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SUPERVISORY CONTROL AND HEALTH MONITORING FRAMEWORK FOR LARGE-SCALE ADDITIVE MANUFACTURING SYSTEMS

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ABSTRACT

ORNL worked with NI to develop a large-scale, complex additive manufacturing (AM) systems framework for remote health monitoring and supervisory control. We found the framework, based on the Lincoln Electric Metal AM system located at ORNL's MDF, capable of controlling the process, leading to improved part quality and digital twin creation.

1. SUPERVISORY CONTROL AND HEALTH MONITORING FRAMEWORK FOR LARGE-SCALE ADDITIVE MANUFACTURING SYSTEMS

We began this phase I technical collaboration project (MDF-TC-2019-158) with NI, a large business, on January 15th, 2019, and concluded it on October 31st, 2020.

1.1 BACKGROUND

NI brings together people, ideas, and technology so forward thinkers and creative problem solvers can take on humanity's biggest challenges. From data and automation to research and validation, NI provides the tailored, software-connected systems engineers and enterprises need to Engineer Ambitiously™ every day. For this MDF, we used NI data acquisition and control system hardware and software.

AM systems of the future will require advanced process-logging, controls, and the ability to create "digital twins" to meet quality-control criteria. But current state-of-the-art, large-scale AM systems offer very limited capabilities. And at this point, there are no standards, universal approaches, compatible interfaces, or paths forward. However, robotics, automation, and modern AM sensing stand to propel advancements in this area. The MDF/ORNL has expertise in AM and access to many different printers, while NI offers robotics and data monitoring and control expertise. Working together, we established a universal supervisory control and health monitoring framework for large-scale AM.

At the beginning of this collaboration, ORNL and NI expected to:

- Improve print quality
- Reduce engineer burden by identifying and resolving system faults
- Lower the required effort to oversee each individual system's operation
- Log data to both provide print-quality reports to industrial customers and give researchers the means to perform fault analysis and analyze print variables for process/system improvements
- Gather feedback to improve NI commercial off-the-shelf software and framework

1.2 TECHNICAL RESULTS

1.2.1 Signals and Alarms

One of the project's first tasks was to create a list of signals, alarms, and system parameters that the framework would collect. Table 1 presents the current list of signals and signal types, and Table 2 shows the list of alarms based on the acquired signals.

Signal	**Source**	**Postprocessed**	**Role**	**Data Type**
Log Time	Robot	No	Log Time	Numeric
Layer Info	Robot	No	Layer Info	String
Task Info	Robot	No	Type of Activity	String
User Pause	User	No	Pause Record	Boolean
Reason for Pause	User	No	Reason for Pause	String
Torch 1 Wire Info	User	No	Description	String
Torch 2 Wire Info	User	No	Description	String
Total Time	DAQ	No	Print Time	Numeric
Uptime	DAQ	No	Active Time	Numeric
Downtime	DAQ	No	Passive Time	Numeric
Current Layer Time	DAQ	No	Amount of Time in Current Layer	Numeric
Current Layer Time	DAQ	Yes	Last Layer—Amount of Time	Numeric
Current Layer Time	DAQ	Yes	Five Layers Average Time	Numeric

Torch	Robot	No	Torch Choice	String
Weld Mode	Robot	No	Weld Mode Type	String
Shielding Gas	Welder	No	Gas Type	String
Weld Voltage	Welder	No	Weld Voltage	Numeric
Weld Current	Welder	No	Welding Current	Numeric
Weld Current	Welder	Yes	Welding ON/OFF	Boolean
Wire Feed Speed	Welder	No	Wire Feed Value	Numeric
Wire Feed Current	Welder		Wire Feeder Motor Current	Numeric
X Position	Robot	No	End Effector X Position	Numeric
Y Position	Robot	No	End Effector Y Position	Numeric
Z Position	Robot	No	End Effector Z Position	Numeric
Positioner Joint 1	Robot	No	Positioner Joint 1 Value	Numeric
Positioner Joint 2	Robot	No	Positioner Joint 2 Value	Numeric
Search Offset	Robot	No	Search Offset Value	Numeric
Z Correction	Robot	No	Z Correction Value	Numeric
Commanded Speed	Robot	No	Commanded Arm Speed	Numeric
Actual Speed	Robot	No	Actual Robot Speed	Numeric
Torch Tip 1 Change	User	No	Torch Tip Change 1	Boolean
Torch Tip 1 Change	User	No	Torch Tip Change 2	Boolean
Infrared (IR) Image	IR Camera	No	Image	Image

