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NIST IR 8604

An Improved Robotic Workcell for Operational Technology (OT) Research

Timothy A. Zimmerman
Michael J. Pease
Michael K. Dawson Jr.

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U.S. DEPARTMENT OF COMMERCE

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Timothy A. Zimmerman
Michael J. Pease
Michael K. Dawson Jr.
Smart Connected Systems Division
Communications Technology Laboratory

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Author ORCID iDs
Timothy A. Zimmerman: 0000-0001-8451-0515
Michael J. Pease: 0000-0002-6489-2621
Michael K. Dawson Jr.: 0000-0002-7151-5664

Contact Information
OTsecurity@nist.gov

Abstract

The National Institute of Standards and Technology (NIST) has constructed a discrete manufacturing workcell to support its operational technology (OT) and critical infrastructure research. This work is an improvement on the existing "Collaborative Robotics Testbed" described in the report NIST IR 8089. The primary intent of the workcell is to emulate a discrete manufacturing system without constructing a real-world manufacturing production line or facility.

This paper describes the goals, objectives, design, implementation, measurement systems, and operational use of the workcell in support of NIST's research mission, specifically in the topics of cybersecurity, digital twins, supply chain traceability, and industrial artificial intelligence.

Keywords

operational technology, industrial artificial intelligence, intelligent manufacturing, cybersecurity, robotics, digital twin, supply chain traceability.

Table of Contents

1. Introduction 1
2. Goals and objectives 1
3. Design and implementation 3
3.1. Manufacturing process 3
3.2. Physical layout 3
3.3. Major mechanical systems and components 5
3.3.1. Shuttles 5
3.3.2. Industrial robotic arms 6
3.3.3. Station A 6
3.3.4. Station B 7
3.3.5. Queue 7
3.3.6. Conveyor 7
3.3.7. Inspection doors 8
3.4. Operational technology 8
3.4.1. Supervisory PLC 8
3.4.2. Manufacturing stations 10
3.4.3. Human-machine interfaces 10
3.4.4. Robot controllers 10
3.4.5. Machine vision cameras 10
3.5. Networking 12
4. Workcell measurement systems and data 12
4.1. Manufacturing process data 15
4.2. Industrial robotic arm data 16
4.3. Inspection camera data 16
4.4. Data collection 17
5. Proposed research topics 17
5.1. Cybersecurity research 17
5.2. Digital twin research 18
5.3. Supply chain traceability research 19
5.4. Industrial artificial intelligence research 21

6. Summary and conclusion 22
References 23
Appendix A. Mechanical drawings 25
Appendix B. Machine vision measurements 31
Appendix C. Gasket G-code 35
C.1. NIST snakes 35
C.2. Asymmetric shape 38

List of Tables

Table 1. Listing of robot jobs and description of their actions. 11
Table 2. Summary of major data-generating sources. 14
Table 3. Listing of NIST logo gasket machine vision measurements. 31
Table 4. Listing of asymmetric gasket machine vision measurements. 33

List of Figures

Fig. 1. Image of the completed workcell in the NIST laboratory. 2
Fig. 2. Simplified manufacturing process flow diagram. 4
Fig. 3. A top-down rendering of the workcell identifying key systems. 5
Fig. 4. A shuttle with NIST logo gasket. 6
Fig. 5. Logical network architecture diagram of the workcell. 12
Fig. 6. Physical network architecture diagram highlighting workcell OT devices. . . . 13
Fig. 7. Data flow diagram of network traffic in the workcell network. 16
Fig. 8. General mechanical assembly drawings of *Station A*. 26
Fig. 9. General mechanical assembly drawings of *Station B*. 27
Fig. 10. General mechanical assembly drawings of a shuttle. 28
Fig. 11. General mechanical assembly drawings of a *Queue* assembly. 29
Fig. 12. General mechanical assembly drawings of the robot end effector. 30
Fig. 13. Machine vision measurements for the NIST “snake” gasket. 32
Fig. 14. Machine vision measurements for the asymmetric gasket. 34

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1. Introduction

The National Institute of Standards and Technology (NIST) has developed a robotic workcell to support research for operational technology (OT). The primary intent of the workcell is to emulate a real-world discrete manufacturing system without constructing an entire manufacturing production line or facility, with the additional goal of encouraging the creation of similar workcells as sources of academic and industrial developmental data.

The workcell provides a data-rich manufacturing process designed specifically to produce relevant data to support OT research at NIST (e.g., cybersecurity performance impacts, industrial networking, cyber-physical interactions, industrial AI). It expands on work previously performed by NIST to generate and evaluate data relevant to cybersecurity in OT [1] and wireless networks [2]. This improved workcell more accurately reflects a real-world industrial workcell by implementing a reconfigurable, discrete, multi-stage manufacturing process based on a robotic liquid gasket dispensing use case.

This report outlines the design and implementation of the workcell (shown in Figure 1), including its underlying control system technologies, industrial networking, measurement systems, and research data generation. Researchers can use this report to understand the underlying workcell systems. We encourage further workcell-derived data creation and sharing to accelerate the development of tools for managing manufacturing process data.

The remainder of this report is organized into four (4) major sections: **Section 2** describes the goals and objectives used to guide the design and engineering of the workcell; **Section 3** describes the workcell's design, physical construction, systems engineering, and communications networks; **Section 4** describes what measurements are taken of the manufacturing process and systems; and finally, **Section 5** discusses the potential uses of the workcell and its data to inform NIST research in areas such as operational technology (OT) cybersecurity guidance, digital twins (DT), industrial artificial intelligence, and supply chain traceability research.

2. Goals and objectives

The Collaborative Robotic System (CRS) is the latest revision of a workcell designed primarily for the Cybersecurity for Operational Technology project at NIST [1, 3]. Previous versions of the workcell were specifically developed to address immediate research needs to support the development of cybersecurity guidance and other related research [4–7].

In contrast, this version of the workcell expands the research scope, process capabilities, and technologies by integrating new processes and systems that enhance its ability to emulate discrete manufacturing robotic workcells. Researchers from NIST's Systems Integration Division (SID) were the first outside of the cybersecurity community to request a collaboration to support their research, resulting in a joint project with the objective of



Fig. 1. Image of the workcell (as-built) in the NIST laboratory. The manufacturing process is located on an optical table, and protected by safety guarding and a light curtain. Two (2) industrial-grade robotic arms move parts through the manufacturing process. Control system components are located in the electrical enclosure at the front.

developing a new multipurpose testbed that could support a broader range of research initiatives beyond just cybersecurity.

The goal was to build a robotic workcell with an underlying manufacturing process representative of those in common use in discrete manufacturing, and that is inherently flexible and adaptable to support research in both OT cybersecurity and advanced manufacturing. Ultimately, five (5) primary objectives were identified. The workcell should:

1. emulate a common manufacturing process and its fundamental actions, and should do so using commercial-off-the-shelf (COTS) hardware;
2. be mechanically, electronically, and technologically extensible to enable modifications in support of unique research challenges;

3. implement a manufacturing process that produces parts that can be quantitatively measured;
4. generate robust and broad data that are representative of real-world manufacturing systems; and
5. be capable of running autonomously with minimal researcher interaction, if required, and potentially perform "lights-out manufacturing" (i.e., experiments without a researcher present).

3. Design and implementation

The objectives listed in Section 2 were used to guide the workcell design process and systems engineering. This section summarizes the general design and construction of the workcell, its underlying systems, and control system technologies.

3.1. Manufacturing process

The manufacturing process moves workpieces through a series of workstations, quality inspections, and storage buffers. A simplified flow chart of the process is shown in Figure 2. The workstations perform two primary functions: 1) draw an operator-selected pattern onto the workpiece, and 2) remove the pattern from the workpiece. Workpieces recirculate through the manufacturing process continuously, enabling large batch sizes to be "produced" without the need for constant researcher intervention to load and/or unload workpieces from the workcell (i.e., as would be required for a workcell performing additive manufacturing, subtractive manufacturing, or mechanical assembly).

To draw a pattern on the workpiece, a robotic arm manipulates the workpiece against a mechanically-constrained dry erase marker, emulating the robotic dispensing of form-in-place liquid gaskets (see an example gasket in Figure 4). To remove the pattern (i.e., dry erase pigment) from the workpiece, another robotic arm manipulates the workpiece against rotating and stationary abrasive pads, emulating robotic sanding, polishing, and deburring.

This process resolves two problems identified in previous workcells: 1) how to emulate the production of large batch quantities with a limited number of real-world workpieces, and 2) how to give each part unique and measurable features that are relevant to, and may be impacted by, the research experiments.

3.2. Physical layout

The workcell is constructed on an optical table (as shown in Figure 3). All equipment involved in the manufacturing process, including two (2) industrial robotic arms, are mounted on top of the optical table. Safety guards surround the robot work area. Physical barriers

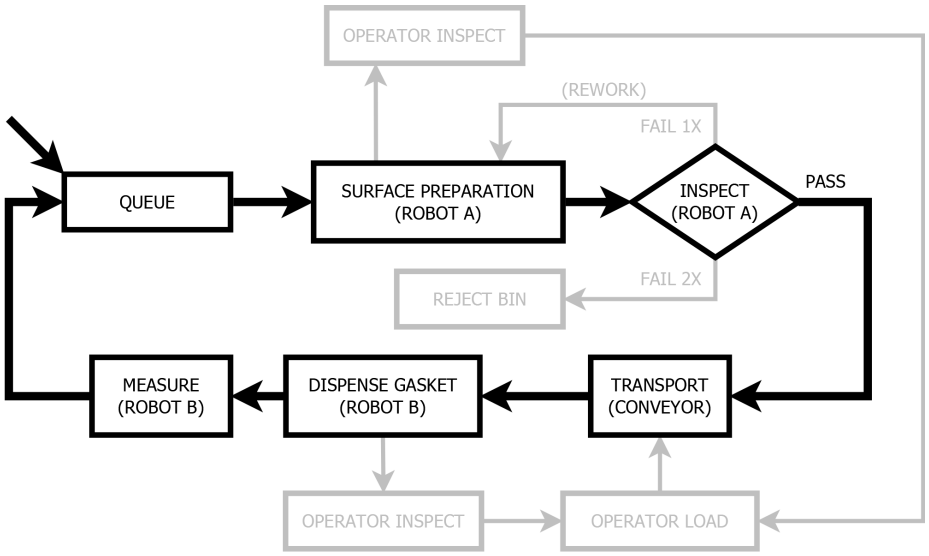


Fig. 2. Simplified manufacturing process flow diagram. The primary path through the process is shown in black, and secondary paths are shown in gray. Parts begin in the *Queue*. A robot removes a part from the *Queue*, prepares the surface, and inspects it. Parts that fail inspection are reworked or removed from the process. Parts that pass inspection get placed on the conveyor. Another robot grabs parts from the conveyor, "dispenses" a gasket onto the part, and measures the finished gasket before placing the part back in the *Queue*.

are installed on the sides and rear of the table, with a safety light curtain on the front to enable an operator to interact with the process safely. The safety guards protects operators and observers from unintended physical interaction with any moving components.

