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Automation Testing and Measurement System (ATaMS) Project: Phase 1

by David Gray

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DEVCOM Army Research Laboratory

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14. ABSTRACT
High-throughput research for materials discovery requires large datasets of mechanical properties, which are crucial for data mining and machine learning tools. To facilitate this need, it is essential to generate vast amounts of data more efficiently and effectively. Collaborative robots—or CoBots—can significantly enhance this process by increasing throughput and reducing the time required for data collection and analysis. In response, DEVCOM Army Research Laboratory has begun to design and develop an automation system by integrating a CoBot with several measurement instruments to deliver accurate, high-volume, and repeatable data with minimal deviation. This technical note outlines ongoing efforts to establish the initial framework for an automated-and-versatile materials dimensioning and characterization system. Preliminary dimensioning results of Izod-tested impact specimens have demonstrated improved efficiency and efficacy.

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Mechanical Sciences, automation, robotics, high-throughput, measurement, programable logic controller, human–machine interface

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1. Introduction

In 1989, Kleinmeyer[1] detailed various functional justifications of a laboratory robotic system such as quality improvement, increased repeatability/productivity, safety, flexibility, and elimination of undesirable tasks. Kleinmeyer1 concluded his report with a cost comparison metrics of manual method versus the proposed method that strongly supported laboratory automation investment.

The U.S. Army Combat Capabilities Development Command Army Research Laboratory is advancing development capabilities to automate new materials characterization. These capabilities would enable the rapid generation of large quantities of both meta and mechanical properties data necessary for driving artificial intelligence/machine learning (AI/ML) efforts for materials or system design relevant to modern U.S. Army applications. Research efforts include intramural programs related to alloy design and the qualification of additively manufactured components, as well as leveraging support with extramural projects such as the High-Throughput Materials Discovery for Extreme Conditions (HTMDEC) Cooperative Research Alliance (CRA).

Furthermore, the scalable capability could be incorporated into a so-called self-driving laboratory in which materials synthesis and processing are integrated with characterization and an optimization routine to iterate through a design problem and arrive at an optimal solution. For example, Gongora et al.[2] demonstrate a cartesian coordinate (involves linear movement on each of the three or more axes) self-driving laboratory including a mechanical load frame and 3D printer to achieve a significant improvement in energy absorption of a truss structure (Figure 1). This autonomous high-throughput (HT) system was designed to run around the clock to produce large volumes of data needed for real-time optimization.

Additionally, an automated characterization capability will likely increase accuracy by eliminating operator effects and facilitate the well-organized and long-term storage of materials data and pedigree. Collecting accurate dimensional data for mechanical specimens is critical to achieving precise, reliable results that adhere to standards such as ASTM International. Typically, this process involves a manual measurement method of data collection of large specimens lots, which can be monotonous and prone to human error. Figure 2 shows examples of the sheer number of injection molded samples requiring dimensional characterizing.

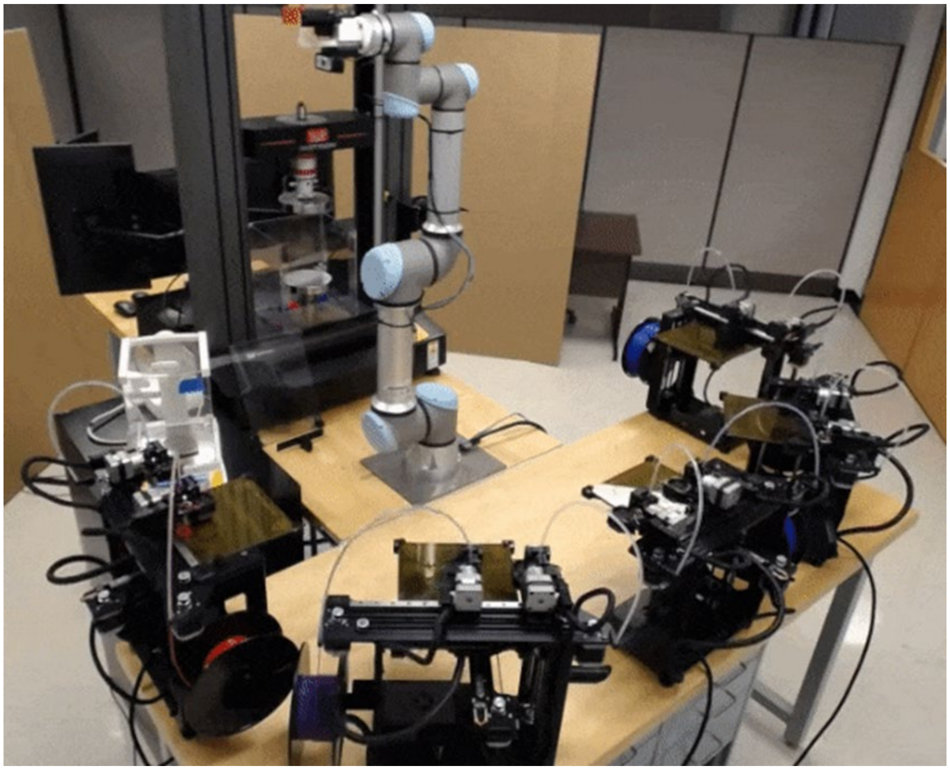

Figure 1. **Reference image of self-driving laboratory including a mechanical load frame and 3D printer. Reprinted with permission from the automated mechanical test of Bayesian experimental autonomous researcher, Dr. Keith Brown, Boston University.[2]**