IR Image	IR Camera	Yes	Max Temperature	Numeric
Thermocouples	DAQ	No	Temperature Value from Thermocouples	Numeric

Table 1. Signals Acquired and Processed by the Supervisory Framework

Alarm	**Signal**	**Purpose**
Wire Feed Status	Wire Feed Current	Possible Wire Feeding Fault Warning
Height Control Status	Z Correction	Height Control Fault or Build Layer Growth Fault
Search Status	Current Task	Bad Part Searches
Weld in Place	Weld Current and Arm Speed	Weld in Place Fault
Temperature High	Maximum Temperature	Temperature over User Defined Value

Table 2. Framework Alarms

We acquired and processed the signals above using an NI cRIO-9035 embedded controller, shown in Figure 1, and used the LabVIEW graphical programming environment to create the framework.

Figure 1. Framework Hardware System

1.2.2. FRAMEWORK ARCHITECTURE

Our project aimed to develop and test a modular and easily extendable framework, as shown in Figure 2.

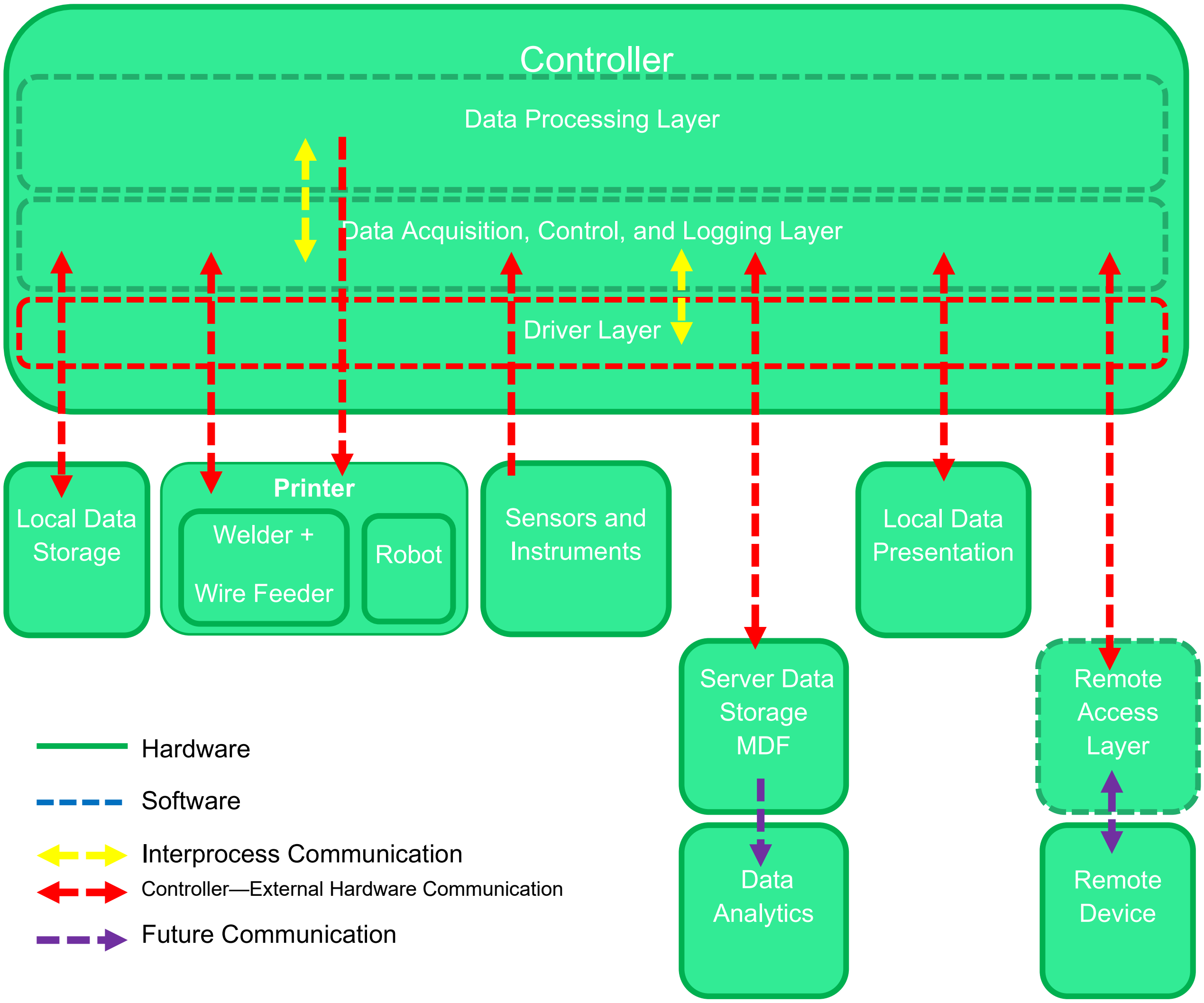

Figure 2. Framework Planned Architecture

Based on this structure, we chose the NI Distributed Control and Automation Framework (DCAF) platform for building and testing the framework. DCAF, based on LabVIEW, is modular and scalable data acquisition software. A DCAF application consists of one or more modules running on one or more runtime engines. These modules share the data with one another using the DCAF tag bus. We selected DCAF for this project because its modular nature makes it easy to make changes and apply to multiple systems. Instead of having to rewrite lots of code, we were able to use the configuration manager to easily reconfigure the system to change what data we're collecting, or even which system we're monitoring. Figure 3 shows the DCAF platform editor.