All supporting equipment (e.g., robot controllers, OT devices, electrical components) are mounted to the base of the table, with most of the devices mounted in an electrical enclosure located at the front of the table. The electronics enclosure contains four (4) programmable logic controllers (PLCs): one (1) supervisory PLC that manages the overall manufacturing process, and three (3) local controllers; one for each workstation (i.e., gasket dispensing, surface preparation, and material handling). The enclosure also contains the light curtain controller, safety PLC, networking equipment, measurement devices, and other supporting electrical components.

Four (4) human-machine interfaces (HMIs) are mounted to the front of the electronics enclosure. These HMIs are used by the operator to independently configure, monitor, and control each individual PLC.

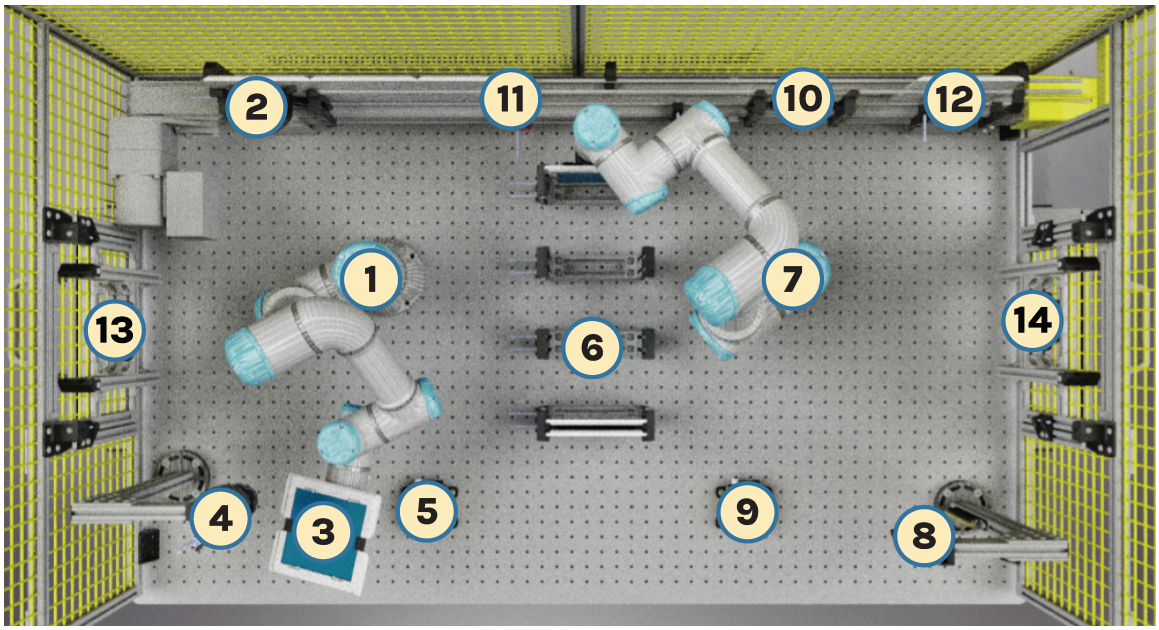


Fig. 3. A top-down rendering of the workcell identifying key systems and components: (1) *Robot B*, (2) conveyor unloading section, (3) a *shuttle*, (4) *Station B*, (5) inspection camera for *Robot B*, (6) *Queue*, (7) *Robot A*, (8) *Station A*, (9) inspection camera for *Robot A*, (10) conveyor "robot loading" section, (11) conveyor "accumulator" section, (12) conveyor "operator loading" section, (13) inspection door for *Robot B*, (14) inspection door for *Robot A*.

3.3. Major mechanical systems and components

This section describes each of the major mechanical systems and components that comprise the workcell. They primarily consist of commercial-off-the-shelf (COTS) items customized by NIST (e.g., T-slotted aluminum framing) or custom designed parts (e.g., robot end effectors, conveyor guide rails, workpieces (i.e., *Shuttles*), calibration tools) manufactured using Fused Filament Fabrication (FFF) 3D printers.

3.3.1. Shuttles

Shuttles, shown in Figure 4, are the primary workpiece of the manufacturing process and are comprised of a sheet of $4.5\ inch\ (114.3\ mm)$ square glass contained within a plastic carrier. The glass is aligned within the carrier using integrated compliant springs, and secured using COTS binder clips. A paper inserted between the glass and carrier incorporates fiducial markers used by the vision system for reference and gauging. Rare earth magnets embedded within the carrier enable passive "gripping" by the robots, and a single steel pin embedded in the center for contactless presence sensing.



Fig. 4. A *shuttle* with the NIST logo "gasket" design drawn on its glass surface, as seen by the machine vision inspection camera located at *Robot B*.

3.3.2. Industrial robotic arms

Two (2) Universal Robots UR3e robotic arms are used to transport the *shuttles* around the manufacturing process and interact with the stations: one (1) dedicated to *Station A*, and the other to *Station B*. The robot end effectors contain four (4) embedded rare earth magnets and three alignment pins to passively grip the *shuttles*.

3.3.3. Station A

The *Station A* mechanical assembly consists of a base plate, an extruded aluminum mounting arm, an eraser motor assembly with rotating abrasive pad (i.e., eraser), and a fixed abrasive pad attached to the vertical section of the mounting arm (see Appendix A Figure 8). *Robot A* moves the *shuttle* underneath the rotating abrasive pad, pressing the *shuttle* into the pad to remove any pigment on the glass surface. The robot will drag the glass across a *fixed* abrasive pad in a single linear motion to eliminate any loose pigment remaining on the glass surface after being subjected to the rotating pad.

3.3.4. Station B

The *Station B* mechanical assembly consists of a base plate, an extruded aluminum mounting arm, and a sliding fixture that retains the dry erase marker (see Appendix A Figure 9). The fixture orients the marker vertically with the tip facing downward. To draw on the shuttle, *Robot B* moves the *shuttle* underneath the marker, pressing the *shuttle* into the marker tip to mark the glass. The fixture is allowed to freely travel up to $25\ mm\ (0.98\ in)$ in the positive z-axis from its resting position, with constant downward force being generated by static masses within the fixture. This creates a consistent line thickness on the glass while also eliminating the need for precise robot movements or force-feedback technologies.

A linear potentiometer is mechanically attached to the fixture to measure the relative displacement of the marker caused by the robot while drawing on the glass. The marker is a standard COTS fine tip dry erase marker fitted with a mechanical shaft collar. The shaft collar provides a positive stop when the marker is inserted into the fixture, enabling the robot and operators to change the marker (i.e., perform tool changes) without the need to recalibrate the relative coordinate systems between the robot and marker every time a new marker is inserted into the *Station B* fixture.

The "gasket" (i.e., pattern) to be drawn by the robot is selected by the operator, and is currently limited to a NIST gasket (see Figure 13 in Appendix B) used primarily for lab demonstrations, and a non-symmetric shape used for machine vision gauging (see Appendix B Figure 14). The tool paths for the "gaskets" are statically defined in G-code (see Figure 14 in Appendix B) and are executed natively by the robotic arms in real world units.

3.3.5. Queue

The *Queue* is located at the center of the workcell between the two (2) robotic arms and consists of four (4) individual queue assemblies that can hold two (2) *shuttles* each, for a total capacity of eight (8) *shuttles*. Each *Queue* assembly is constructed of extruded aluminum in a U-shape with internal slots to constrain a shuttle, and an alignment cap to assist with guiding *shuttles* into the slots (see Figure 11 in Appendix A). Each slot contains an embedded retroreflective sensor to inform the control system of *shuttle* presence. The robots insert and remove *shuttles* from the *Queue* per the programmed queueing strategy.

3.3.6. Conveyor

A COTS conveyor located at the rear of the workcell (see Figure 3) moves *shuttles* between the robots and allows operators to load *shuttles* from outside the safety guarding. The conveyor is fitted with guide rails to orient and constrain the *shuttles*, and a low-friction accumulator belt. The conveyor is segmented into four (4) major sections: "operator loading", "robot loading", "accumulator", and "robot pickup".

The "operator loading" section allows an operator to safely load a *shuttle* from outside of the safety guards. *Shuttles* are held in this section by a control system-actuated gate until it is safe for them to enter the next section. Part presence sensing is performed by a single retroreflective sensor.

The "robot loading" section is where *Robot A* will place a *shuttle* to be transported to *Robot B*. *Shuttles* placed in this section automatically travel to the "accumulator" section unimpeded, allowing up to four (4) *shuttles* to accumulate. Part presence sensing and overflow detection is performed by two (2) retroreflective sensors.

The final section is the "robot pickup" section, where *Robot B* will pick up *shuttles* to be gasketed. *Shuttles* are held in the accumulator section by a control system-actuated gate until it is safe for them to enter this section. Part presence in the robot pickup area is performed by a single retroreflective sensor.

3.3.7. Inspection doors

Two (2) inspection doors are located on the workcell safety guarding, allowing the robots to safely transfer a *shuttle* to an operator located outside of the safety guarding. One (1) door is within reach of *Robot A*, and the other door within reach of *Robot B*.

The doors are held closed with electromagnets that are monitored and operated by the supervisory control system. After a robot loads a *shuttle* into the inspection door, the control system will unlock the door and inform the operator it is safe to remove the shuttle. Once the *shuttle* is removed and the door closed by the operator, the control system automatically locks the door.

3.4. Operational technology

This section describes the OT components (e.g., programmable logic controllers (PLCs), industrial personal computers (IPCs), human-machine interfaces (HMIs), machine vision systems) that comprise the workcell's control system.

3.4.1. Supervisory PLC

The supervisory PLC (Beckhoff CX2040) monitors the states of the workcell and low-level systems, and controls some aspects of the manufacturing process. The primary functions of the PLC are: safety monitoring, trouble call monitoring and alerting, selecting which "jobs" should be performed by the robots, manufacturing process monitoring, data collection, and other general workcell functions (e.g., operator commands, tool changeovers, inspection doors).

Safety monitoring. An integrated safety controller (Beckhoff TwinSAFE EL6910) is used to monitor and act on unsafe conditions in the workcell. Two (2) types of unsafe conditions

are handled by the safety controller: emergency stops and protective stops. An operator pressing an emergency stop button on the workcell enclosure or robot pendants will remove all power from the robots and activate their mechanical brakes. An operator tripping the light curtain plane will put the robots into a protective stop condition, immediately ceasing all robot motion. Both of these conditions require the operator to reset the safety controller and restart the manufacturing process.

Robot jobs. Tasks for the robots to perform (i.e., "jobs") are dynamically assigned by the supervisory PLC, and are based on the current workcell state. Individual robot movements and actions to perform each step of the manufacturing process are statically defined in the robot controllers and grouped together as "jobs" (see Table 1).

Part tracking. One of the most critical research functions performed by the supervisory PLC is tracking parts as they traverse the manufacturing process. All metrics related to the life cycle of each part are stored by the PLC and are collected by researchers at the end of an experiment. Some of the metrics captured include timestamps of each part's arrival and departure at each major process location, and machine vision inspection results and measurements. These data are the primary key performance indicators (KPIs) used to detect performance impacts to the manufacturing process.