Figure 2. **Large lots of injected molded test samples with manual micrometer measurement gage.**

To meet the need to generate and collect vast amounts of material data for HT research efforts for materials discovery, collaborative robots (CoBots) can play an integral part to significantly enhance this process. They enable HT testing by automating repetitive tasks; thus, significantly increasing data generation rates while ensuring consistent and precise measurements. This acceleration not only enhances the efficiency of the research process but also opens the door to exploring a broader range of materials and properties, ultimately driving innovation and discovery in material science.

As mentioned above, Kleinmeyer[1] provided cost comparison metrics of manual versus automated methods and strongly concluded that support for laboratory automation investments was viable. To date, companies like Instron and ZwickRoell offer automated mechanical testing, but these systems are designed to conduct experiments from a single geometry shape. Hence, they lack the versatility to meet the need for multidisciplinary materials research for DEVCOM Army Research Laboratory's Sciences of Extreme Materials Competency. To date, we have designed and developed an automated routine to measure sample dimensions with high volume and accuracy. This initial effort lays the foundation for a versatile, automated materials characterization and testing system.

Upon completion of this objective, future expansion will integrate additional high-value instrumentation, such as sample marking and tracking, as well as equipment for hardness and strength testing (including tensile, compression, and flexural tests). Ultimately, this project will showcase a versatile and scalable automated system for fast, accurate mechanical testing and characterization that will support numerous Sciences of Extreme Materials programs for additive manufacturing (AM) alloys and polymers. Moreover, this project can complement ongoing research efforts with the HTMDEC partners, where dynamic testing methods, such as laser shock at Johns Hopkins University and BIRDSHOT at Texas A&M, are a primary focus. In the sections that follow, the design goals and framework for the system are described, followed by its implementation and demonstration. Other important supporting programming and communication protocols are provided in Appendix A.

2. System Design: Phase 1

The conceptual design uses commercially available automation and measurement instruments from suppliers such as Keyence Corporation, Universal Robotics, and Mitutoyo. Figure 3 shows the workflow that is controlled by a Programmable Logic Controller (PLC) using Ladder Logic programming language. The PLC performs three basic main tasks: evaluate digital input commands, process a ladder logic program, and execute a digital output command. Ladder Logic programming is a symbolic formulation of binary inputs/outputs, normally open/normally closed relays, triggers, and other control type expressions. Other scalable capabilities could include a mechanical loading stage and temperature conditioning, but those were not included at the time of this writing. The system also incorporates a Human–Machine Interface (HMI) touch panel for user-friendly GUI interaction and selection of preprogrammed measurement recipes, batch quantities, and sample identification.

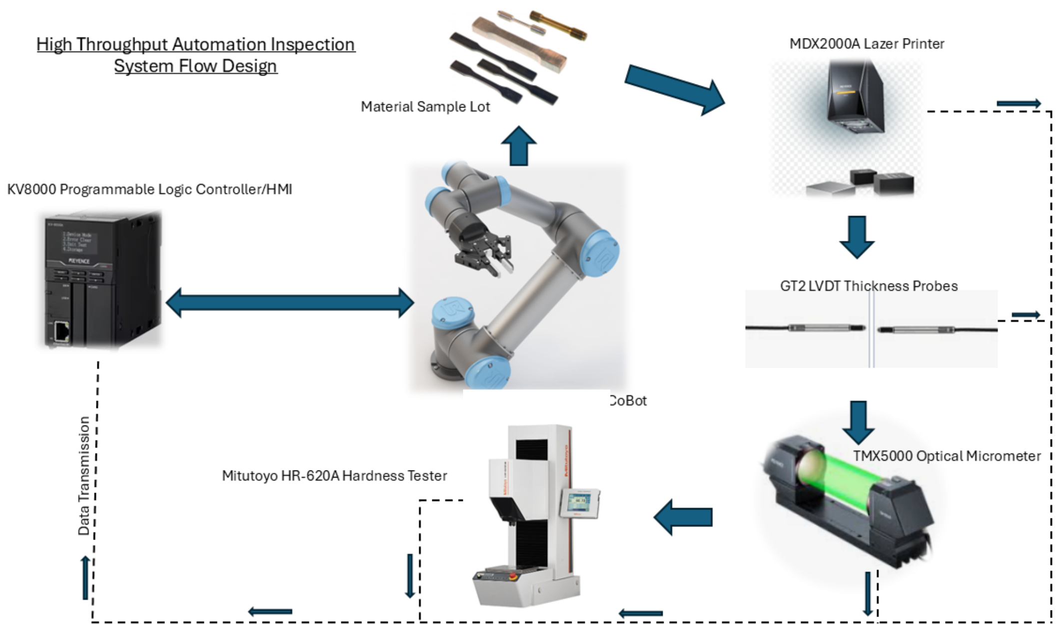

Figure 3. Conceptual automation measurement system workflow.