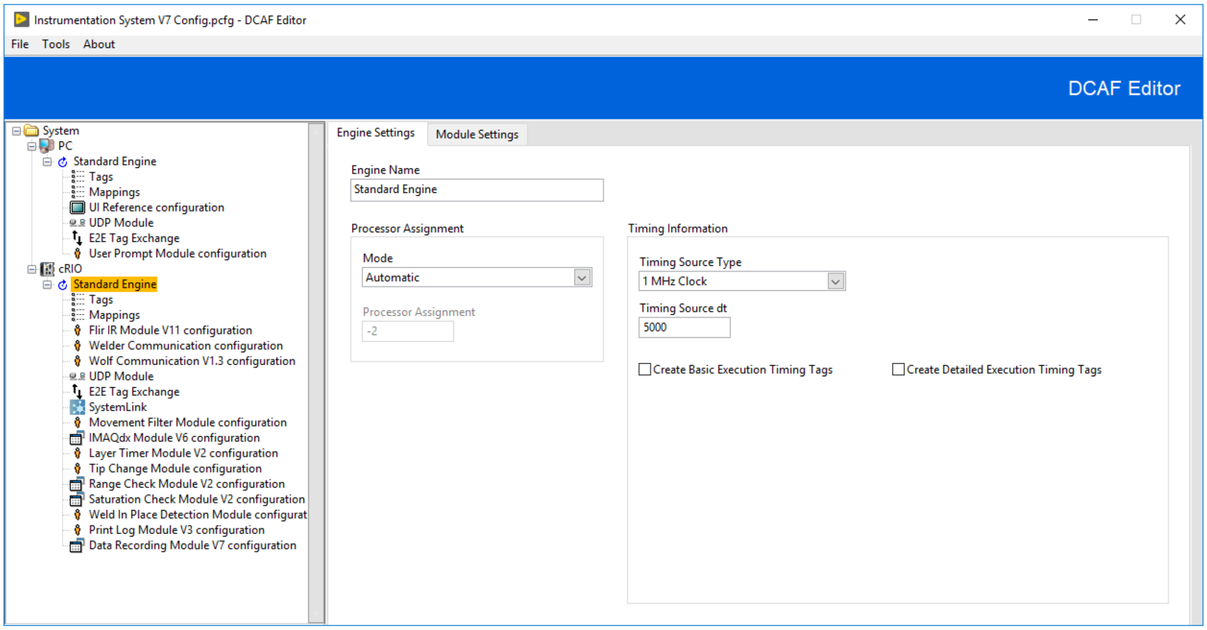

Figure 3. DCAF Editor Panel (Host and Target Modules on the Left)

1.2.3 Framework Modules

We developed DCAF modules for both the local host computer (operator interface) and remote target (the CompactRIO device).

Host computer

- **UI Module—**Displays information from the tag bus on the user interface
- **UDP Module—**Passes small pieces of data, such as numerics and strings, between the PC and CompactRIO device
- **E2E Tag Exchange Module—**Passes larger pieces of data, such as images, between the PC and CompactRIO device
- **User Prompt Module—**Hands over user-prompted information requests triggered by modules running on the CompactRIO device to the PC

Remote Target (CompactRIO Device)

- **Flir IR Module—**Handles IR camera setup and data processing
- **Welder Communication Module—**Receives data from the welder
- **Wolf Communication Module—**Receives data from and sends commands to the robot

- **UDP Module—**Passes small pieces of data, such as numerics and strings, between the PC and CompactRIO device
- **E2E Tag Exchange Module—**Passes larger pieces of data, such as images, between the PC and CompactRIO device
- **SystemLink Module—**Passes data to the SystemLink™ software server for remote monitoring
- **Movement Filter Module—**Filters out movement that occurs when the weld is off for better process monitoring
- **IMAQdx Module—**Uses the NI-IMAQdx driver to configure and acquire images from GigE compatible cameras
- **Layer Timer Module—**Provides information relating to uptime, downtime, and layer times
- **Tip Change Module—**Records tip changes
- **Range Check Module—**Checks if values are within a given range
- **Saturation Check Module—**Checks control signals for saturation
- **Weld in Place Detection Module—**Looks at the welder and robot status to determine if a weld-in-place error is occurring
- **Print Log Module—**Creates a log containing information that doesn't change in the middle of a build, such as consumables, slice parameters, weld parameters, and build plate data
- **Data Recording Module—**Records data received from other modules
- **Save Image Module—**Saves images of the printed part

1.2.4. USER INTERFACE

A critical component is the user interface or UI module, which is presented in Figure 4.

The primary UI tab gives quick access to the most important data for monitoring build progress. The system displays the current build status, including the current bead and layer, current task, weld mode, and shielding gas, as well as data from the robot, including its current speed and position, and the torch that is currently in use. Also, the system creates and displays a plot of the current robot movement speed versus the error in build height. By monitoring this plot during the build, we quickly can determine if the system is making the necessary adjustments for a high-quality build, or if operator intervention is required. Additionally, the system displays an IR image of the current layer, along with any thermocouples in use. This, along with the built-in alarm, directly affects print quality and increases operator awareness.