Other general workcell tasks. The supervisory PLC performs many other general workcell tasks. These include:

- **Workcell state collection and sharing.** The supervisory PLC continuously collects state information from each system to understand the current workcell state. The PLC also acts as the central repository for state sharing between low-level OT devices.
- **Trouble call monitoring.** Many of the low-level systems have the ability to generate trouble calls (e.g., operator configuration errors, communication faults). The supervisory PLC will monitor these trouble calls and determine if other workcell actions must be performed in response.
- **Key performance indicators.** The supervisory PLC calculates KPIs for the manufacturing process (e.g., throughput), as is common in industry.
- **Tooling changeovers.** Station B allows the robots to autonomously perform a tool change (i.e., changing the marker) if commanded by the operator. The actions required to complete the changeover are coordinated by the supervisory PLC.
- **Inspection door logic.** The logic that controls the inspection doors are implemented in the supervisory PLC, which consists of state monitoring, locking/unlocking the doors, and indicating the door condition to the operator.
- **Manufacturing process disturbances.** The supervisory PLC has the ability to disturb the process (primarily the robots, e.g., increasing and decreasing robot velocities, robot movement jitter, incorrect toolpaths, false-positive operator fault indications) to support research into human interaction.

3.4.2. Manufacturing stations

Three (3) KUNBUS Revolution PI Connect+ industrial PCs (IPC) are used to control *Station A*, *Station B*, the *Queue*, and the conveyor). Control logic is programmed in Python 3 using finite state machines and executed in real-time. Each IPC shares its state with the supervisory PLC via Modbus TCP.

3.4.3. Human-machine interfaces

Human-machine interfaces (HMIs) are used on the workcell to allow the operator to directly monitor and control individual workcell systems. Three (3) Red Lion CR1000 HMIs directly control each individual *Station*. One (1) large Red Lion G310 HMI acts as the primary operator HMI and monitors many of the workcell OT systems either through direct network communications or through the Supervisory PLC. Finally, one (1) OnLogic P100-10AS "panel PC" monitors the two (2) inspection cameras and enables operator interaction for configuration and calibration.

3.4.4. Robot controllers

Each robotic arm, Universal Robots UR3e, has its own independent robot controller and operator pendant. The waypoints, variables, and program logic are programmed and stored in the robot controller using the native interface, *Polyscope*, and programming language, *URScript*. Each set of robot actions (e.g., "move the *shuttle* from the conveyor to *Station B*") are organized and enumerated into one of eight (8) "jobs" (see Table 1). During typical workcell operations, the supervisory PLC will identify which job each robot should be performing, based on the current workcell state, and transmit that job directly to the robot.

3.4.5. Machine vision cameras

Two (2) Cognex InSight 7802 color inspection cameras are used on the workcell for machine vision tasks and data collection. The camera used by *Robot A* verifies the *shuttle* was properly cleaned by *Station A*. Blob detection is used to find remaining pigment on the glass and, if found, will cause a *shuttle* to be cleaned by *Station A* a second time. If pigment is found after the second cycle, the *shuttle* is rejected from the process entirely and the operator is notified to remove it for further rework.

The camera used by *Robot B* measures the gaskets based on parameters defined in the camera. These measurements are used in real-time to pass or reject the workpiece, and each individual measurement performed by the camera is logged by the control system for data collection. A `PASS` or `FAIL` on *Camera B* does not affect the part flow (i.e., Robot B will not rework a gasket based on its inspection result).

Table 1. Listing of robot jobs and description of their actions.

Job ID	Robot actions	Prerequisites
201	**Clean a part.** *Robot A* removes a part from the *queue*, passes the part through the rotating and stationary abrasive pads, presents the finished part to the inspection camera, and triggers the camera.	*Robot A* is idle, does not have a part, and there is a part in the *queue*.
202	**Finished part.** *Robot A* moves the part from the inspection camera to the conveyor drop-off.	Machine vision inspection result is `PASS`, and the conveyor is not in the `OVERFLOW` state.
203	**Rework.** *Robot A* moves the part from the inspection camera, passes the part through the rotating and stationary abrasive pads a second time, presents the finished part to the inspection camera, and triggers the camera.	Machine vision inspection result is `FAIL` for the first time.
204	**Reject.** *Robot A* moves the part from the inspection camera to the rejected parts bin.	Machine vision inspection result is `FAIL` after the part has been reworked.
205	**Operator inspection request.** *Robot A* moves the part from the inspection camera to the inspection door.	Machine vision inspection has completed, and the operator has requested the part be placed in the inspection door, and the door is empty.
101	**Draw gasket on a part.** *Robot B* removes a part from the conveyor, applies the gasket, presents the finished part to the inspection camera, and triggers the camera.	*Robot B* is idle, does not have a part, a part is ready at the conveyor, and there's an empty slot in the queue.
102	**Finished part.** *Robot B* moves the part from the inspection camera to an available *queue* slot.	Machine vision inspection has completed.
103	**Operator inspection request.** *Robot B* moves the part from the inspection camera to the inspection door.	Machine vision inspection has completed, and the operator has requested the part be placed in the inspection door, and the door is empty.

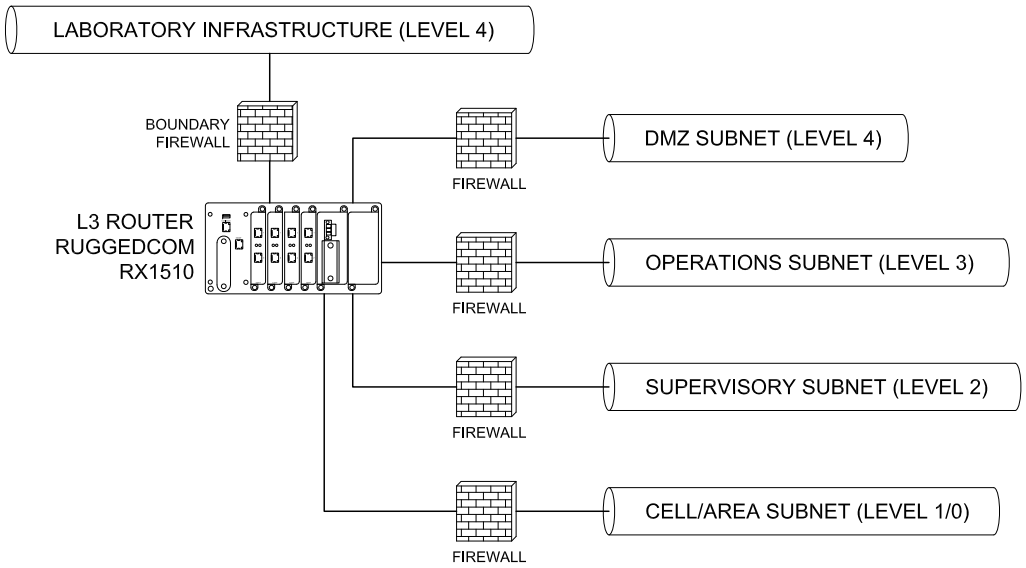


Fig. 5. Logical network architecture diagram of the workcell.

3.5. Networking

The network is modeled after the typical Purdue network architecture (see Figures 5 and 6), with a protected subnet at each "level". The top-level networking device is a Siemens RUGGEDCOM RX1510, which is configured to host four (4) subnets: a demilitarized zone (DMZ) (Purdue Level 4), an Operations subnet (Purdue Level 3), a Supervisory Control subnet (Purdue Level 2), and a Basic Control subnet (Purdue Level 1). Firewalls are configured between each Purdue level to allow only approved communications across each boundary. Local Ethernet (L2) switches (e.g., Siemens RUGGEDCOM RSG2288, WAGO 852-1812, and WAGO 852-1813) are used to give Ethernet access to the individual OT devices to the network.

The majority of network traffic in the workcell is the industrial network protocol Modbus TCP, as this is the primary protocol used for OT inter-device communication. However, there are numerous other types of network traffic present within the network including: HTTP/HTTPS traffic generated by the HMI interfaces, Beckhoff ADS traffic generated by the Supervisory PLC, and TCP/IP traffic produced by the robotic arm data loggers. Specific data flows and their protocols are described in Figure 7.

4. Workcell measurement systems and data

Each workcell device collects and stores some subset of manufacturing process data. Some of these data are captured because of their relevance to the research and experiments, such as those outlined in Table 2, while some data are incidentally captured (e.g., operating

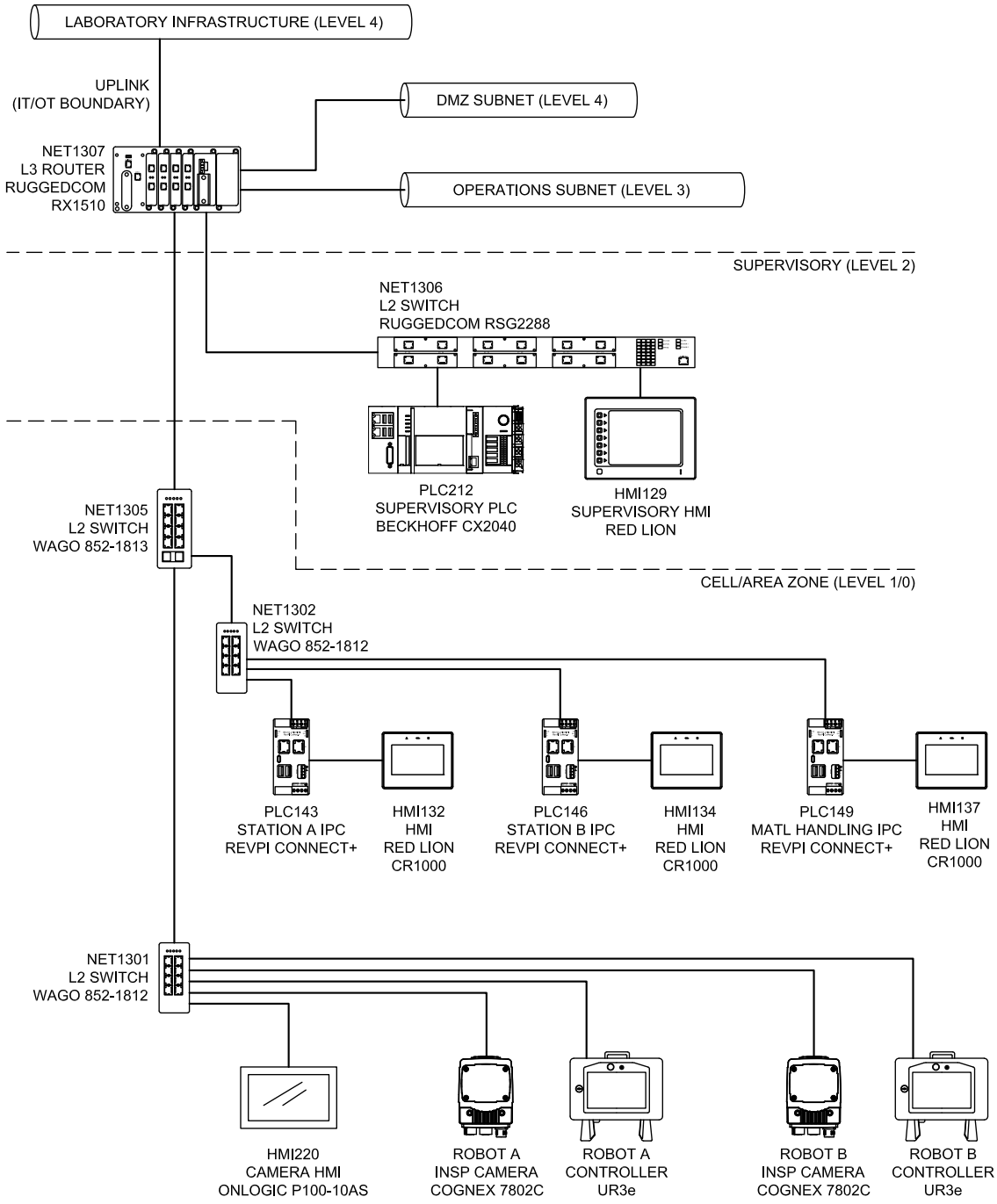


Fig. 6. Diagram of the physical network architecture, highlighting the location of OT devices. Individual devices and hosts above the “Supervisory level” (i.e., Purdue Level 2) are not shown for clarity.