At the center of the measurement system is a six-axis robotic arm, which serves as the sample distribution command, linear variable differential transducer (LVDT) thickness probes, and an optical silhouette micrometer providing precise 1D and 2D measurements, respectively, for sample dimensions. A cold laser-based printer provides sample marking for identification, tracking, and data management purposes. A hardness tester for metals and plastics can provide additional relevant data. From this setup, data is generated and saved using a File Transfer Protocol (FTP) server established on a non-network local PC.

3. System Implementation

The conceptualized design has yielded a baseline automation dimensioning system consisting of Keyence KV8000A PLC, Universal Robotics UR5e CoBot, Keyence TMX5000, and Keyence GT2 LVDT thickness probes. Plans to integrate the hardness tester (e.g., Mitutoyo HR 620A), and cold laser printer system (e.g., Keyence MDX2000A) will occur during Phase II of this project. Figure 4 shows the actual photograph of the Automation Testing and Measurement System (ATaMS) with the Keyence 1D and 2D measurement devices along with placeholders for the system expansion. As depicted in the workflow concept, the CoBot is at the center of the measurement system with set programs to retrieve and distribute samples to the various instrument cells. Figures 5 and 6 are photographs of the Keyence—the GT2 LVDT and Keyence TMX5000, respectively.

Each measurement cell communicates its data and operations back to the PLC central processing hub via Ethernet/IP. Figure 7 shows the central processing communication in a self-contained cabinet. The PLC is synchronized to the UR5e CoBot and each of the measurement cell's configuration structures via Ladder Logic program (KV Studio, version 11.64). As this system gains more measurement and process cells, the Ladder Logic programing increases in complexity. Figure 8 shows an example screenshot of the Keyence KV Studio Ladder Logic programming structure.

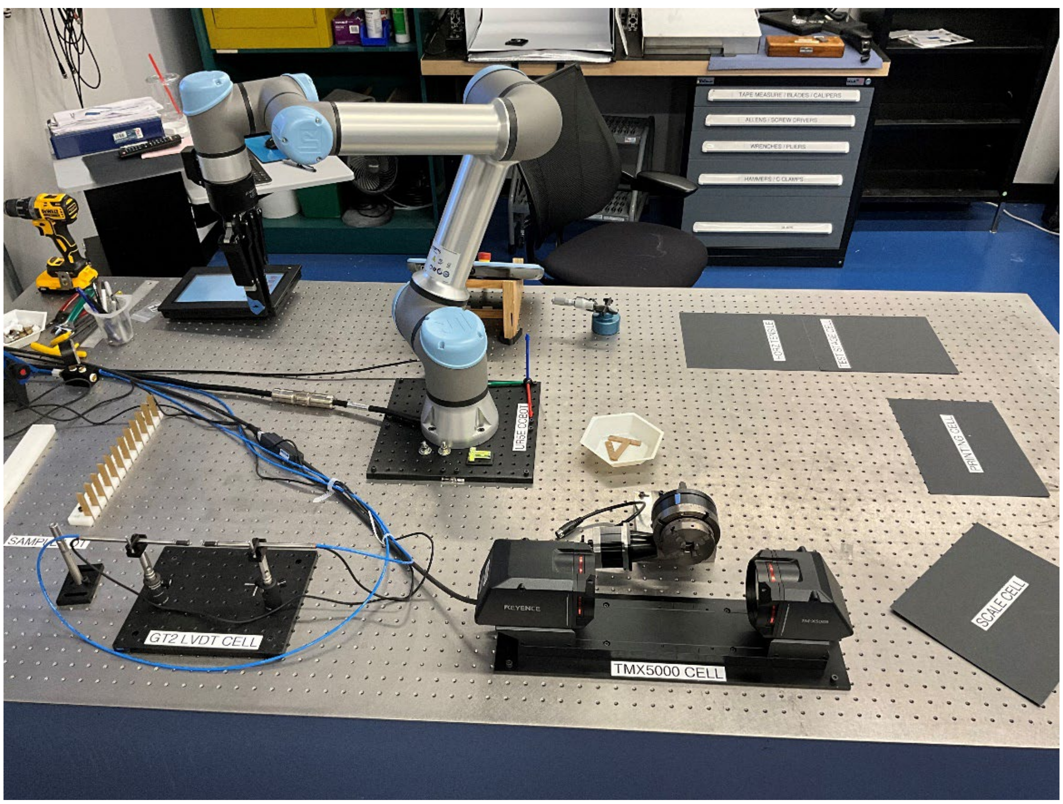

Figure 4. Automated dimensioning measurement system.