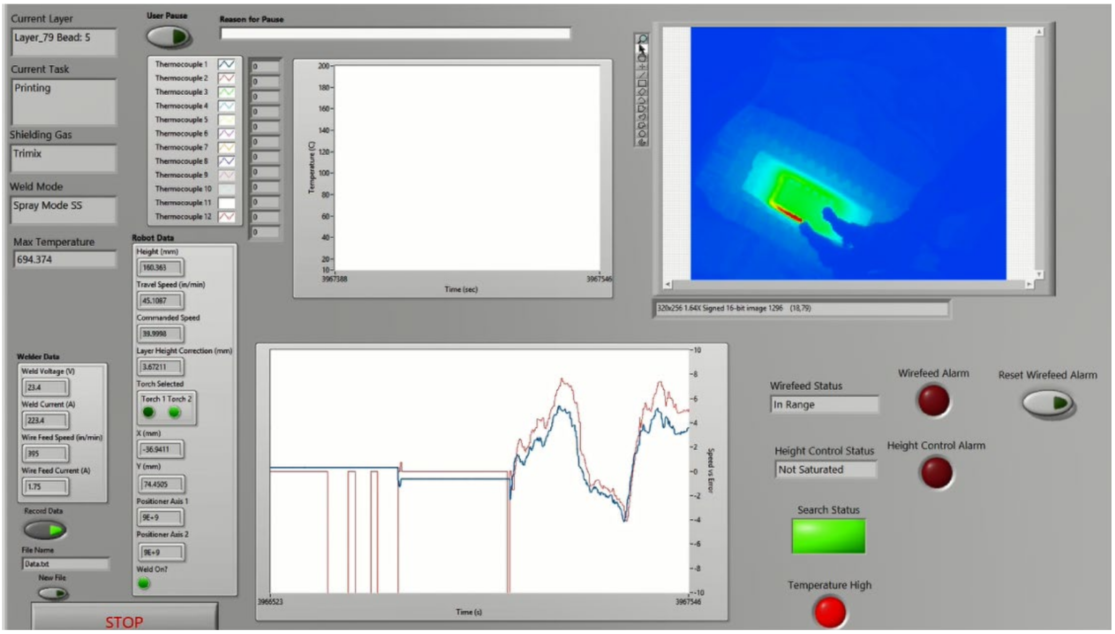

Figure 4. Primary Framework User Interface

In addition to the primary UI tab, there are tabs that give more in-depth looks into the current process (Figure 5). These include a tab dedicated to weld data, IR imaging tabs for both a