Table 2. Summary of major data-generating sources producing manufacturing process data.

Data source	Description of data	Sample frequency	Time of collection
Historian	**Operational state data.** Operational state data are provided by each device via Modbus TCP and is periodically collected and stored by the Historian. This data may include: device states (e.g., `ONLINE`, `BUSY`, `TROUBLE`, `FAULT`), part telemetry, actuator positions (e.g., conveyor gates, inspection doors), jobs and actions being performed, and operator button events.	1 Hz (periodic)	Real-time
Inspection cameras	**Inspection images.** Images captured by the machine vision cameras are collected and stored for each part. The bitmap (BMP) images are transferred via secure file transfer protocol (SFTP) to a data collection server within the workcell network.	On-capture	Live
Station A IPC	**Control logic events.** Critical events that occur within the control system logic are timestamped and logged on the IPC. These events include: logic state changes, actuator actions (e.g., extruders, motors, conveyor gates), operator actions (e.g., inspection requests, inspection door events), part counter updates, and trouble calls events.	On-event	Post-experiment
Station B IPC	**Control logic events.** Critical events that occur within the control system logic are timestamped and logged on the IPC. These events include: logic state changes, actuator actions (e.g., extruders, motors, conveyor gates), operator actions (e.g., inspection requests, inspection door events), part counter updates, and trouble calls events.	On-event	Post-experiment
Station B IPC	**Marker displacement.** The station records the linear displacement of the marker at a periodic rate when the "extruder" is activated by *Robot B*. Displacement is measured in millimeters (as calibrated by the operator) and raw DC voltage.	10 Hz (periodic)	Post-experiment

Table 2. Summary of the primary data-generating sources related to the manufacturing process (continued).

Data source	Description of data	Sample frequency	Time of collection
Material handling IPC	**Control logic events.** Critical events that occur within the control system logic are timestamped and logged on the IPC. These events include: logic state changes, actuator actions (e.g., extruders, motors, conveyor gates), operator actions (e.g., inspection requests, inspection door events), part counter updates, and trouble calls events.	On-event	Post-experiment
Supervisory PLC	**Process events.** Critical events are captured by the Supervisory PLC as parts flow through the process. These events are stored in volatile memory within the PLC and primarily consist of part arrival and departure timestamps, machine vision measurements, and batch metadata.	On-event	Post-experiment
Robotic arms	**Robot motion and kinematics.** The UR3e robotic arms periodically capture arm and joint positions, velocities, tool locations, and other operational data via the UR Real-Time Data Exchange (RTDE) service.	100 Hz (periodic)	Live

system logs, software event logs). Regardless of the type, the data must be extracted from the devices to be useful.

To reduce the chances of impacting network performance or influencing experimental results, workcell network traffic is limited to operational data directly supporting the manufacturing process. There are some exceptions, but most systems are configured to store their data in internal volatile memory until the experiment is completed and the researcher can export them. Some of these logs are listed in Table 2.

4.1. Manufacturing process data

To reduce the impact of propagation delays as data moves between OT devices, each OT device logs and stores its events in internal volatile memory until the researcher can export the data after the experiment has completed. Network Time Protocol (NTP) is used by all devices to synchronize their internal clocks to a grandmaster (Meinberg LANTIME M900) located in the laboratory network. The workcell is also capable of utilizing Precision Time Protocol (PTP).

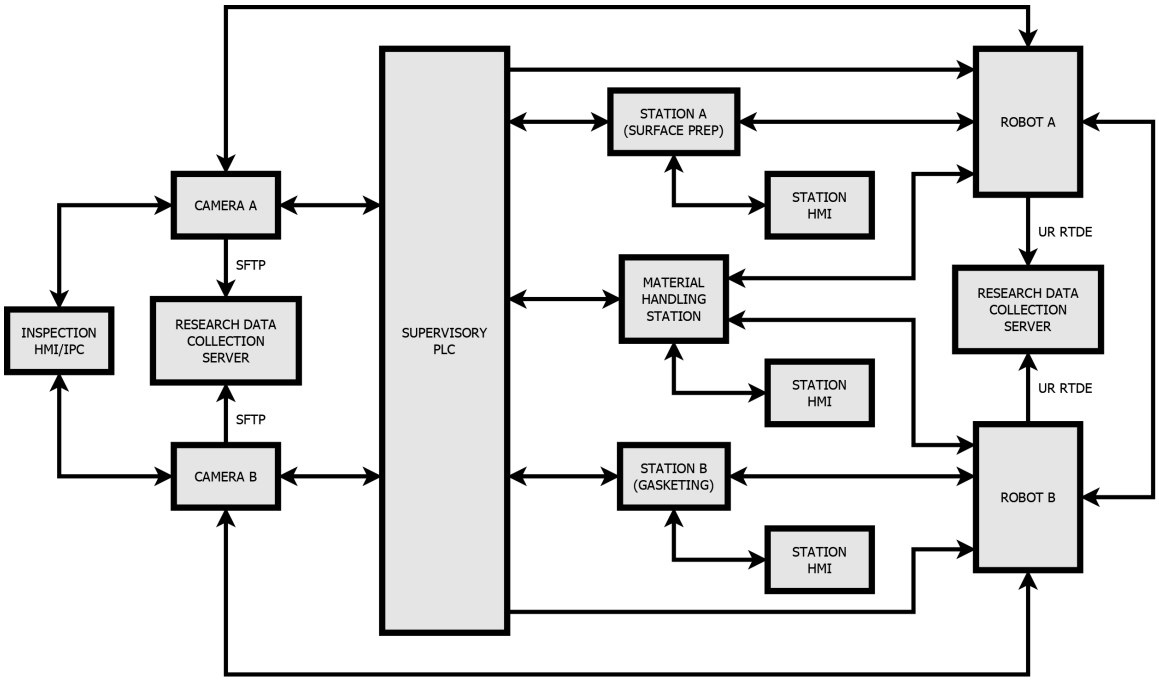


Fig. 7. Diagram identifying data flows in the workcell network. All data flows shown in the diagram utilize the industrial network protocol "Modbus TCP" unless otherwise noted. Data flows to and from the supervisory HMI and Historian are not shown for clarity.

4.2. Industrial robotic arm data

Data from the robotic arms are collected at $100\ Hz$ via Real-Time Data Exchange (RTDE) [8], a native service provided by the robot controllers for synchronizing robot data with external applications and systems. The robot data are continuously logged as long as the workcell is producing parts. To reduce the impact of RTDE traffic on the network, the data collection server is on the same network subnet as the robots.

4.3. Inspection camera data

Part inspection images captured by the machine vision cameras are transmitted to a data collection server immediately after an inspection has completed. The camera will transfer the image as a bitmap (BMP) to the server via secure file transfer protocol (SFTP). Due to the long delay between successive inspections and the relatively small image file size, there is minimal impact to the network when images are transmitted. Regardless, the cameras are located on the same subnet as the data collection server to reduce any potential network performance impacts.

4.4. Data collection

After an experiment has completed, the researcher will begin the process of exporting experiment data from all workcell devices. A collection of Python and `bash` scripts are used to autonomously collect the data. Some of the data are collected using native OT protocols and services from specialized OT devices (e.g., *Supervisory PLC* data are downloaded via the Beckhoff Automation Device Specification (ADS) protocol). Other data are collected via the secure copy protocol (SCP).

The files are then processed, organized, archived into a tarball file, and transferred to a staging server for further processing, analysis, and report generation. A subset of the data collected from the workcell systems are described in Table 2. NIST intends to make these data available to researchers.

5. Proposed research topics

The workcell was constructed to support ongoing and future research activities across multiple NIST research areas. Four (4) of those research areas (cybersecurity, digital twins, and supply chain traceability, industrial AI) are discussed in the following sections, and describes how the workcell is able to support each research area.

5.1. Cybersecurity research

The workcell will be used to advance cybersecurity guidance for discrete manufacturing and OT, more specifically the implementation, performance analysis, and validation of security controls for the constantly-evolving suite of NIST cybersecurity publications (e.g., Special Publication 800-82 [9], Cybersecurity Framework [10], Manufacturing Profile [11]). Some proposed research projects include:

- **Advanced cybersecurity strategies for OT.** Advanced cybersecurity strategies like zero-trust (ZT) and the convergence of IT and OT are creating implementation challenges within OT environments. The workcell can be used to investigate the adoption of advanced cybersecurity strategies to identify challenges, implement defensive mechanisms, and inform best practices for securing OT.
- **Collaborations with NCCoE.** The National Cybersecurity Center of Excellence (NCCoE) and NIST work together to produce guidance that accelerates the implementation of cutting-edge cybersecurity technologies for small- and medium-size organizations. Leveraging the workcell as an additional and distinct manufacturing environment, alongside existing NCCoE testbeds, will enable parallel research efforts that can accelerate guidance development and validation.
- **Analysis methods for cybersecurity performance impacts.** Security controls have the potential to cause performance impacts on OT devices. Methodologies and

tools can be developed to predict, plan, and mitigate these performance impacts (e.g., evaluating performance tradeoffs, identifying metrics for impact assessments, creating models or frameworks for decision making).

5.2. Digital twin research

The workcell enables applied research into the design, implementation, and validation of digital twins (DTs) in discrete manufacturing environments. The high-fidelity, multimodal data collected throughout the workcell (e.g. process KPIs, network traffic, station-level events, operator actions, physical outputs) provides a suitable environment to assess the trustworthiness and reliability of DT models in real-time industrial scenarios.