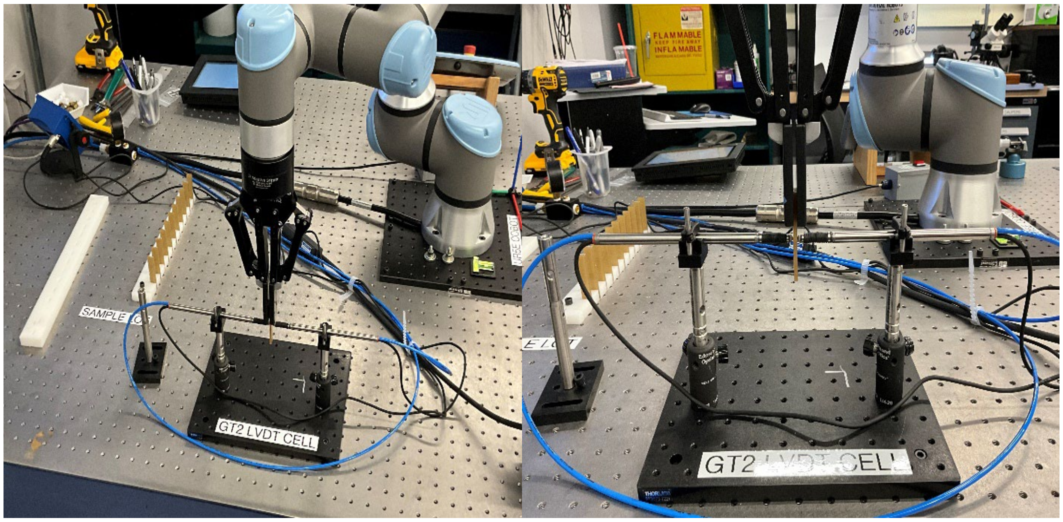

Figure 5. **Retrieved samples at GT2 LVDT measurement cell.**

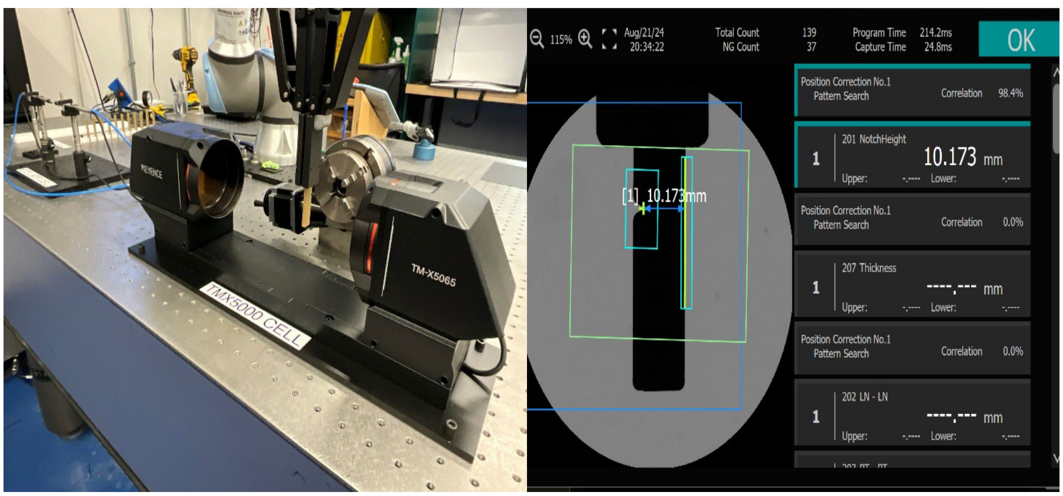

Figure 6. **Retrieved samples at TMX5000 optical micrometer measurement cell.**

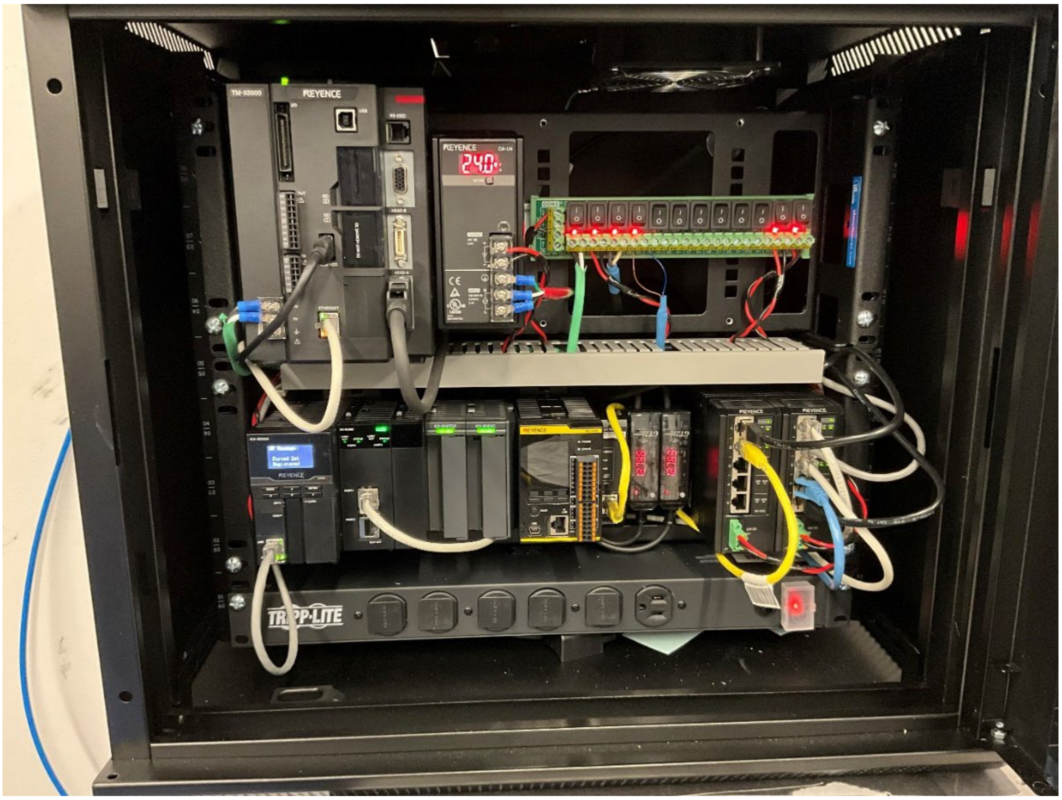

Figure 7. Central processing communications cabinet.

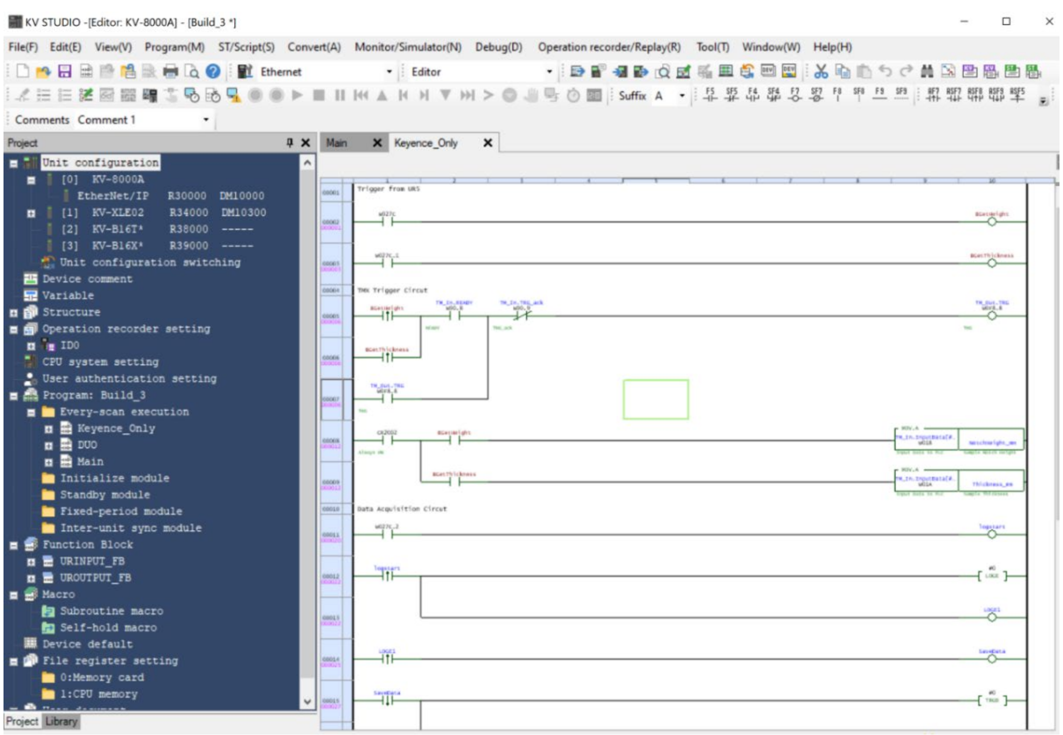

Figure 8. Ladder Logic program structure for TMX5000 measurement cell.

4. Measurement Results

Table 1 shows the comma separated values (.csv) formatted measurements data of the Izod-tested impact specimens transferred from the Keyence storage using the PLC's FTP command feature to the local non-network PC's FTP server (see Appendix B). Note the measurement time averages around 25 s per sample to complete both thickness and notch height commands, meeting a core expedience objective of the ATaMS project.

