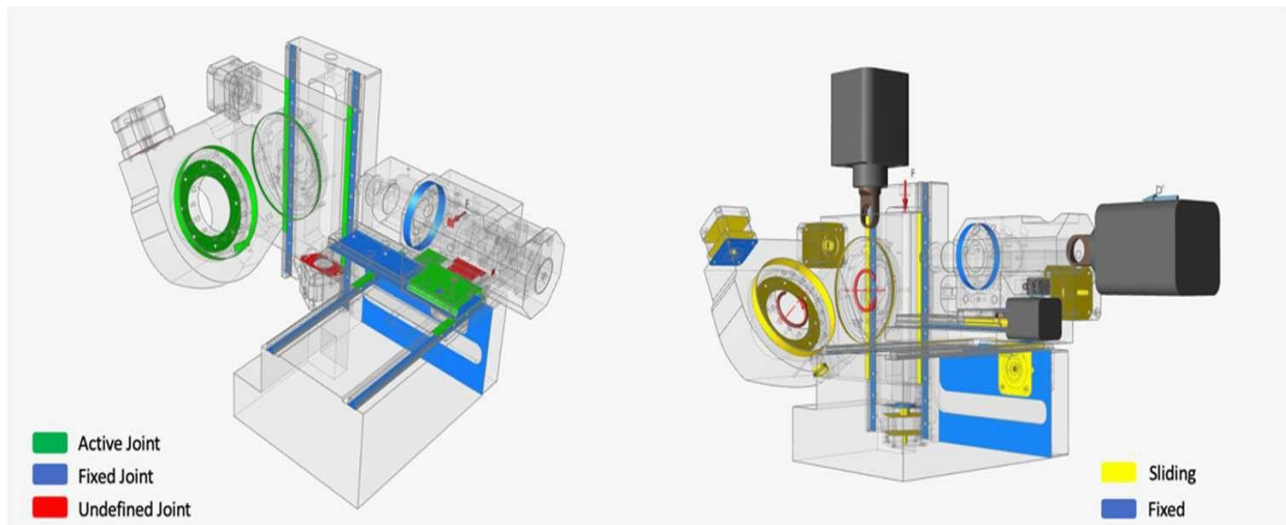


Fig. 7. In progress robot digital twin for model validation and improvement

The digital twin model for the robot was developed in MATLAB Simulink is a simplified mathematical description of the physical robot. Real-time data was integrated with the Simulink model using MATLAB Simulink Desktop Real-Time, which provides a real-time kernel for executing Simulink models, and the analytics application was developed in JAVA. Currently, this digital twin does not have automated feedback to improve the model or affect the physical system. This is one of the future research objectives of the DTL.

### 5.2.2. CNC Machine Tool Digital Twin

The DTL work cell includes a CNC machine tool. As mentioned in Section 2.2, the machine tool is a five-axis desktop CNC. By deploying external sensors, researchers can gather more datasets, such as vibrational and temperature measurements, and better inform digital twins for use cases. The foundations, described as follows, for a data visualization digital twin are currently implemented in the DTL. The CNC was modeled in Altair (see Figure 8), and the joint positions were updated with data collected from the physical machine to reflect the CNC's motion during operation.



**Fig. 8. Altair simulation of CNC machine tool**

The model simulates the motion of the CNC by replaying historical datasets provided by the CNC in the DTL. In the future, capabilities of Altair and other modeling tools to explore multiple use cases of digital twins will be leveraged. Additionally, methods for streaming collected data to update the digital twin in real time will be investigated.

### 5.3. Augmented Reality (AR) and Virtual Reality (VR)

While developing digital twins, an important topic cannot be avoided – the user interface. Specifically, we are researching interface design for digital twins using AR/VR technologies, which present significant challenges to manufacturers due to the unique expertise required. One research effort in the DTL is developing an authoring tool [5] that addresses this challenge by allowing manufacturing end users who do not have the programming skills to create AR/VR

interfaces for digital twins easily and quickly. The initial prototype demonstrates the ability to parse MTConnect machine operational data and provide menu-based interfaces and a sandbox of data visualizations to guide users through interpreting and analyzing the data.

## **6. Conclusion and Future Work**

In this report, we outlined the vision and objectives of the DTL. Additionally, we described the hardware and software setups for the DTL that enable it to support multiple research areas. Some of these research areas result in the implementations of specific case studies that are documented in this report. Lastly, we presented a list and description of standards that are implemented in the DTL.

Looking forward, the lab will support the pursuit of various research objectives. First, we will make data publicly available for external stakeholders. This will not only further establish the DTL as a managed source of data but also increase the impact of research from the DTL. Future work will address making the data available in a secure manner as well as allowing external researchers to utilize both real time and historical datasets. Second, we will fully integrate the CMM with the existing data pipeline. This would allow us to view data from the entirety of the work cell in a standardized format and would make the process of digital twin development much more efficient. Software for the CMM will need to be upgraded and we will collaborate with the vendor to ensure that the CMM is compatible with the DTL's data pipeline as the pipeline evolves. Third, we will collaborate with external stakeholders to develop and test methods for VVUQ (Verification, Validation, and Uncertainty Quantification) of digital twins. The DTL will be instrumental in testing results of these collaborations. The research could potentially impact standards for digital twins such as ISO 23247. Lastly, we will work with SDOs to test and provide feedback on relevant standards. As a result, new use-cases could arise and require different lab configurations, data pipelines, and enabling technologies.