This research will inform best practices and guidance for the development, deployment, and assurance of DTs, particularly to support their use in industrial settings where high-consequence decisions depend on model accuracy and performance. Some proposed research focus areas for DTs include:

- **Verification and validation (V&V).** As DTs become more integrated into manufacturing systems, establishing rigorous methodologies for verifying and validating their accuracy, behavior, and boundaries is essential. Using data from the workcell, researchers can:
  - validate DT outputs against ground-truth process data (e.g., cycle times, robot positional accuracy, robot joint torque signatures),
  - investigate the effects of data fidelity and update rates on model validity, and
  - develop guidance and metrics for model acceptance thresholds, especially when applied to high-integrity functions such as predictive maintenance or process control.
- **Quantifying trustworthiness attributes.** Broader adoption of DTs depends on establishing and communicating their trustworthiness. The workcell enables experiments that characterize key trust attributes, providing measurable criteria for evaluating DT reliability in industrial settings. Research will focus on:
  - **Fidelity.** The degree to which the DT replicates the structure and behavior of a real-world system.
  - **Transparency.** The extent to which the assumptions, data sources, and internal logic of the DT are accessible and documented.
  - **Robustness.** The ability of the DT to maintain performance under adverse conditions (e.g., sensor loss, latency, data degradation).
  - **Explainability.** The clarity with which the outputs of a DT and its decision-making processes can be interpreted by human users.

These experiments will contribute to the development of structured DT assurance frameworks and advance ongoing NIST initiatives focused on DT trustworthiness.

- **Synchronization and latency effects.** It is critical to maintain synchronization between a DT and its physical system in many use cases, especially for real-time diagnostics, process control, and anomaly detection. The workcell allows researchers to:
  - measure the impact of network latency and sampling rates on DT synchronization,
  - quantify the acceptable bounds of ”misalignment” for different application domains (e.g., monitoring vs. control), and
  - explore degradation modes and develop resilience strategies for desynchronized DTs.
- **Uncertainty propagation in DT models.** Data from manufacturing systems are complex and expansive, but also noisy and uncertain. The workcell can be used to investigate how uncertainties in sensing, actuation, and communication propagate through DT models, and how those uncertainties impact downstream decision-making. Research could focus on:
  - methods for quantifying and bounding uncertainty in DT outputs,
  - evaluating how uncertainty affects trust and usability for operators and automation systems, and
  - integration of probabilistic models or confidence scoring into DT architectures.
- **DT integration with AI.** The high-quality datasets produced by the workcell make it a natural environment to study how DTs can be enhanced or enabled by AI tools. Research in this area can include:
  - using DTs to generate synthetic data for AI model training (e.g., anomaly scenarios, rare event generation),
  - embedding AI models within the DT for predictive analytics, adaptive control, or process optimization, and
  - investigating how AI-driven DTs can be verified, validated, and trusted—especially when they exhibit non-deterministic behavior.

5.3. Supply chain traceability research

The workcell will support applied research associated with the NIST/NCCoE Supply Chain Traceability Meta-Framework (NIST IR 8536) project. This effort seeks to build a scalable, extensible reference implementation that can simulate real-world supply chain ecosystems

and support the development of practical guidance for governance, data integrity, interoperability, and cybersecurity.

The manufacturing process can act as a source of traceability records by deploying the reference implementation in the lab and integrating it with the workcell. These records, related to component sourcing, system integration, and process history, can be submitted to simulated ecosystems to evaluate how traceability chains are formed, maintained, and verified in operational environments.

The workcell provides a realistic industrial context for testing and refining the frameworks and technologies behind supply chain traceability. Some proposed research projects include:

- **Evaluating integration methods for traceability record capture.** Experiments will explore multiple strategies for capturing traceability data from the workcell manufacturing process, including the use of embedded traceability agents, integration with existing system components such as the historian, and data extraction from control and monitoring systems. These approaches will be compared based on ease of deployment, data completeness, system performance impact, and cybersecurity posture. The goal is to identify practical and scalable integration strategies for diverse manufacturing environments.
- **Digital provenance and product genealogy.** The workcell will support controlled experiments to simulate real-world product lifecycle events (e.g. part assembly, component replacement, rework). These events will be recorded to establish product provenance and material flow to form the basis for traceability record generation and testing.
- **Trusted data repositories and ecosystem integration.** The simulated ecosystem will host secure data repositories to evaluate how traceability records are stored, validated, and shared across a simulated supply chain. Experiments will assess the performance, security, and usability of different systems and technology stacks in manufacturing environments.
- **Interoperability and trust in traceability exchanges.** The workcell will help explore challenges of data model interoperability, schema alignment, and semantic trust between diverse participants in the supply chain. Research will focus on developing techniques and best practices to ensure that traceability records are verifiable, consistent, and actionable across organizational boundaries.
- **Cybersecurity considerations for traceability systems.** As traceability systems are integrated into OT environments, new security risks may emerge. The workcell will evaluate the cybersecurity implications of traceability systems, including attack surfaces introduced by traceability agents, third-party integrations, and cloud-based record exchanges. The findings will inform the guidance on the security of the traceability infrastructure in critical manufacturing systems.

5.4. Industrial artificial intelligence research

The workcell provides a prime opportunity for researching the applications of industrial artificial intelligence (IAI). This area of research focuses on the development of machine learning techniques as applied in industrial contexts [12]. Key among these contexts is the manufacturing process, an area for which there is little research characterizing the fusion of human-generated data with traditional sensors.

In the course of a manufacturing process life cycle, a manufacturer must make decisions regarding operational logistics and maintenance scheduling to maximize process uptime. These decisions are informed by their expertise, available process and equipment data, and operator knowledge [13, 14]. However, collecting this information, and knowing how to interpret it, can prove to be difficult.

Understanding what data should be measured, mustering the resources to enable such measurements, and extracting insightful information from that data, can prove burdensome. And though operator feedback (e.g., maintenance reports, observation records) can improve the quality of information available to decision-makers [15–22], the degree of improvement depends on how the text is processed and how it is integrated with other data [17].

By providing an abundance of sensor data and the opportunity for human interaction and feedback, the workcell enables researchers to evaluate the accuracy of different operator feedback and measurement data representing the health of the process. The results of this research will inform guidance on what human- and sensor-generated data is most valuable to collect, while improving the quality of information available to manufacturers when making decisions. Some proposed focus areas for this research include:

- **Identifying useful data.** Investigating what human observation data is most useful to collect, and what method of collection is most effective.
- **Data fusion.** Investigating how collected human observation data could and should be integrated with sensor data.
- **Data augmentation.** Given a limited set of sensors, determine which human observation data should be collected to augment and enhance the desired output. Conversely, given a limited set of human observations, determine which sensor data should be collected to augment and enhance the desired output.
- **IAI guidance.** Developing guidance for manufacturers to develop and implement standard operating procedures for system monitoring with human-in-the-loop operations.

6. Summary and conclusion

In response to research challenges, the National Institute of Standards and Technology (NIST) has outlined the construction of a small-scale discrete manufacturing workcell testbed. This report detailed the construction, operation, telemetry, and data collection methods in an effort to prepare researchers to utilize workcell datasets published by NIST, and to facilitate and encourage the creation of similar systems as sources of research data in academia and industry. NIST intends to use the workcell to enable research in areas related to OT and discrete manufacturing, including cybersecurity, digital twins, supply chain traceability. and industrial artificial intelligence.

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Appendix A. Mechanical drawings

This section includes general mechanical assembly drawings for the major workcell components. Standard drawing views (i.e., front, side, top, ISO) are typically shown. Major dimensions and leaders *may* be included depending on the importance of the part within the scope of this report. All primary dimensions are in imperial inches with metric alternate dimensions (i.e., millimeters) identified in square brackets.

Figures are included for the following assemblies:

- *Station A* (page 26).
- *Station B* (page 27).
- *Shuttles* (i.e., workpiece) (page 28).
- *Queue* (page 29).
- Robot end-effector (page 30).

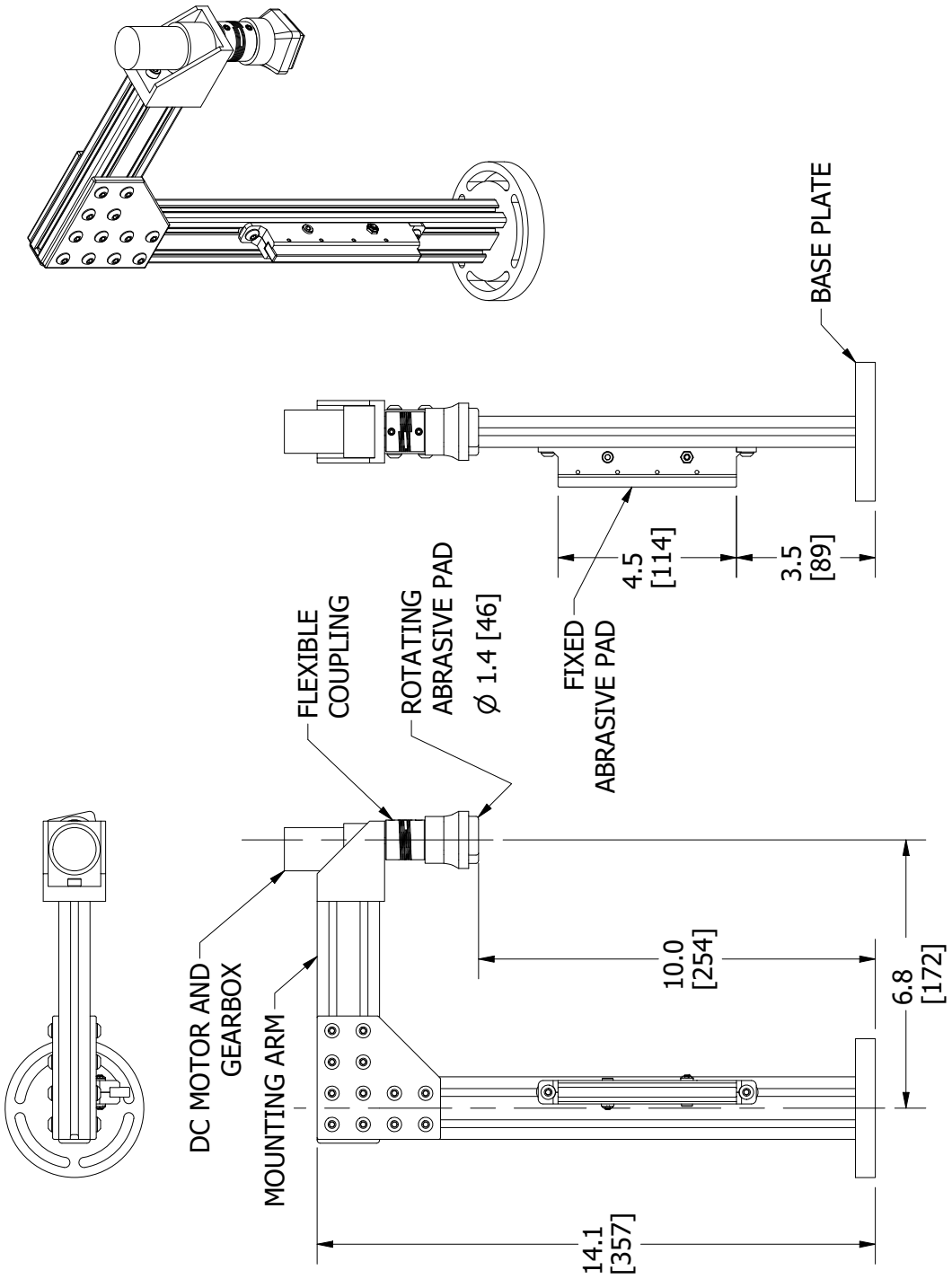


Fig. 8. General mechanical assembly drawings of *Station A*.