Each cell station program for the UR5e CoBot is written independently as a subroutine to allow PLC Ladder Logic programming to discriminately operate a single cell or group of cells based on required measurements and testing needs from the researcher. As other cell stations are brought online, new UR5e subprograms will be added and communicated to the PLC structure (Figure 9).

Table 1. Lot of 11 injection molding samples .csv data file generated from TMX5000 measurement cell and transferred via FTP.

PoCTestSample					
Sample Number	DATE	TIME	Thickness_mm	NotchHeight_mm	
0	8/21/2024	9:38:41	3.4340	10.1750	
1	8/21/2024	9:39:06	3.3950	10.1650	
2	8/21/2024	9:39:32	3.3900	10.1640	
3	8/21/2024	9:39:57	3.4040	10.1930	
4	8/21/2024	9:40:22	3.3940	10.1520	
5	8/21/2024	9:40:47	3.4030	10.1670	
6	8/21/2024	9:41:13	3.4100	10.1700	
7	8/21/2024	9:41:38	3.3890	10.1620	
8	8/21/2024	9:42:03	3.4050	10.1640	
9	8/21/2024	9:42:29	3.4000	10.1730	
10	8/21/2024	9:42:54	3.4110	10.1680	
Standard Deviation			1.2640%	1.0172%	

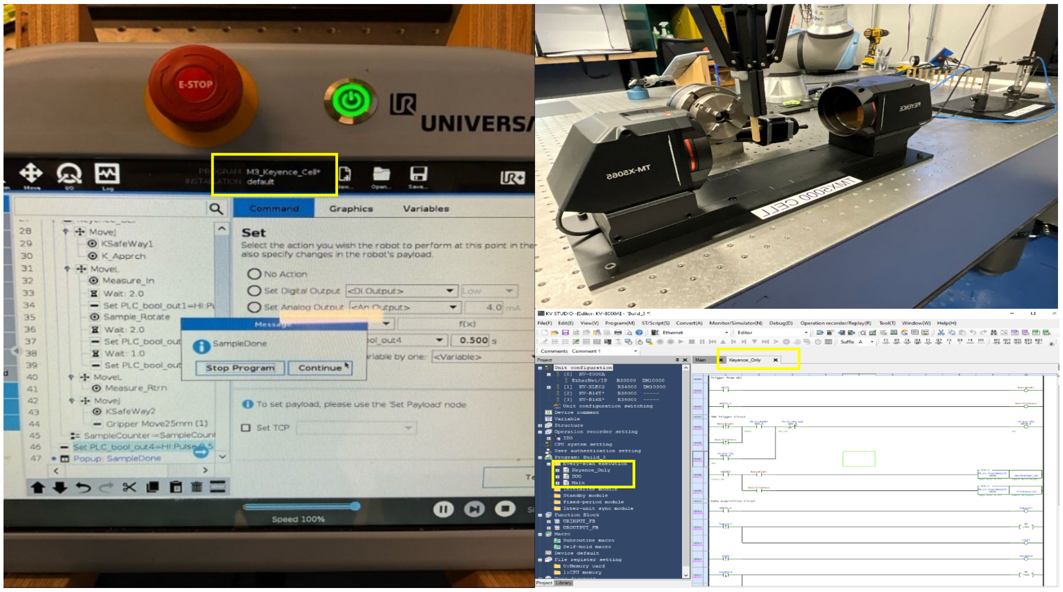

Figure 9. **Independent UR5e programming called by PLC Ladder Logic program.**

5. System Integration

After completing the installation, connection assemblies, and baseline programming of CoBot, PLC, TMX5000, and GT2 LVDT probes, an automation systems integration engineer was contracted to provide more advanced processes for the closed-loop PLC programing. The integrator's contributions to the project included the following:

- Integrated CoBot with PLC by initiating the run sequence from the PLC, program selection from HMI panel, and safety input/output status to PLC.
- Integrated GT2 LVDT measurement probe, created PLC Start Trigger, created PLC Data Collect Trigger, collected and verified raw data, converted raw data into units of measure.
- Integrated TMX 5000 Optical Measurement device, created PLC Start Trigger, created PLC Data Collect Trigger, setup PLC recipe to allow up to four measurements during a cycle, collected and verified raw data, converted raw data into units of measure.
- Constructed HMI screens to include Recipe Screen, batch nomenclature, quantity of sample parts to be processed, robot recipe\program selection, and process start/stop control. Provided process current count.

The HMI integration established the Phase 1 efforts for the ATaMS project for a fully functional baseline automation loop that can perform rapid and consistent sample geometry measurements and data handling from a GUI touchscreen panel.

Figure 10 shows the main home screen and program selection screens of the HMI control panel.

Figure 10. HMI main (left) and program selection (right) screens.

6. Future Developments

Additional hardware and station integration for the ATaMS project are described in this section.