## References

- [1] Grieves, Michael. (2016). Origins of the Digital Twin Concept. 10.13140/RG.2.2.26367.61609.
- [2] U.S. National Economic Council. (2022). *National strategy for advanced manufacturing*. The White House. <https://www.whitehouse.gov/wp-content/uploads/2022/10/National-Strategy-for-Advanced-Manufacturing-2022.pdf>
- [3] ISO. 2020. ISO (DIS) 23247-1: Automation Systems and Integration - Digital Twin Framework for Manufacturing - Part 2: Reference Architecture. ISO/TC 184/SC4/WG15
- [4] Kibira, D., Shao, G., Venketesh, R., and Triebe, M. "Building a Digital Twin of a CNC Machine Tool" Proceedings of the Winter Simulation Conference 2024.
- [5] Simonson, A. and Shao, G. "An Authoring Tool for Manufacturing Digital Twin Visualization" APMS 2024.
- [6] Shao, G.; Frechette, S.; and Srimi, V. An analysis of the new ISO 23247 series of standards on digital twin framework for manufacturing, ASME MSEC 2023.
- [7] Kibira, D. and Shao, G. "Data Requirements for Digital Twins of a Robot Workcell," Proceedings of the Winter Simulation Conference 2023.
- [8] Kibira, D., Shao, G. and Weiss B. Building a Digital Twin for Robot Workcell Prognostics and Health Management. Proceedings of the Winter Simulation Conference 2021.
- [9] Kiran DR (2022) Chapter Twenty – Plan Location and Layout. *Principles of Economics and Management for Manufacturing Engineering*, ed Kiran DR (Woburn, MA, Butterworth-Heinemann), Chapter 20, pp 227-242
- [10] Sakran, H. K., Mahbuba, H. M., & Jafer, A. S. (2016). A review of a basic concept of cellular manufacturing. *International Journal of Design and Manufacturing Technology*, 8(1), 30-37.
- [11] Kibira, D., Shao, G., & Venketesh, R. (2023, May). Building A Digital Twin of AN Automated Robot Work cell. *2023 Annual Modeling and Simulation Conference (ANNSIM)*, (IEEE, Hamilton, ON, Canada), pp 196-207.
- [12] Gaha, R., A. Durupt, and B. Eynard. (2021). Towards the implementation of the Digital Twin in CMM inspection process: Opportunities, challenges, and proposals. *Procedia Manufacturing*, 54:216-221.
- [13] Helu M, Hedeberg T, (2020) Connecting, Deploying, and Using the Smart Manufacturing Systems Test Bed. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Advanced Manufacturing Series (AMS) 200-2, <https://doi.org/10.6028/NIST.AMS.200-2>
- [14] MTConnect Institute (2023, Last Accessed September 2023) MTConnect Standard, Version 2.2, Part 2 – Device Information Model, Standard. URL <https://docs.mtconnect.org/>.
- [15] ISO. 2021. ISO (DIS) 23247-1: Automation Systems and Integration - Digital Twin Framework for Manufacturing - Part 1: Overview and fundamental principles. ISO/TC 184/SC4/WG15

- [16] ISO. 2021. ISO 10303-1: Industrial automation systems and integration - product data representation and exchange - Part 1: Overview and fundamental principles. ISO/TC 184/SC4
  - [17] MTConnect Institute (2023, Last Accessed September 2023) MTConnect Standard, Version 2.2, Part 1 – Fundamentals, Standard. URL <https://docs.mtconnect.org/>.
- QIF. 2020: The quality information framework standard. URL <http://qifstandards.org/>.

## **Appendix A. MTConnect Device Configuration File**

Below is the MTConnect Device Configuration file. The file is in XML format and lists the available data items and associated metadata. This file covers data being streamed from all machines in the laboratory. By using the Device Configuration file in combination with the MTConnect standard documentation, stakeholders can understand what data attributes are being collected and their context within manufacturing.