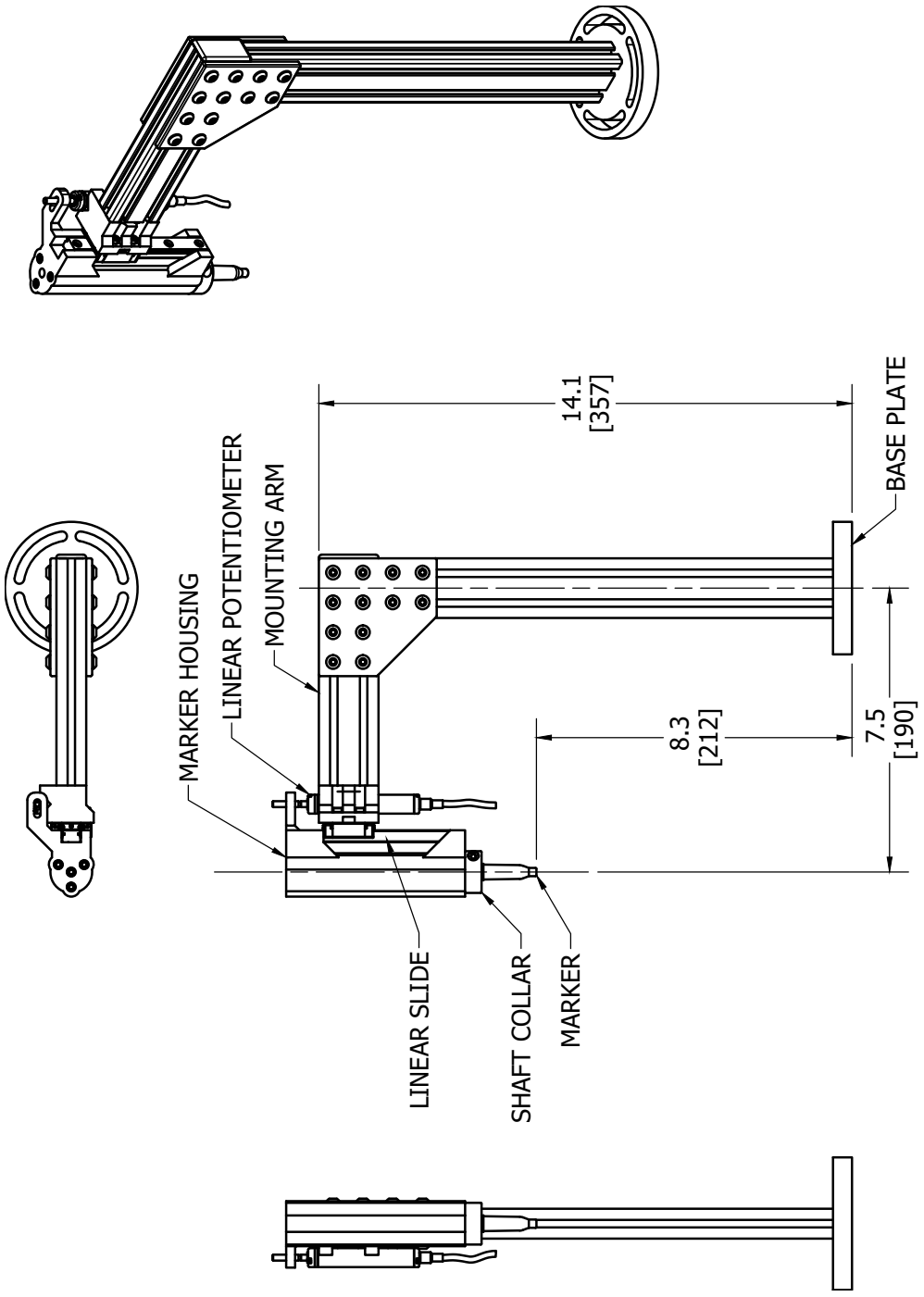


Fig. 9. General mechanical assembly drawings of *Station B*.

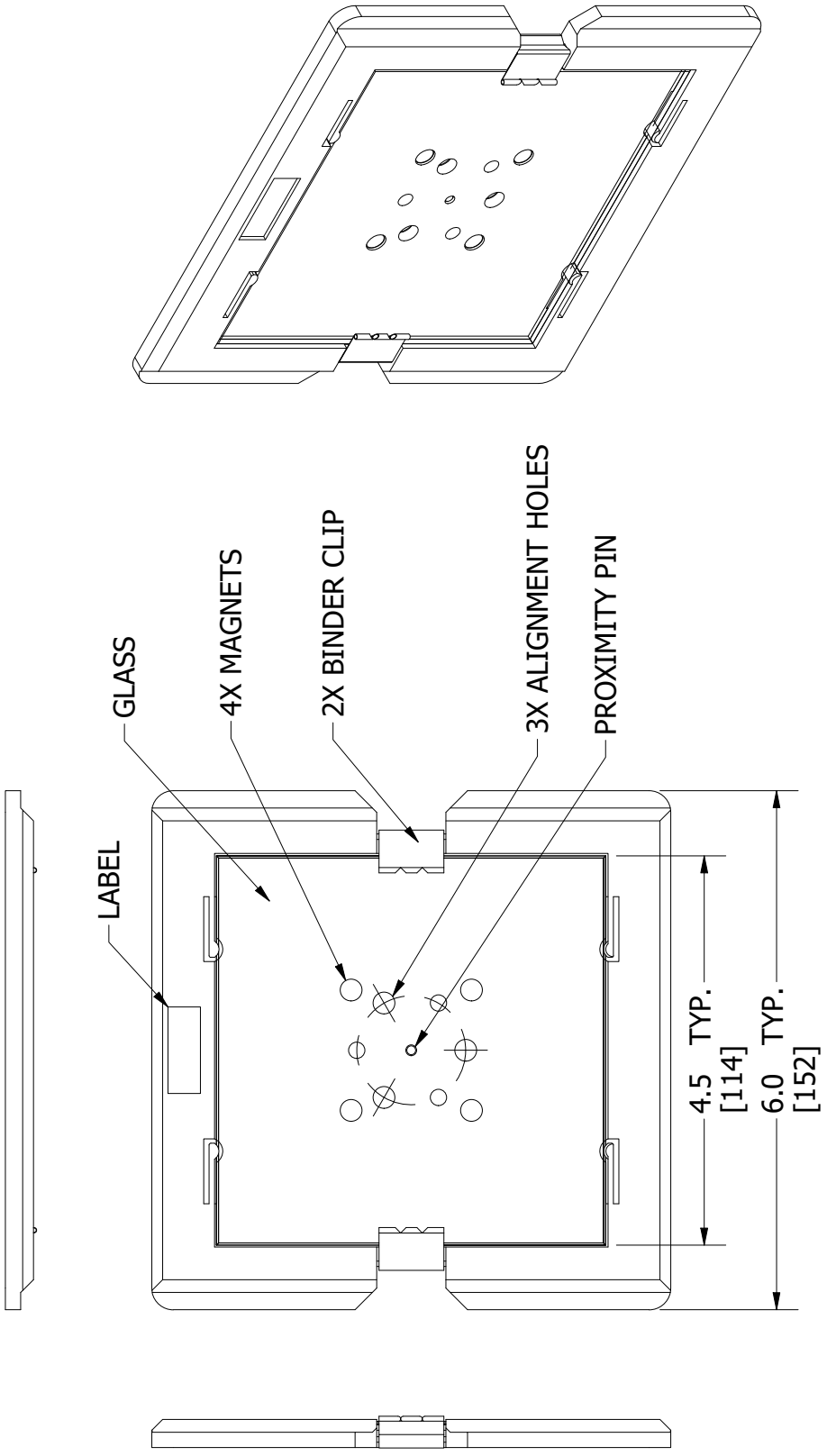


Fig. 10. General mechanical assembly drawings of a shuttle.

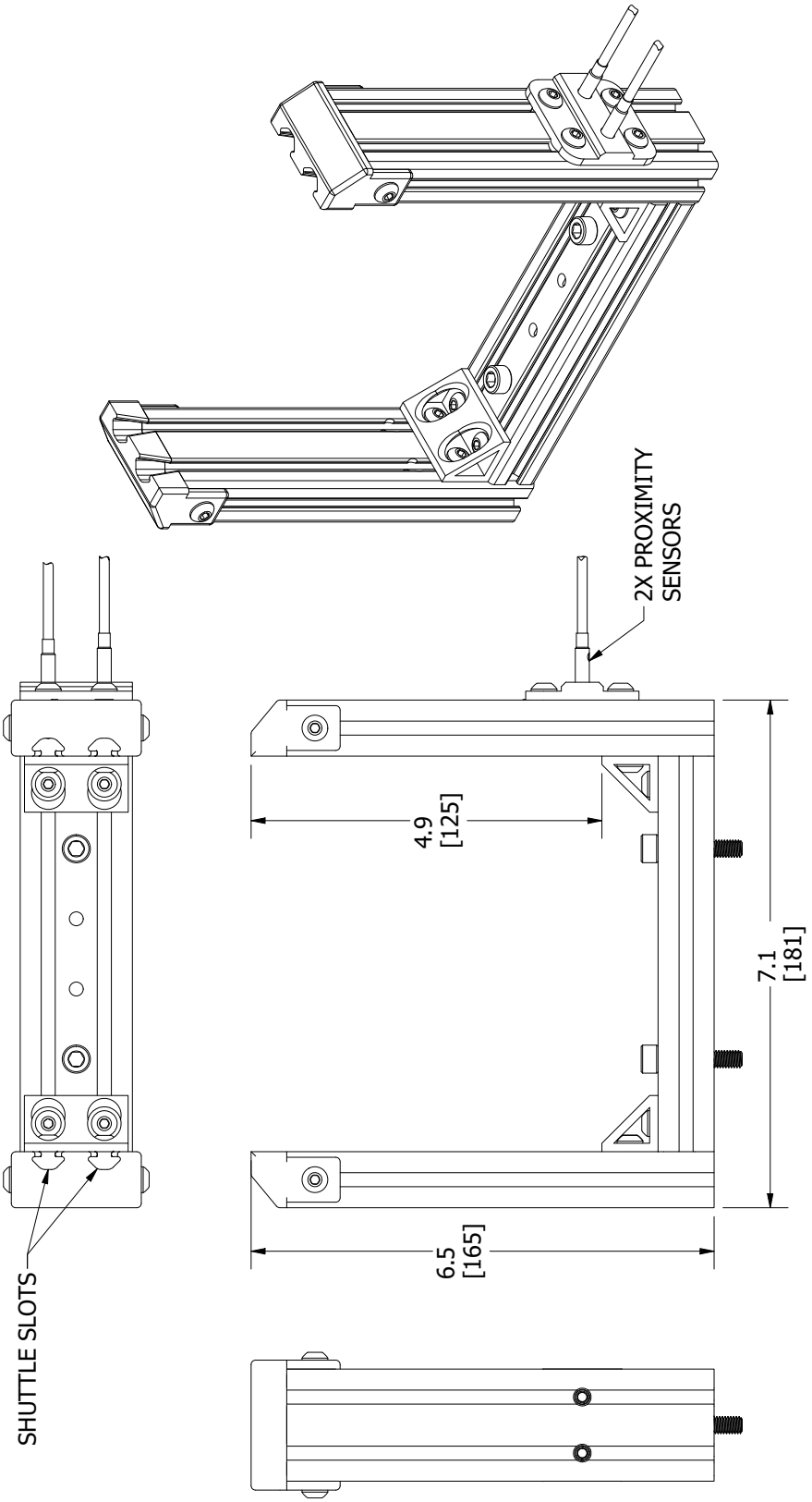


Fig. 11. General mechanical assembly drawings of a *Queue* assembly.