Phase II:

1) Install and implement Apera 4D vision-guided AI-power technology for UR5e CoBot for programming. This system uses multiple sets of cameras and proprietary AI software, which identifies and maps sample location, guiding the robot manipulator for rapid “Pick and Place” from a bin, rather than formed sample trays and thus improving system efficiency. Figure 11 shows an example of Apera’s overhead camera system bin picking scenario versus sample tray “Pick and Place.”

2) Laser marking.

3) Database repository and management.

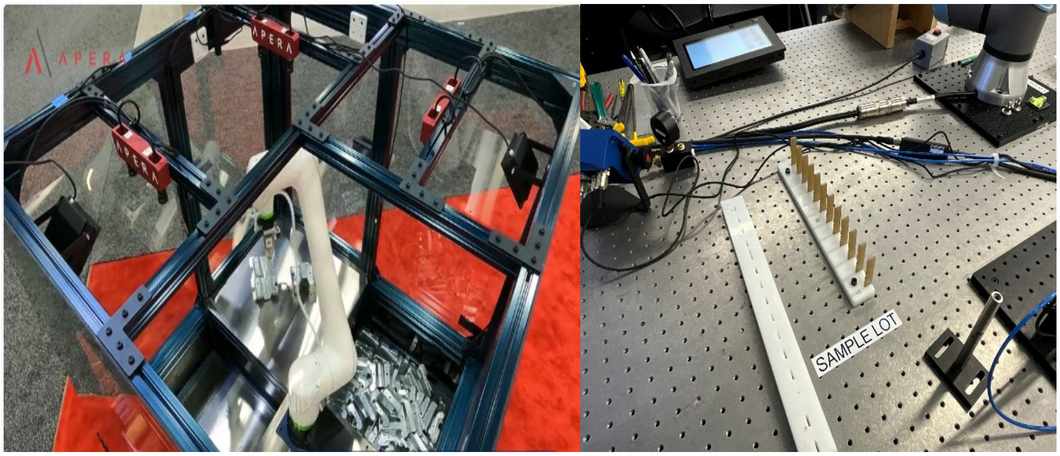

Figure 11. Apera 4D vision-guided AI-powered robotic guidance system vs. sample trays.

Phase III:

1) Integrate electro-mechanical benchtop mechanical loading stage.
2) Sample conditioning at low and elevated temperatures to add additional functionality for ATaMS.
3) Design and develop a mobile version of this system that can easily adapt for integration with other ARL Sciences of Extreme Materials research areas such as AM laboratories.

7. Conclusion: Summary of Development

Phase 1 of the ATaMS project focuses on advancing automation in materials characterization to accelerate HT testing for materials discovery, particularly in the context of ARL Sciences of Extreme Materials research. The system, centered around a Universal Robotics UR5e CoBot, automates the measurement of material specimens using precision instruments from Keyence, such as the GT2 LVDT probes and TMX5000 Optical Micrometer. Phase 1 achieved a fully functional baseline automation system that enhances efficiency and accuracy by automating repetitive tasks like dimensional measurements; thus, reducing human error and ensuring consistent data collection. The system's integration with a Keyence PLC and HMI interface allows for user-friendly control and batch processing. Future expansions will introduce advanced robotic vision, laser marking, temperature conditioning, and additional mechanical testing capabilities.

8. References

1. Klienmeyer JD. Requirements and selection of laboratory robotic systems. Materials Technology Laboratory (US); 1989 July. Report No.: MTL-TR-89-57, AD-A211-773.

2. Gongora AE et al. A Bayesian experimental autonomous researcher for mechanical design. Science Advances. 2020;6(15):1708.

Appendix A. Hardware Specifications

TM-X5065 Specifications

- Transmitter/receiver distance: 270 mm/10.63 inches
- Measurement range – Field of View: 40–65 mm/1.57–2.56 inches
- Measurement range – Depth of Field: 20–30 mm/0.79–1.18 inches
- Exposure time: 25/50/100 ms (adjustable three-stage)
- Imaging time: ~3–24 ms
- Light source: InGaN green LED
- Measurement position accuracy: ±2.2 microns/±0.000047 inches
- Repeatability: ±0.1 micron/±0.000004 inches
- Pixel resolution: ~37 microns/0.01457 inches

UR5e Specifications

- Payload 5 kg (11 lb)
- Reach 850 mm (33.5 inches)
- Degrees of freedom: six rotating joints
- Programming: 12-inch touchscreen with PolyScope GUI
- Power consumption (average): maximum power 570 W
- Force sensing, tool flange/torque sensor: force, x–y–z; torque, x–y–z
- Range: 50.0 N, 10.0 Nm
- Precision: 3.5 N, 0.2 Nm
- Accuracy: 4.0 N, 0.3 Nm
- Typical Transmission Control Protocol speed: 1 m/s
- Pose repeatability per International Organization for Standardization: 9283 ± 0.03 mm
- Axis movement working range maximum speed
- Base: ± 360° ± 180°/s
- Shoulder: ± 360° ± 180°/s
- Elbow: ± 360° ± 180°/s