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <MTConnectDevices xmlns="urn:mtconnect.org:MTConnectDevices:2.0" xmlns:xsi="
  http://www.w3.org/2001/XMLSchema-instance" xsi:schemaLocation="
  urn:mtconnect.org:MTConnectDevices:2.0 http://schemas.mtconnect.org/schemas/
  MTConnectDevices_2.0.xsd">
3   <Header version="2.0" creationTime="2020-02-20T00:00:00Z" instanceId="1" sender="
  ur5e" bufferSize="131072" assetBufferSize="1024" assetCount="0"/>
4   <Devices>
5     <Device id="r1" uuid="ur5e_r1" name="UR5e_r1">
6       <Description manufacturer="Universal RobotsFactory" model="ur5e"/>
7       <DataItems>
8         <DataItem id="avail_r1" name="avail_r1" type="AVAILABILITY" category="
  EVENT"/>
9         <DataItem id="estop_r1" name="estop_r1" type="EMERGENCY_STOP" category="
  EVENT"/>
10      </DataItems>
11      <Components>
12        <Controller id="ur_controller">
13          <DataItems>
14            <DataItem type="ACCUMULATED_TIME" category="SAMPLE" id="
  start_time_r1" name="start_time_r1" units="SECOND"/>
15            <DataItem type="ACCUMULATED_TIME" category="SAMPLE" id="
  exec_time_r1" name="exec_time_r1" units="SECOND"/>
16          </DataItems>
17        </Controller>
18        <Axes id="a">
19          <Components>
20            <Rotary id="a01_r1" name="J1_r1" nativeName="base_joint_r1">
21              <DataItems>
22                <DataItem name="angle_j1_r1" category="SAMPLE" id="
  angle_j1_r1" type="ANGLE" subType="ACTUAL" units="
  DEGREE"/>
23                <DataItem name="vel_j1_r1" category="SAMPLE" id="
  vel_j1_r1" type="ANGULAR_VELOCITY" subType="ACTUAL"
  units="DEGREE/SECOND"/>
24                <DataItem name="acc_j1_r1" category="SAMPLE" id="
  acc_j1_r1" type="ANGULAR_ACCELERATION" subType="ACTUAL"
  units="DEGREE/SECOND^2"/>
25                <DataItem name="tor_j1_r1" category="SAMPLE" id="
  tor_j1_r1" type="TORQUE" units="NEWTON_METER"/>
26              </DataItems>
27            </Rotary>
28            <Rotary id="a02_r1" name="J2_r1" nativeName="shoulder_joint_r1">
29              <DataItems>
30                <DataItem name="angle_j2_r1" category="SAMPLE" id="
  angle_j2_r1" type="ANGLE" subType="ACTUAL" units="
  DEGREE"/>
31                <DataItem name="vel_j2_r1" category="SAMPLE" id="
  vel_j2_r1" type="ANGULAR_VELOCITY" subType="ACTUAL"
  units="DEGREE/SECOND"/>
32                <DataItem name="acc_j2_r1" category="SAMPLE" id="
  acc_j2_r1" type="ANGULAR_ACCELERATION" subType="ACTUAL"
  units="DEGREE/SECOND^2"/>
33                <DataItem name="tor_j2_r1" category="SAMPLE" id="
  tor_j2_r1" type="TORQUE" units="NEWTON_METER"/>
34              </DataItems>
35            </Rotary>
36            <Rotary id="a03_r1" name="J3_r1" nativeName="elbow_joint_r1">
37              <DataItems>
38                <DataItem name="angle_j3_r1" category="SAMPLE" id="
  angle_j3_r1" type="ANGLE" subType="ACTUAL" units="
  DEGREE"/>
39                <DataItem name="vel_j3_r1" category="SAMPLE" id="
  vel_j3_r1" type="ANGULAR_VELOCITY" subType="ACTUAL"
  units="DEGREE/SECOND"/>
40                <DataItem name="acc_j3_r1" category="SAMPLE" id="
  acc_j3_r1" type="ANGULAR_ACCELERATION" subType="ACTUAL"
  units="DEGREE/SECOND^2"/>
41                <DataItem name="tor_j3_r1" category="SAMPLE" id="
  tor_j3_r1" type="TORQUE" units="NEWTON_METER"/>
42              </DataItems>
43            </Rotary>

```

```
44 ▼ <Rotary id="a04_r1" name="J4_r1" nativeName="wrist_joint_1_r1">
45 ▼   <DataItems>
46     <DataItem name="angle_j4_r1" category="SAMPLE" id="
         angle_j4_r1" type="ANGLE" subType="ACTUAL" units="
         DEGREE"/>
47     <DataItem name="vel_j4_r1" category="SAMPLE" id="
         vel_j4_r1" type="ANGULAR_VELOCITY" subType="ACTUAL"
         units="DEGREE/SECOND"/>
48     <DataItem name="acc_j4_r1" category="SAMPLE" id="
         acc_j4_r1" type="ANGULAR_ACCELERATION" subType="ACTUAL"
         units="DEGREE/SECOND^2"/>
49     <DataItem name="tor_j4_r1" category="SAMPLE" id="
         tor_j4_r1" type="TORQUE" units="NEWTON_METER"/>
50   </DataItems>
51 </Rotary>
52 ▼ <Rotary id="a05_r1" name="J5_r1" nativeName="wrist_joint_2_r1">
53 ▼   <DataItems>
54     <DataItem name="angle_j5_r1" category="SAMPLE" id="
         angle_j5_r1" type="ANGLE" subType="ACTUAL" units="
         DEGREE"/>
55     <DataItem name="vel_j5_r1" category="SAMPLE" id="
         vel_j5_r1" type="ANGULAR_VELOCITY" subType="ACTUAL"
         units="DEGREE/SECOND"/>
56     <DataItem name="acc_j5_r1" category="SAMPLE" id="
         acc_j5_r1" type="ANGULAR_ACCELERATION" subType="ACTUAL"
         units="DEGREE/SECOND^2"/>
57     <DataItem name="tor_j5_r1" category="SAMPLE" id="
         tor_j5_r1" type="TORQUE" units="NEWTON_METER"/>
58   </DataItems>
59 </Rotary>
60 ▼ <Rotary id="a06_r1" name="J6_r1" nativeName="wrist_joint_3">
61 ▼   <DataItems>
62     <DataItem name="angle_j6_r1" category="SAMPLE" id="
         angle_j6_r1" type="ANGLE" subType="ACTUAL" units="
         DEGREE"/>
63     <DataItem name="vel_j6_r1" category="SAMPLE" id="
         vel_j6_r1" type="ANGULAR_VELOCITY" subType="ACTUAL"
         units="DEGREE/SECOND"/>
64     <DataItem name="acc_j6_r1" category="SAMPLE" id="
         acc_j6_r1" type="ANGULAR_ACCELERATION" subType="ACTUAL"
         units="DEGREE/SECOND^2"/>
65     <DataItem name="tor_j6_r1" category="SAMPLE" id="
         tor_j6_r1" type="TORQUE" units="NEWTON_METER"/>
66   </DataItems>
67 </Rotary>
68 </Components>
69 </Axes>
70 ▼ <Auxiliaries id="aux1">
71 ▼   <Components>
72 ▼     <Gripper id="g_1_r1" name="gripper_r1">
73 ▼       <DataItems>
74         <DataItem type="POSITION_CARTESIAN" category="SAMPLE" id="
             posit_tcp_r1" name="posit_tcp_r1" units="MILLIMETER_3D
             "/>
75         <DataItem type="ORIENTATION" category="SAMPLE" id="
             orient_tcp_r1" name="orient_tcp_r1" units="DEGREE_3D"/>
76         <DataItem type="ANGULAR_VELOCITY" name="ang_vel_rx_r1"
             category="SAMPLE" id="ang_vel_rx_r1" subType="ACTUAL"
             units="DEGREE/SECOND"/>
77         <DataItem type="ANGULAR_VELOCITY" name="ang_vel_ry_r1"
             category="SAMPLE" id="ang_vel_ry_r1" subType="ACTUAL"
             units="DEGREE/SECOND"/>
78         <DataItem type="ANGULAR_VELOCITY" name="ang_vel_rz_r1"
             category="SAMPLE" id="ang_vel_rz_r1" subType="ACTUAL"
             units="DEGREE/SECOND"/>
79         <DataItem type="VELOCITY" name="vel_x_r1" category="
             SAMPLE" id="vel_x_r1" subType="ACTUAL" units="
             MILLIMETER/SECOND"/>
80         <DataItem type="VELOCITY" name="vel_y_r1" category="
             SAMPLE" id="vel_y_r1" subType="ACTUAL" units="
             MILLIMETER/SECOND"/>
```