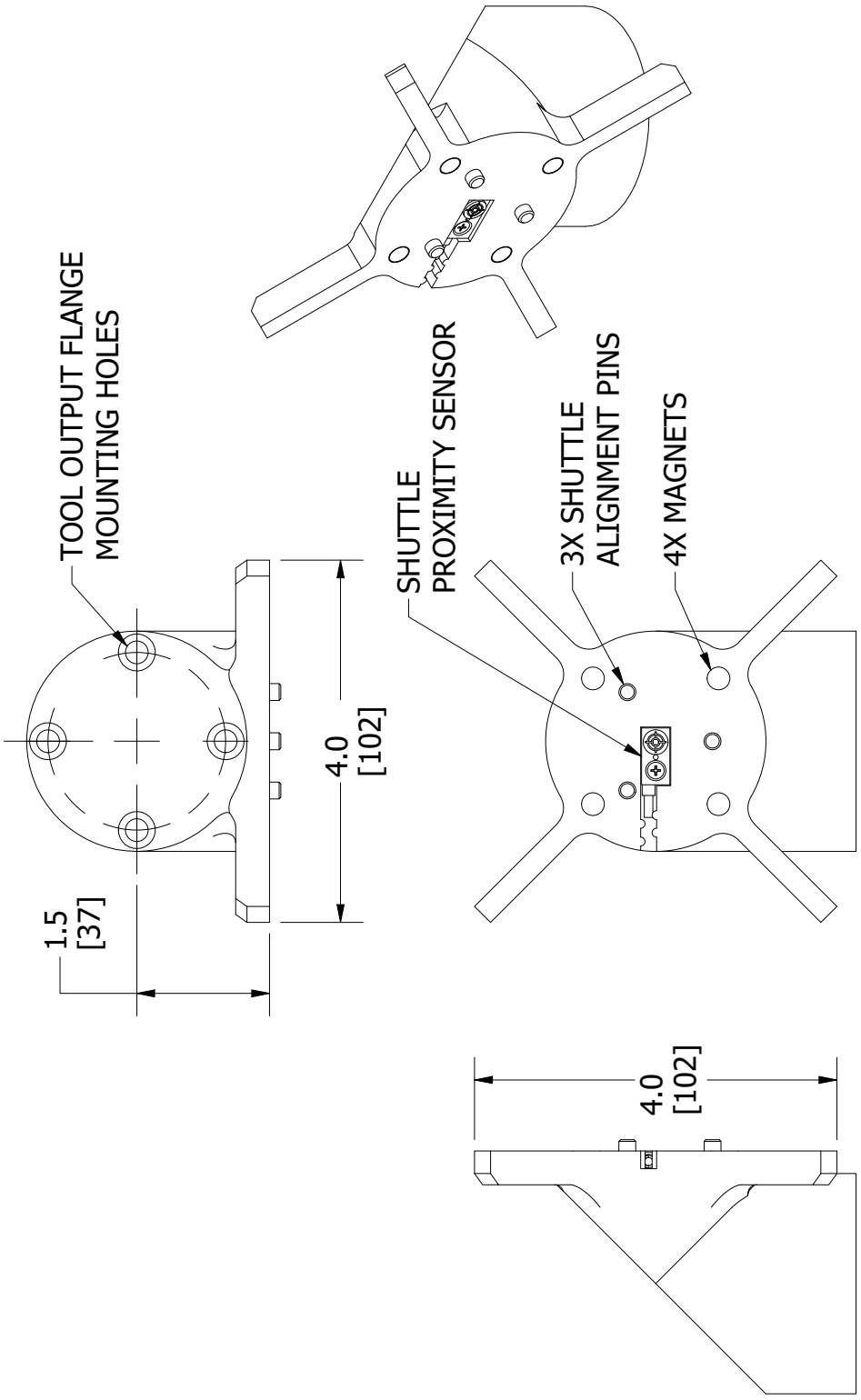


Fig. 12. General mechanical assembly drawings of the robot end effector.

Appendix B. Machine vision measurements

This appendix describes the measurements taken of each gasket type, and their expected values. Table 3 and Figure 13 describe the measurements taken of the NIST "snake" gasket, and Table 4 and Figure 14 describe the measurements taken of the asymmetric gasket. Comparatively less measurements are performed on the NIST logo gasket since it is typically used only for workcell demonstrations.

All "expected values" listed in the tables are derived from the G-code (i.e., based on the ideal gasket). No tolerances or measurement uncertainties are included because workcell characterization was not completed by the time this report was published.

Table 3. Listing of the measurements taken on NIST "snake" gaskets by the machine vision system.

Gasket	Measurement Type	Label	Expected Value
NIST logo	Line thickness	A1	$2.0 \pm 0.5\ mm\ (0.08 \pm 0.2\ in)$
		A2	
		A3	
		B1	
		B2	
		B3	
		C1	
		C2	
		C3	
	Linear	A	$55\ mm\ (2.19\ in)$
		B	
		C	
	Angle	AB	$60^\circ\ (1.05\ rad)$
		BC	
		CA	

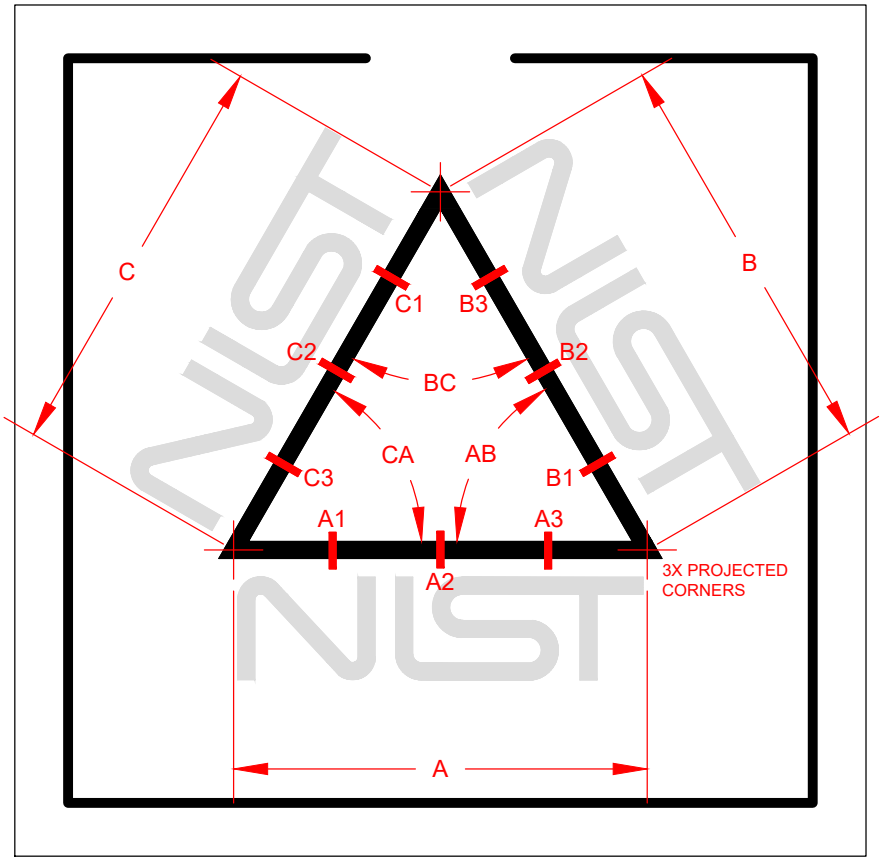


Fig. 13. Diagram identifying the measurements taken of the NIST “snake” gasket by the machine vision system. Measurements are limited to the triangle since this gasket is used only for workcell demonstrations. Gasket line thickness, linear distance, and angle measurements of the triangle are recorded. NIST “snakes” (shown in gray) are included as part of the “gasket”, but are not measured. Actual locations of measurements shown in the figure are approximate.

Table 4. Listing of the measurements taken on asymmetric gaskets by the machine vision system.

Gasket	Measurement Type	Label	Expected Value
Asymmetric	Line thickness	A1	$2.0 \pm 0.5\ mm\ (0.08 \pm 0.2\ in)$
		A2	
		B1	
		C1	
		C2	
		D1	
		E1	
		F1	
		G1	
		G2	
		G3	
		H1	
		I1	
		I2	
		I3	
		J1	
	Linear	AC1	$10\ mm\ (0.39\ in)$
		AC2	$10\ mm\ (0.39\ in)$
		AH	$50\ mm\ (1.97\ in)$
		AJ	$20\ mm\ (0.79\ in)$
		BI	$30\ mm\ (1.18\ in)$
		D	$30\ mm\ (1.18\ in)$
		DF	$10\ mm\ (0.39\ in)$
		FIXX	$49\ mm\ (1.95\ in)$
		FIXY	$70\ mm\ (2.76\ in)$
		G1	$10\ mm\ (0.39\ in)$
		G2	$10\ mm\ (0.39\ in)$
		G3	$10\ mm\ (0.39\ in)$
		IJ	$15\ mm\ (0.59\ in)$
	Angle	FG	$45^\circ\ (0.79\ rad)$
	Radius	RJ	$5\ mm\ (0.20\ in)$