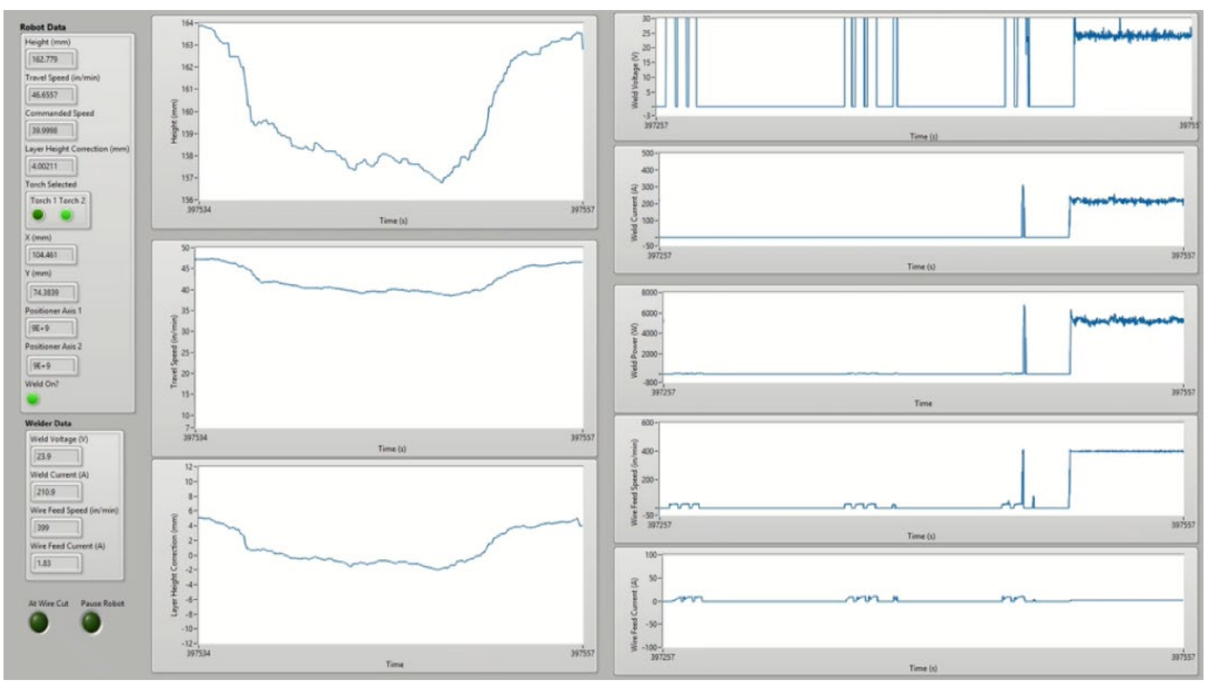

Figure 5. Additional User Interface Information

top-down view and side view, a tab for setting alarm parameters, and a tab displaying a detailed build-time breakdown.

1.2.5. Data Storage

The system stores all data in three file types:

- **Data File**—Basic build info in header followed by real-time build data recorded at 1 Hz (rate can be adjusted as needed) shown in Figure 6
- **Print Log File**—Detailed settings including build plate info, consumable info, slicing parameters, and detailed weld parameters
- **Images**—Build progress images automatically taken by the system

Project Name: TPipe
Operator Name: Bill
Program Name: TPipeFinal
Wire 1: 410
Gas 1: Trimix

Timestamp	Thermocouple 1	Thermocouple 2	Thermocouple 3	Thermocouple 4	Thermocouple 5	Thermocouple 6	Thermocouple 7
10-24-19 12:08:45	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
10-24-19 12:08:46	23.073851	23.066100	22.867270	22.953260	22.764326	1381.183140	1381.183
10-24-19 12:08:47	23.079509	23.078607	22.876354	22.961081	22.786932	1381.193602	1381.193
10-24-19 12:08:48	23.072938	23.070595	22.883844	22.960819	22.774411	1381.188504	1381.188
10-24-19 12:08:49	23.072495	23.067809	22.878894	22.961999	22.775951	1381.189676	1381.189
10-24-19 12:08:50	23.068947	23.059034	22.878410	22.963137	22.777090	1381.184178	1381.184