```
81         <DataItem type="VELOCITY" name="vel_z_r1" category="
82             SAMPLE" id="vel_z_r1" subType="ACTUAL" units="
83             MILLIMETER/SECOND"/>
84     </DataItems>
85 </Gripper>
86 </Components>
87 </Auxiliaries>
88 </Components>
89 </Device>
90 <Device id="r2" uuid="ur5e_r2" name="UR5e_r2">
91     <Description manufacturer="Universal RobotsFactory" model="ur5e"/>
92     <DataItems>
93         <DataItem id="avail_r2" name="avail_r2" type="AVAILABILITY" category="
94             EVENT"/>
95         <DataItem id="estop_r2" name="estop_r2" type="EMERGENCY_STOP" category="
96             EVENT"/>
97     </DataItems>
98 <Components>
99     <Controller id="ur_controller">
100         <DataItems>
101             <DataItem type="ACCUMULATED_TIME" category="SAMPLE" id="
102                 start_time_r2" name="start_time_r2" units="SECOND"/>
103             <DataItem type="ACCUMULATED_TIME" category="SAMPLE" id="
104                 exec_time_r2" name="exec_time_r2" units="SECOND"/>
105         </DataItems>
106     </Controller>
107     <Axes id="a">
108         <Components>
109             <Rotary id="a01_r2" name="J1_r2" nativeName="base_joint_r2">
110                 <DataItems>
111                     <DataItem name="angle_j1_r2" category="SAMPLE" id="
112                         angle_j1_r2" type="ANGLE" subType="ACTUAL" units="
113                         DEGREE"/>
114                     <DataItem name="vel_j1_r2" category="SAMPLE" id="
115                         vel_j1_r2" type="ANGULAR_VELOCITY" subType="ACTUAL"
116                         units="DEGREE/SECOND"/>
117                     <DataItem name="acc_j1_r2" category="SAMPLE" id="
118                         acc_j1_r2" type="ANGULAR_ACCELERATION" subType="ACTUAL"
119                         units="DEGREE/SECOND^2"/>
120                     <DataItem name="tor_j1_r2" category="SAMPLE" id="
121                         tor_j1_r2" type="TORQUE" units="NEWTON_METER"/>
122                 </DataItems>
123             </Rotary>
124             <Rotary id="a02_r2" name="J2_r2" nativeName="shoulder_joint_r2">
125                 <DataItems>
126                     <DataItem name="angle_j2_r2" category="SAMPLE" id="
127                         angle_j2_r2" type="ANGLE" subType="ACTUAL" units="
128                         DEGREE"/>
129                     <DataItem name="vel_j2_r2" category="SAMPLE" id="
130                         vel_j2_r2" type="ANGULAR_VELOCITY" subType="ACTUAL"
131                         units="DEGREE/SECOND"/>
132                     <DataItem name="acc_j2_r2" category="SAMPLE" id="
133                         acc_j2_r2" type="ANGULAR_ACCELERATION" subType="ACTUAL"
134                         units="DEGREE/SECOND^2"/>
135                     <DataItem name="tor_j2_r2" category="SAMPLE" id="
136                         tor_j2_r2" type="TORQUE" units="NEWTON_METER"/>
137                 </DataItems>
138             </Rotary>
139             <Rotary id="a03_r2" name="J3_r2" nativeName="elbow_joint_r2">
140                 <DataItems>
141                     <DataItem name="angle_j3_r2" category="SAMPLE" id="
142                         angle_j3_r2" type="ANGLE" subType="ACTUAL" units="
143                         DEGREE"/>
144                     <DataItem name="vel_j3_r2" category="SAMPLE" id="
145                         vel_j3_r2" type="ANGULAR_VELOCITY" subType="ACTUAL"
146                         units="DEGREE/SECOND"/>
147                     <DataItem name="acc_j3_r2" category="SAMPLE" id="
148                         acc_j3_r2" type="ANGULAR_ACCELERATION" subType="ACTUAL"
149                         units="DEGREE/SECOND^2"/>
150                 </DataItems>
151             </Rotary>
152         </Components>
153     </Axes>
154 </Components>
155 </Device>
```