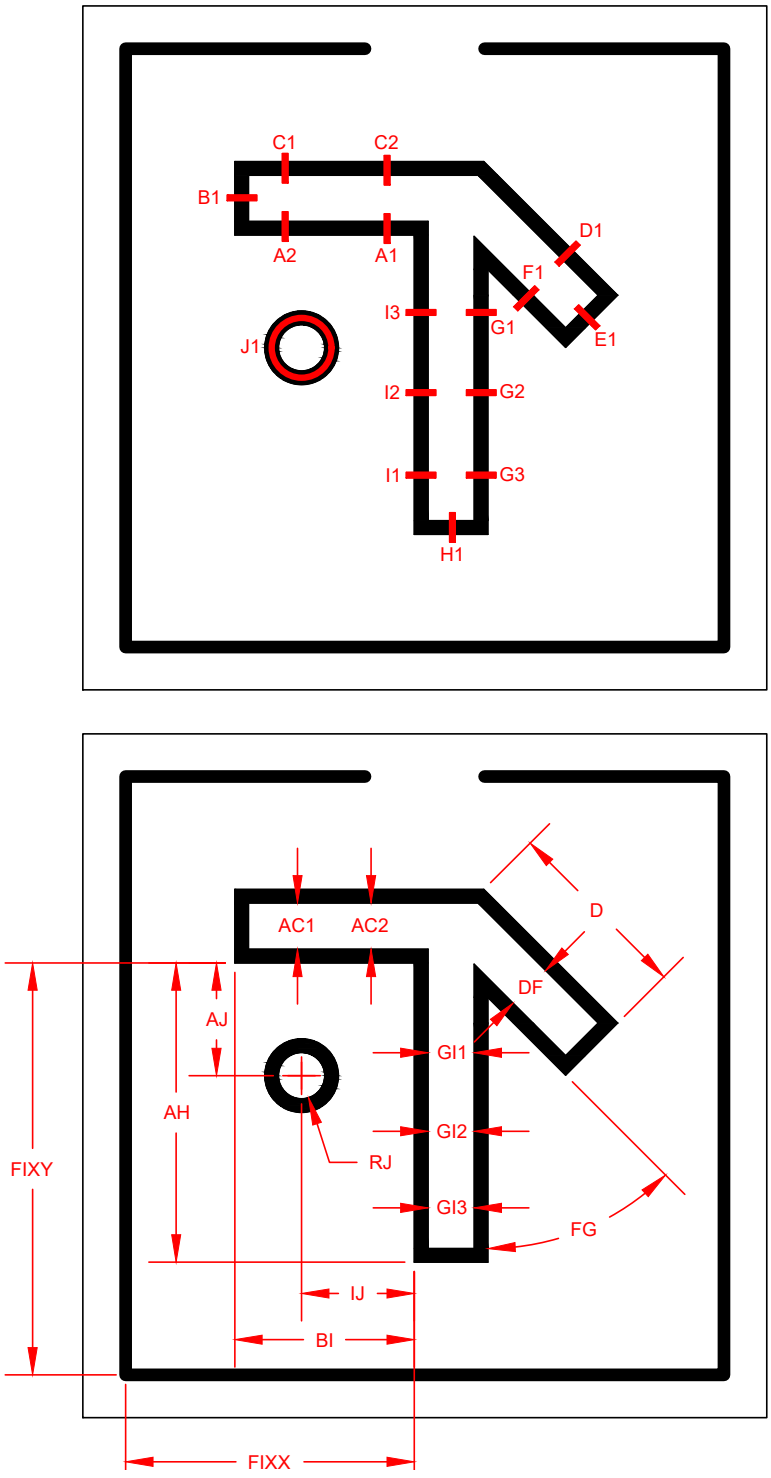


Fig. 14. Diagrams identifying the measurements taken of the asymmetric gasket by the machine vision system. Gasket line thickness measurements are shown in the figure at top, and linear distance, angle, and radius measurements are shown in the figure at bottom. Actual locations of measurements shown in the figure are approximate.

Appendix C. Gasket G-code

This appendix lists the G-code used by the UR robotic arms to draw the "gasket" patterns on the *shuttles*. The G-code is stored directly in the UR robot file system. "Remote TCP" (a native feature in Polyscope) is used execute the G-code. The origin (i.e., `X=0`, `Y=0`) on the *shuttle* is located at the intersection of the two (2) fiducial lines in the bottom-left corner. The G-code used by *Robot A* to erase the gaskets from the shuttles is not included.

Appendix C.1. NIST snakes

```
( Name:          CRS NIST Snakes Gasket G-Code                    )
( Authors:       Timothy A. Zimmerman                             )
( Organization:  National Institute of Standards and Technology   )
(                U.S. Department of Commerce                      )
( License:       Public Domain                                    )
( Last Modified: 21 MAR 2025                                      )
(                                                                 )
( Description:                                                    )
(   G-code for three NIST snakes parallel to the three outside    )
(   edges of an equilateral triangle. The triangle is also drawn. )
(   This file is used by a UR3e robotic arm with the "Remote TCP" )
(   URCap installed to draw the NIST logos and triangle onto a    )
(   part in the Collaborative Robotics System.                    )
(                                                                 )
(   This file is part of the software library used to operate the )
(   Collaborative Robotics System "version 2" at the National     )
(   Institute of Standards and Technology in Gaithersburg,        )
(   Maryland. More information on NIST's OT cybersecurity projects)
(   can be found at:                                              )
(                                                                 )
(  https://csrc.nist.gov/Projects/operational-technology-security )
(                                                                 )
(  NOTE: Remote TCP URCap supported codes                         )
(    G00-G03, G17-G19, G20-G21, G68.2, G69, G90-G91               )

G21 G90       ; mm, ABSOLUTE POSITIONING
G00 Z6        ; SAFE HEIGHT.

(BOTTOM NIST SNAKE)
("N")
G00 X23.94 Y17.67          ; RAPID
G01 Z-10 F500              ; PLUNGE
G01 Y27.29                 ; DRAW LINE
G02 X27.28 Y28.61 R1.93    ; DRAW CW ARC
G01 X37.14 Y18.04          ; DRAW LINE
G03 X40.08 Y19.35 R1.88    ; DRAW CCW ARC
G01 Y29.17                 ; DRAW LINE
G00 Z6                     ; RETRACT
("IST")
```

```
G00 X45.14 Y29.17          ; RAPID
G01 Z-10                   ; PLUNGE
G01 Y19.92                 ; DRAW LINE
G03 X47.45 Y17.67 R2.35    ; DRAW CCW ARC
G01 X62.31                 ; DRAW LINE
G03 Y23.37 R2.89           ; DRAW CCW ARC
G01 X52.95                 ; DRAW LINE
G02 Y29.17 I0 J2.90        ; DRAW CW ARC
G01 X76.06                 ; DRAW LINE
G00 Z6                     ; RETRACT
("T" TOP LINE)
G00 X69.88                 ; RAPID
G01 Z-10                   ; PLUNGE
G01 Y17.67                 ; DRAW LINE
G00 Z6                     ; RETRACT

(RIGHT NIST SNAKE)
("N")
G00 X55.30 Y82.85          ; RAPID
G01 Z-10                   ; PLUNGE
G01 X63.64 Y87.67          ; DRAW LINE
G02 X66.45 Y85.42 R1.93    ; DRAW CW ARC
G01 X62.23 Y71.60          ; DRAW LINE
G03 X64.84 Y69.72 R1.88    ; DRAW CCW ARC
G01 X73.34 Y74.62          ; DRAW LINE
G00 Z6                     ; RETRACT
("IST")
G00 X75.87 Y70.24          ; RAPID
G01 Z-10                   ; PLUNGE
G01 X67.85 Y65.62          ; DRAW LINE
G03 X67.06 Y62.49 R2.35    ; DRAW CCW ARC
G01 X74.49 Y49.62          ; DRAW LINE
G03 X79.42 Y52.48 R2.89    ; DRAW CCW ARC
G01 X74.75 Y60.58          ; DRAW LINE
G02 X79.73 Y63.56 I2.54 J1.41 ; DRAW CW ARC
G01 X91.33 Y43.46          ; DRAW LINE
G00 Z6                     ; RETRACT
("T" TOP LINE)
G00 X88.24 Y48.82          ; RAPID
G01 Z-10                   ; PLUNGE
G01 X78.27 Y43.07          ; DRAW LINE
G00 Z6                     ; RETRACT

(LEFT NIST SNAKE)
("N")
G00 X18.90 Y38.17          ; RAPID
G01 Z-10                   ; PLUNGE
G01 X10.56 Y42.98          ; DRAW LINE
G02 X11.09 Y46.54 R1.93    ; DRAW CW ARC
G01 X25.18 Y49.79          ; DRAW LINE
G03 X25.51 Y52.99 R1.88    ; DRAW CCW ARC
```

```
G01 X17.01 Y57.90          ; DRAW LINE
G00 Z6                     ; RETRACT
("IST")
G00 X19.54 Y62.28          ; RAPID
G01 Z-10                   ; PLUNGE
G01 X27.55 Y57.65          ; DRAW LINE
G03 X30.65 Y58.51 R2.35    ; DRAW CCW ARC
G01 X38.09 Y71.40          ; DRAW LINE
G03 X33.14 Y74.24 R2.89    ; DRAW CCW ARC
G01 X28.55 Y66.28          ; DRAW LINE
G02 X23.40 Y68.96 I-2.57 J1.36 ; DRAW CW ARC
G01 X35.00 Y89.06          ; DRAW LINE
G00 Z6                     ; RETRACT
("T" TOP LINE)
G00 X31.91 Y83.70          ; RAPID
G01 Z-10                   ; PLUNGE
G01 X41.87 Y77.95          ; DRAW LINE
G00 Z6                     ; RETRACT

(TRIANGLE)
G00 X50. Y82.07            ; RAPID TO TOP VERTEX
G01 Z-10                   ; PLUNGE
G01 X77.77 Y33.97          ; DRAW LINE B
G01 X22.23 Y33.97          ; DRAW LINE A
G01 X50. Y82.07            ; DRAW LINE C
G00 Z6                     ; RETRACT

(GO HOME)
G00 X0 Y0                  ; RAPID
```

Appendix C.2. Asymmetric shape

```
( Name:          CRS Asymmetric Gasket G-Code                          )
( Authors:       Timothy A. Zimmerman                                  )
( Organization:  National Institute of Standards and Technology        )
(                U.S. Department of Commerce                           )
( License:       Public Domain                                         )
( Last Modified: 21 MAR 2025                                           )
(                                                                      )
( Description:                                                         )
(   G-code to draw an asymmetric shape and a circle.                   )
(   This file is used by a UR3e robotic arm with the "Remote TCP"      )
(   URCap installed to draw the shape onto a part in the               )
(   Collaborative Robotics System.                                     )
(                                                                      )
(   This file is part of the software library used to operate the      )
(   Collaborative Robotics System "version 2" at the National          )
(   Institute of Standards and Technology in Gaithersburg,             )
(   Maryland. More information on NIST's OT cybersecurity projects     )
(   can be found at:                                                   )
(                                                                      )
(  https://csrc.nist.gov/Projects/operational-technology-security      )
(                                                                      )
(  NOTE: Remote TCP URCap supported codes                              )
(    G00-G03, G17-G19, G20-G21, G68.2, G69, G90-G91                    )

G21 G90       ; mm, ABSOLUTE POSITIONING
G00 Z6        ; SAFE HEIGHT.

(MAIN GASKET)
G00 X49.39 Y70.00          ; RAPID TO INTERSECTION AI
G01 Z-10 F500              ; PLUNGE
G01 X19.39                 ; DRAW LINE A
G01 Y80.01                 ; DRAW LINE B
G01 X59.40                 ; DRAW LINE C
G01 X80.61 Y58.80          ; DRAW LINE D
G01 X73.53 Y51.72          ; DRAW LINE E
G01 X59.40 Y65.86          ; DRAW LINE F
G01 Y19.99                 ; DRAW LINE G
G01 X49.39                 ; DRAW LINE H
G01 Y70.00                 ; DRAW LINE I
G00 Z6                     ; RETRACT

(CIRCLE)
G00 X29.40 Y55.00          ; RAPID TO TOP OF CIRCLE J
G01 Z-10 F25               ; PLUNGE
G02 J-5.0                  ; DRAW ARC J
G00 Z6                     ; RETRACT

(GO HOME)
G00 X0 Y0                  ; RAPID
```