10-24-19 12:08:51	23.080609	23.066730	22.888631	22.972276	22.779199	1381.191829	1381.191
10-24-19 12:08:52	23.082552	23.071016	22.885527	22.971876	22.787633	1381.198061	1381.198
10-24-19 12:08:53	23.077825	23.063766	22.885847	22.972196	22.781102	1381.193541	1381.193
10-24-19 12:08:54	23.084996	23.073640	22.886349	22.965307	22.775473	1381.193502	1381.193
10-24-19 12:08:55	23.070714	23.067290	22.889552	22.965265	22.777415	1381.188443	1381.188
10-24-19 12:08:56	23.083070	23.073877	22.886406	22.966265	22.786168	1381.200368	1381.200
10-24-19 12:08:57	23.072590	23.069346	22.882955	22.967141	22.778750	1381.193892	1381.193
10-24-19 12:08:58	23.077334	23.070304	22.885536	22.965395	22.787281	1381.196636	1381.196
10-24-19 12:08:59	23.081426	23.070251	22.883499	22.969849	22.775869	1381.194612	1381.194
10-24-19 12:09:00	23.071180	23.066493	22.878660	22.965370	22.772832	1381.189623	1381.189

Figure 6. Data File Created by the Supervisory Framework

1.2.6. Remote Monitoring

Finally, we achieved remote monitoring over multiple systems using the NI SystemLink software platform, which helps remote operators easily check system status. The system sends instrumentation data—including robot, weld, and task data—to the SystemLink software server and displays it on a customizable dashboard, as shown in Figure 7.