```
124         <DataItem name="tor_j3_r2" category="SAMPLE" id="
125         tor_j3_r2" type="TORQUE" units="NEWTON_METER"/>
126     </DataItems>
127 </Rotary>
128 <Rotary id="a04_r2" name="J4_r2" nativeName="wrist_joint_1_r2">
129     <DataItems>
130         <DataItem name="angle_j4_r2" category="SAMPLE" id="
131         angle_j4_r2" type="ANGLE" subType="ACTUAL" units="
132         DEGREE"/>
133         <DataItem name="vel_j4_r2" category="SAMPLE" id="
134         vel_j4_r2" type="ANGULAR_VELOCITY" subType="ACTUAL"
135         units="DEGREE/SECOND"/>
136         <DataItem name="acc_j4_r2" category="SAMPLE" id="
137         acc_j4_r2" type="ANGULAR_ACCELERATION" subType="ACTUAL"
138         units="DEGREE/SECOND^2"/>
139         <DataItem name="tor_j4_r2" category="SAMPLE" id="
140         tor_j4_r2" type="TORQUE" units="NEWTON_METER"/>
141     </DataItems>
142 </Rotary>
143 <Rotary id="a05_r2" name="J5_r2" nativeName="wrist_joint_2_r2">
144     <DataItems>
145         <DataItem name="angle_j5_r2" category="SAMPLE" id="
146         angle_j5_r2" type="ANGLE" subType="ACTUAL" units="
147         DEGREE"/>
148         <DataItem name="vel_j5_r2" category="SAMPLE" id="
149         vel_j5_r2" type="ANGULAR_VELOCITY" subType="ACTUAL"
150         units="DEGREE/SECOND"/>
151         <DataItem name="acc_j5_r2" category="SAMPLE" id="
152         acc_j5_r2" type="ANGULAR_ACCELERATION" subType="ACTUAL"
153         units="DEGREE/SECOND^2"/>
154         <DataItem name="tor_j5_r2" category="SAMPLE" id="
155         tor_j5_r2" type="TORQUE" units="NEWTON_METER"/>
156     </DataItems>
157 </Rotary>
158 <Rotary id="a06_r2" name="J6_r2" nativeName="wrist_joint_3">
159     <DataItems>
160         <DataItem name="angle_j6_r2" category="SAMPLE" id="
161         angle_j6_r2" type="ANGLE" subType="ACTUAL" units="
162         DEGREE"/>
163         <DataItem name="vel_j6_r2" category="SAMPLE" id="
164         vel_j6_r2" type="ANGULAR_VELOCITY" subType="ACTUAL"
165         units="DEGREE/SECOND"/>
166         <DataItem name="acc_j6_r2" category="SAMPLE" id="
167         acc_j6_r2" type="ANGULAR_ACCELERATION" subType="ACTUAL"
168         units="DEGREE/SECOND^2"/>
169         <DataItem name="tor_j6_r2" category="SAMPLE" id="
170         tor_j6_r2" type="TORQUE" units="NEWTON_METER"/>
171     </DataItems>
172 </Rotary>
173 </Components>
174 </Axes>
175 <Auxiliaries id="aux1">
176     <Components>
177         <Gripper id="g_1_r2" name="gripper_r2">
178             <DataItems>
179                 <DataItem type="POSITION_CARTESIAN" category="SAMPLE" id
180                 ="posit_tcp_r2" name="posit_tcp_r2" units="MILLIMETER_3D
181                 "/>
182                 <DataItem type="ORIENTATION" category="SAMPLE" id="
183                 orient_tcp_r2" name="orient_tcp_r2" units="DEGREE_3D"/>
184                 <DataItem type="ANGULAR_VELOCITY" name="ang_vel_rx_r2"
185                 category="SAMPLE" id="ang_vel_rx_r2" subType="ACTUAL"
186                 units="DEGREE/SECOND"/>
187                 <DataItem type="ANGULAR_VELOCITY" name="ang_vel_ry_r2"
188                 category="SAMPLE" id="ang_vel_ry_r2" subType="ACTUAL"
189                 units="DEGREE/SECOND"/>
190                 <DataItem type="ANGULAR_VELOCITY" name="ang_vel_rz_r2"
191                 category="SAMPLE" id="ang_vel_rz_r2" subType="ACTUAL"
192                 units="DEGREE/SECOND"/>
193             </DataItems>
194         </Gripper>
195     </Components>
196 </Auxiliaries>
197 </Components>
198 </Robot>
199 </RobotModel>
```