- Wrist 1: ± 360° ± 180°/s
- Wrist 2: ± 360° ± 180°/s
- Wrist 3: ± 360° ± 180°/s
- Footprint: Ø 149 mm
- Materials: aluminum, plastic, steel
- Weight including cable: 20.6 kg (45.4 lb)

GT2-PA12 Linear Variable Differential Transformer (LVDT) Pencil Probes

- Detection system Scale Shot System II: absolute (no tracking errors) type
- Measuring range: 12 mm/0.47 inches
- Resolution: 0.5 µm
- Indicated accuracy: 2 µm (P-P)
- Measuring force: downward mounting 1.2 N
- Measuring force: side mounting 1.15 N
- Measuring force: upward mounting 1.1 N
- Sampling cycle: 4 ms
- Applied pressure range: 0.24–0.26 MPa
- Pressure resistance: 0.5 MPa
- Materials:
    - Main body case: SUS 303
    - Status indicator: PET
    - Sensor head-relay connector cable: PUR
    - Relay connector: PBT
    - Spindle of GT2-PA12K/PA12: SUS430 (fluorine coating)
- Weight (not including cable): ~35 g

HR-620A Specifications

- High-end CNC Rockwell hardness testing machine, providing a fully automatic Rockwell hardness test sequence.

- It is operated either with the provided display unit or using AVPAK 3.1 hardness testing software (11AAE525-DEE AVPAK for HR-600A).
- When run with AVPAK 3.1, it can easily be integrated in an automation cell via the programmable Mitutoyo Form EIO automation interface.
- Rockwell hardness testing
- Brinell hardness testing (indentation only)
- Brinell depth measurement hardness testing
- Vickers depth measurement hardness testing
- Hardness testing of plastic materials
- Single machine test methods

Appendix B. Establishing a File Transfer Protocol (FTP) Server between a Keyence Programmable Logic Controller (PLC) and Automation Testing and Measurement System (ATaMS) Server PC

ATaMS PC:

- Control Panel > Programs > Turn Windows Features On/Off
- Scroll to Internet Information Services and expand > Enable FTP Service > Enable IIS Management Console > Ok
- After Control Panel restarts > Re-open and change view to "Small Icons" for better viewing
- Click on Windows Tools (Admin Tools) > Internet Information Services
- In the next window that opens under the heading **Connections**, locate your computer name and expand the selection. **Right-click** on the **Sites** option and choose **Add FTP Site . . .**
- In the **Add FTP Site** window, input the **FTP site name** (this can be any name you choose) and browse or enter the **Physical path:** to the folder you will be using. Then click **Next**.
- In the next window titled **Binding and SSL Settings**, open the drop-down menu under **IP Address** and choose your IP address. Also, under **SSL**, click on **No SSL**. Then choose **Next**.
- In the next window:
    - Under **Authentication**, choose **Basic**
    - Under **Authorization > Allow access to,** choose **Specified users**. Then **create a username** in the text box below.
    - Under **Permissions**, ensure there is a check in the boxes next to **Read** and **Write.**
    - Then, choose **Finish.**
- Allow FTP through firewall > **Control Panel** and ensure that **View by** is set to **Small icons.** Click on **Windows Defender Firewall**.
- Choose **Allow a program (an app) or feature through Windows Firewall**.
- Click on the **Change Settings** button to allow for changes to take place.
- Scroll down and locate the **FTP Server** option. Be sure that the box for **Private and Public** is checked. Then click **OK** and close all open windows.

- Create the new user (Specified above). In the Settings app, select **Accounts** > **Other user > Local Account**
- Create password to be used for PLC FTP setup.
- On PC, > File Explorer > Locate the folder that was assigned to the physical path for FTP Server and right click > permissions > give newly created user permission to folder.
- Keyence PLC: Follow Keyence Simple Usage Guide, Logging/Trace Function Vol2.pdf, p. 12–13

List of Symbols, Abbreviations, and Acronyms

1/2/3/4D	one-/two-/three-/four-dimensional
.csv	comma separated values
AI	artificial intelligence
AM	additive manufacturing
ARL	Army Research Laboratory
ATaMS	Automation Testing and Measurement System
CoBot	collaborative robot
CRA	Cooperative Research Alliance
DEVCOM	U.S. Army Combat Capabilities Development Command
FTP	File Transfer Protocol
GUI	graphical user interface
HMI	Human–Machine Interface
HT	high-throughput
HTMDEC	High-Throughput Materials Discovery for Extreme Conditions
IP	Internet Protocol
LED	light-emitting diode
LVDT	linear variable differential transformer
ML	machine learning
PC	personal computer
PLC	Programmable Logic Controller

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