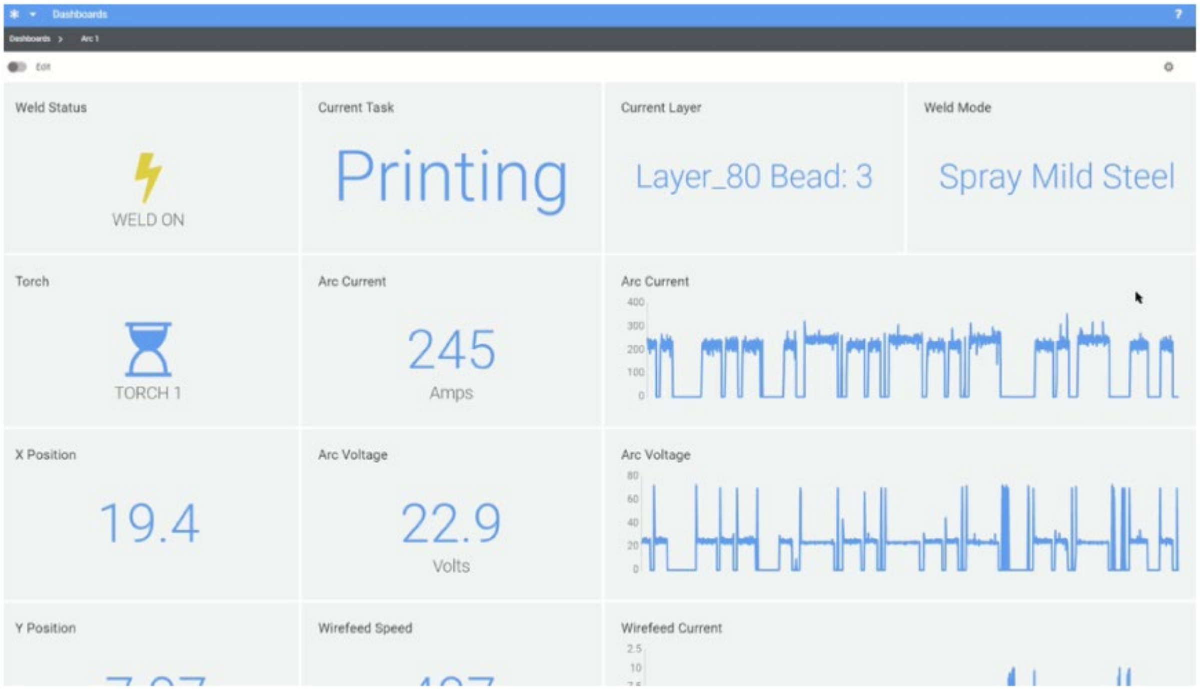

Figure 7. SystemLink Software Dashboard for Remote AM Process Monitoring

1.3 Impacts

By properly monitoring the complex processes of large-scale AM, we:

- Quickly developed a new AM method and material
- Created a new standard for logging and data analytics
- More quickly identified system faults
- Reduced feedstock usage through more efficient process control
- Lowered operator device monitoring and technical expertise requirements

NI expressed interest in a phase 2 of the project, in which we expand and test the framework on multiple systems with varying configurations. As such, we have created a foundation for future AM direct energy deposition system products.

1.3.1 Subject Inventions

N/A

1.4 Conclusions

We created and tested a modular supervisory framework using an NI data acquisition hardware and software platform. We implemented the framework on the existing Lincoln Electric ARC1 system located at the ORNL Manufacturing Demonstration Facility. We use it to gather process data from different subcomponents, present the data, store the data for later postprocessing (digital twin), and remotely access the system if needed. We also can use it to control signals to be transferred back from the control modules (user or algorithmic) to the printer. Using the modular DCAF architecture, we can achieve quick deployment and changes without costly code adaptations.

2. Partner Background

For more than 40 years, NI, a global company headquartered in Austin, TX, has developed automated test and automated measurement systems that help engineers solve the world's toughest challenges.