```
162 <DataItem type="VELOCITY" name="vel_x_r2" category="
163 SAMPLE" id="vel_x_r2" subType="ACTUAL" units="
MILLIMETER/SECOND"/>
164 <DataItem type="VELOCITY" name="vel_y_r2" category="
165 SAMPLE" id="vel_y_r2" subType="ACTUAL" units="
MILLIMETER/SECOND"/>
166 <DataItem type="VELOCITY" name="vel_z_r2" category="
167 SAMPLE" id="vel_z_r2" subType="ACTUAL" units="
MILLIMETER/SECOND"/>
168 </DataItems>
169 </Gripper>
170 </Components>
171 </Auxiliaries>
172 </Components>
173 </Device>
174 <Device id="pnc" uuid="pocketnc" name="pocketNC">
175 <Description>Pocket NC : Machine Kit</Description>
176 <DataItems>
177 <DataItem id="avail" name="avail" type="AVAILABILITY" category="EVENT"/>
178 <DataItem id="functionalmode" name="functionalmode" type="
FUNCTIONAL_MODE" category="EVENT"/>
179 </DataItems>
180 <Components>
181 <Axes id="a" name="base">
182 <DataItems>
183 <DataItem type="ACTUATOR" category="CONDITION" id="servo" name="
servo_cond"/>
184 <DataItem type="SYSTEM" category="CONDITION" id="spnd1" name="
spindle_cond"/>
185 </DataItems>
186 <Components>
187 <Linear id="x" name="X">
188 <DataItems>
189 <DataItem type="POSITION" subType="ACTUAL" id="xpm"
category="SAMPLE" name="Xabs" units="MILLIMETER"
coordinateSystem="MACHINE"/>
190 <DataItem type="POSITION" subType="ACTUAL" id="xpw"
category="SAMPLE" name="Xpos" units="MILLIMETER"
coordinateSystem="WORK"/>
191 <DataItem type="POSITION" id="xt" category="CONDITION"
name="Xtravel"/>
192 <DataItem type="LOAD" id="xl" category="SAMPLE" name="
Xload" units="PERCENT"/>
193 <DataItem type="AXIS_FEEDRATE" id="xf" category="SAMPLE"
name="Xfprt" units="MILLIMETER/SECOND"/>
194 </DataItems>
195 </Linear>
196 <Linear id="y" name="Y">
197 <DataItems>
198 <DataItem type="POSITION" subType="ACTUAL" id="ypm"
category="SAMPLE" name="Yabs" units="MILLIMETER"
coordinateSystem="MACHINE"/>
199 <DataItem type="POSITION" subType="ACTUAL" id="ypw"
category="SAMPLE" name="Ypos" units="MILLIMETER"
coordinateSystem="WORK"/>
200 <DataItem type="POSITION" id="yt" category="CONDITION"
name="Ytravel"/>
201 <DataItem type="LOAD" id="yl" category="SAMPLE" name="
Yload" units="PERCENT"/>
202 <DataItem type="AXIS_FEEDRATE" id="yf" category="SAMPLE"
name="Yfprt" units="MILLIMETER/SECOND"/>
203 </DataItems>
204 </Linear>
205 <Linear id="z" name="Z">
206 <DataItems>
207 <DataItem type="POSITION" subType="ACTUAL" id="zpm"
category="SAMPLE" name="Zabs" units="MILLIMETER"
coordinateSystem="MACHINE"/>
```

```
206 <DataItem type="POSITION" subType="ACTUAL" id="zpw"  
207 category="SAMPLE" name="Zpos" units="MILLIMETER"  
208 coordinateSystem="WORK"/>  
209 <DataItem type="POSITION" id="zt" category="CONDITION"  
210 name="Ztravel"/>  
211 <DataItem type="LOAD" id="z1" category="SAMPLE" name="Zload"  
212 units="PERCENT"/>  
213 <DataItem type="AXIS_FEEDRATE" id="zf" category="SAMPLE"  
214 name="Zfrt" units="MILLIMETER/SECOND"/>  
215 </DataItems>  
216 </Linear>  
217 <Rotary id="c" name="C">  
218 <DataItems>  
219 <DataItem type="LOAD" id="c1" category="SAMPLE" name="Cload"  
220 units="PERCENT"/>  
221 <DataItem type="LOAD" id="s1" category="SAMPLE" name="Sload"  
222 units="PERCENT"/>  
223 <DataItem type="ANGLE" id="ct" category="CONDITION" name="Ctravel"/>  
224 <DataItem type="ANGULAR_VELOCITY" id="cf" category="SAMPLE" name="Cfrt" units="DEGREE/SECOND" nativeUnits="DEGREE/MINUTE"/>  
225 <DataItem type="ROTARY_VELOCITY" id="cs" category="SAMPLE" name="Srpm" subType="ACTUAL" units="REVOLUTION/MINUTE"/>  
226 <DataItem type="TEMPERATURE" id="ctemp" category="SAMPLE" name="Stemp" units="CELSIUS"/>  
227 <DataItem type="ANGLE" coordinateSystem="MACHINE" id="cposm" category="SAMPLE" name="Cabs" subType="ACTUAL" units="DEGREE"/>  
228 <DataItem type="ANGLE" coordinateSystem="WORK" id="cposw" category="SAMPLE" name="Cpos" subType="ACTUAL" units="DEGREE"/>  
229 <DataItem type="ROTARY_MODE" id="rf" category="EVENT" name="crfunc">  
230 <Constraints>  
231 <Value>CONTOUR</Value>  
232 <Value>SPINDLE</Value>  
233 <Value>INDEX</Value>  
234 </Constraints>  
235 </DataItem>  
236 <DataItem type="LOAD" category="CONDITION" id="spc" name="Sload_cond"/>  
237 <DataItem type="TEMPERATURE" category="CONDITION" id="tmp" name="Stemp_cond"/>  
238 </DataItems>  
239 </Rotary>  
240 <Rotary id="ar" name="A">  
241 <DataItems>  
242 <DataItem type="LOAD" id="a1" category="SAMPLE" name="Aload" units="PERCENT"/>  
243 <DataItem type="ANGULAR_VELOCITY" id="af" category="SAMPLE" name="Afrt" units="DEGREE/SECOND" nativeUnits="DEGREE/MINUTE"/>  
244 <DataItem type="ANGLE" id="at" category="CONDITION" name="Atravel"/>  
245 <DataItem type="ANGLE" coordinateSystem="MACHINE" id="aposm" category="SAMPLE" name="Aabs" subType="ACTUAL" units="DEGREE" />  
246 <DataItem type="ANGLE" coordinateSystem="WORK" id="apow" category="SAMPLE" name="Apos" subType="ACTUAL" units="DEGREE" />  
247 <DataItem type="ROTARY_MODE" id="arf" category="EVENT" name="arfunc">  
248 <Constraints>  
249 <Value>CONTOUR</Value>  
250 <Value>INDEX</Value>  
251 </Constraints>  
252 </DataItem>  
253 </DataItems>  
254 </Rotary>
```

```

248 <Rotary id="br" name="B">
249   <DataItems>
250     <DataItem type="LOAD" id="b1" category="SAMPLE" name="
251       Bload" units="PERCENT"/>
252     <DataItem type="ANGULAR_VELOCITY" id="bf" category="
253       SAMPLE" name="Bfrt" units="DEGREE/SECOND" nativeUnits="
254       DEGREE/MINUTE"/>
255     <DataItem type="ANGLE" id="bt" category="CONDITION" name
256       ="Btravel"/>
257     <DataItem type="ANGLE" coordinateSystem="MACHINE" id="
258       bposm" category="SAMPLE" name="Babs" subType="ACTUAL"
259       units="DEGREE" />
260     <DataItem type="ANGLE" coordinateSystem="WORK" id="bposw
261       " category="SAMPLE" name="Bpos" subType="ACTUAL" units="
262       DEGREE" />
263     <DataItem type="ROTARY_MODE" id="brf" category="EVENT"
264       name="brfunc">
265       <Constraints>
266         <Value>CONTOUR</Value>
267         <Value>INDEX</Value>
268       </Constraints>
269     </DataItem>
270   </DataItems>
271 </Rotary>
272 </Components>
273 </Axes>
274 <Controller id="cont" name="controller">
275   <DataItems>
276     <DataItem type="COMMUNICATIONS" category="CONDITION" id="ccond"
277       name="comms_cond"/>
278     <DataItem type="LOGIC_PROGRAM" category="CONDITION" id="logic"
279       name="logic_cond"/>
280     <DataItem type="SYSTEM" category="CONDITION" id="system" name="
281       system_cond"/>
282     <DataItem type="EMERGENCY_STOP" id="estop" category="EVENT" name
283       ="estop"/>
284     <DataItem type="ACCUMULATED_TIME" subType="x:AUTO"
285       category="SAMPLE" id="atime" name="auto_time"/>
286     <DataItem type="ACCUMULATED_TIME" subType="x:TOTAL"
287       category="SAMPLE" id="yltime" name="total_time"/>
288     <DataItem type="ACCUMULATED_TIME" subType="x:CUT"
289       category="SAMPLE" id="ctime" name="cut_time"/>
290     <DataItem type="PALLET_ID" id="pltnum" category="EVENT"
291       name="pallet_num"/>
292   </DataItems>
293 </Components>
294 <Path id="path1" name="path">
295   <DataItems>
296     <DataItem id="peditmode" type="PROGRAM_EDIT" category="
297       EVENT"/>
298     <DataItem id="peditname" type="PROGRAM_EDIT_NAME"
299       category="EVENT"/>
300     <DataItem category="EVENT" id="pfr" name="Frapidovr"
301       subType="RAPID" type="PATH_FEEDRATE_OVERRIDE" />
302     <DataItem category="EVENT" id="pfo" name="Fovr" subType=
303       "PROGRAMMED" type="PATH_FEEDRATE_OVERRIDE" />
304     <DataItem category="EVENT" id="Sovr" name="Sovr" type="
305       ROTARY_VELOCITY_OVERRIDE" />
306     <DataItem type="PROGRAM" id="pgm" category="EVENT" name=
307       "program"/>
308     <DataItem type="PROGRAM" subType="x:SUB" id="spgm"
309       category="EVENT" name="subprogram"/>
310     <DataItem type="LINE" id="ln" category="EVENT" name="
311       line"/>
312     <DataItem type="x:UNIT" id="unit" category="EVENT" name=
313       "unitNum"/>
314     <DataItem type="x:SEQUENCE_NUMBER" id="seq" category="
315       EVENT" name="sequenceNum"/>

```

```
292 <DataItem type="PART_COUNT" id="pc" category="EVENT"  
293 name="PartCountAct"/>  
294 <DataItem type="PATH_FEEDRATE" id="pf" category="SAMPLE"  
295 name="Fact" units="MILLIMETER/SECOND" subType="ACTUAL"  
296 coordinateSystem="WORK"/>  
297 <DataItem type="TOOL_NUMBER" id="tid" category="EVENT"  
298 name="Tool_number"/>  
299 <DataItem type="x:TOOL_GROUP" id="tid2" category="EVENT"  
300 name="Tool_group"/>  
301 <DataItem type="x:TOOL_SUFFIX" id="tid3" category="EVENT"  
302 name="Tool_suffix"/>  
303 <DataItem type="EXECUTION" id="exec" category="EVENT"  
304 name="execution"/>  
305 <DataItem type="CONTROLLER_MODE" id="mode" category="EVENT"  
306 name="mode"/>  
307 <DataItem type="PROGRAM_COMMENT" category="EVENT" id="pcmt"  
308 name="program_cmt"/>  
309 <DataItem type="PROGRAM_COMMENT" subType="x:SUB"  
310 category="EVENT" id="spcmt" name="subprogram_cmt"/>  
311 <DataItem type="MOTION_PROGRAM" category="CONDITION" id="motion"  
312 name="motion_cond"/>  
313 <DataItem category="CONDITION" id="path_system" name="path_system"  
314 type="SYSTEM"/>  
315 </DataItems>  
316 </Path>  
317 </Components>  
318 </Controller>  
319 <Door id="door1" name="door">  
320 <DataItems>  
321 <DataItem id="door" type="DOOR_STATE" category="EVENT"  
322 name="doorstate"/>  
323 </DataItems>  
324 </Door>  
325 <Systems id="systems" name="systems">  
326 <Components>  
327 <Electric name="electric" id="elec">  
328 <DataItems>  
329 <DataItem type="SYSTEM" category="CONDITION" id="electric"  
330 name="electric_cond"/>  
331 </DataItems>  
332 </Electric>  
333 <Hydraulic name="hydraulic" id="hydraulic">  
334 <DataItems>  
335 <DataItem type="SYSTEM" category="CONDITION" id="hydhealth"  
336 name="hydra_cond"/>  
337 </DataItems>  
338 </Hydraulic>  
339 <Coolant name="coolant" id="coolant">  
340 <DataItems>  
341 <DataItem type="SYSTEM" category="CONDITION" id="coolhealth"  
342 name="coolant_cond"/>  
343 <DataItem id="cooltemp" type="TEMPERATURE" category="SAMPLE"  
344 name="cooltemp" units="CELSIUS"/>  
  
<DataItem id="concentration" type="CONCENTRATION" category="SAMPLE"  
name="CONCENTRATION" units="PERCENT"/>  
  
</DataItems>  
</Coolant>  
<Pneumatic name="pneumatic" id="pneumatic">  
<DataItems>  
<DataItem type="SYSTEM" category="CONDITION" id="pneucond"  
name="pneu_cond"/>  
  
</DataItems>  
</Pneumatic>  
<Lubrication id="lubrication" name="lubrication">  
<DataItems>
```

```
345         <DataItem type="SYSTEM" category="CONDITION" id="lube" name="
346         "lubrication_cond"/>
347     </DataItems>
348 </Lubrication>
349
350     </Components>
351 </Systems>
352 </Components>
353 </Device>
354 <Device name="cmm" uuid="cmm" id="227b1235-6f35-465d-93de-827cd7496e85">
355     <Description manufacturer="Mitutoyo" />
356     <DataItems>
357         <DataItem category="SAMPLE" id="WORKOFFSET_XYZ_AXIS" name="current
358         position" type="PATH_POSITION" units="MILLIMETER_3D" />
359         <DataItem category="SAMPLE" id="TEMPERATURE" name="current part
360         temperature" type="PART_TEMPERATURE" units="CELSIUS" />
361         <DataItem category="EVENT" id="MachineControllerProgram" name="part
362         program name" type="PROGRAM" />
363         <DataItem category="EVENT" id="MachinePart" name="part name" type="
364         PART_ID" />
365         <DataItem category="EVENT" id="StartMeasurementTime" name="measurement
366         start time" type="PROCESS_TIME" />
367         <DataItem category="EVENT" id="ExpectedEndMeasurementTime" name="
368         expected measurement end time" type="PROCESS_TIME" />
369         <DataItem category="EVENT" id="EndMeasurementTime" name="actual
370         measurement end time" type="PROCESS_TIME" />
371         <DataItem category="EVENT" id="CharacteristicsAll" name="total number
372         of characteristics" type="PART_COUNT" subType="ALL" />
373         <DataItem category="EVENT" id="CharacteristicsOutOfTolerance" name="
374         number of characteristics out of tolerance" type="PART_COUNT" subType="
375         BAD" />
376         <DataItem category="EVENT" id="CharacteristicsInTolerance" name="number
377         of characteristics in tolerance" type="PART_COUNT" subType="GOOD" />
378         <DataItem category="EVENT" id="PlannedRepetition" name="number of
379         planned repetition" type="PART_COUNT" subType="ALL" />
380         <DataItem category="EVENT" id="RemainingRepetition" name="number of
381         remaining repetition" type="PART_COUNT" subType="REMAINING" />
382         <DataItem category="EVENT" id="MachinePartSerialNumber" name="part
383         serial number" type="SERIAL_NUMBER" />
384         <DataItem category="EVENT" id="MachinePartId" name="part id" type="
385         PART_ID" />
386         <DataItem category="EVENT" id="MachinePartNumber" name="part number"
387         type="PART_NUMBER" />
388         <DataItem category="EVENT" id="MachineState" name="status" type="
389         EXECUTION" />
390         <DataItem category="EVENT" id="FunctionalMode" name="functional mode"
391         type="FUNCTIONAL_MODE" />
392         <DataItem category="EVENT" id="ControllerMode" name="controller mode"
393         type="CONTROLLER_MODE" />
394         <DataItem category="EVENT" id="ErrorText" name="error details" type="
395         MESSAGE" />
396         <DataItem category="CONDITION" id="StatusCondMotionProgram" name="
397         status motion program" type="MOTION_PROGRAM" />
398         <DataItem category="CONDITION" id="StatusCond" name="status" type="
399         PROGRAM" />
400     </DataItems>
401 </Device>
402 </Devices>
403 </MTConnectDevices>
404
```

## Appendix B. MTConnect Agent Configuration File

Below is the agent configuration file. This file configures the MTConnect Agent to connect to the MTConnect adapters installed on each machine using their network addresses. The file also sets the directory for the device configuration file, basic agent settings, and logging configurations. Stakeholders can use the agent configuration file for similar setups and can modify it to accommodate more machines and different data pipelines.

```
1  Devices = ./Devices.xml
2  PreserveUUID = yes
3  IgnoreTimestamps = yes
4  BufferSize = 17
5  Port = 5000
6  ServiceName = MTConnect Agent
7  Pretty = yes
8
9  Adapters {
10     ur5e_r1 {
11         Host = <IP>
12         Port = 7878
13     }
14     ur5e_r2 {
15         Host = <IP>
16         Port = 7878
17     }
18     pocketnc {
19         Host = <IP>
20         Port = 7878
21     }
22     cmm {
23         Host = <IP>
24         Port = 7878
25     }
26 }
27
28 logger_config
29 {
30     logging_level = info
31     output = file ./agent.log
32 }
33
```