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Reviewed Paper

AN OPEN-ARCHITECTURE MULTI-LASER RESEARCH PLATFORM FOR ACCELERATION OF LARGE-SCALE ADDITIVE MANUFACTURING (ALSAM)

William Carter[1], Michael Tucker[1], Michael Mahony[1], David Toledano[1], Robert Butler[1], Subhrajit Roychowdhury[1], Abdalla R. Nassar[2], David J. Corbin[2], Mark D. Benedict[3], Adam S. Hicks[3]

[1] GE Research, [2]Penn State, [3]United States Air Force

Abstract

As Selective Laser Melting (SLM) technology matures, researchers and engineers responsible for transitioning the technology from rapid prototyping into manufacturing are gaining a better understanding of the opportunities with this revolutionary technology. A step for accelerating solutions is to allow researchers complete access to all aspects of the process for experimentation. As part of an AFRL-sponsored program with America Makes, a production-grade SLM machine (a Concept Laser M2) will be enhanced to allow operation with either the original OEM controls and scan path generation or an open-source set of software developed under America Makes programs. This machine will be referred to as the ALSAM Platform and will be delivered to the Air Force along with the source code for the open scan path generation software (written in C++) and the open machine controller (written in LabVIEW™).

Introduction

Interest in the production of large-scale parts using Selective Laser Melting (SLM) has grown as additive manufacturing has matured and, to respond to this interest, machines are entering the market with increased build volumes. Single laser systems can successfully print large components for prototypes or limited production but build times can become untenable for mass production. A natural solution to allow larger parts on economical time scales is to use multiple lasers. Proprietary multi-laser solutions are emerging, but to date there is no consensus regarding optimal strategies for employing multiple lasers and issues including stitching, alignment, and coordination arise.

To address these concerns, the US Air Force sponsored a series of four research programs through America Makes (America Makes is managed and operated by the National Center for Defense Manufacturing and Machining, NCDMM). These programs, summarized in Table 1, were aimed at developing open-source and open-architecture SLM for metals to foster creative research in the field. Three of these programs are complete, and a fourth is ongoing. This paper will give an overview of these programs.

Table 1. America Makes "Open SLM" Projects. America Makes sponsored four research projects related to open-source, open-architecture additive manufacturing systems.

Project #1:	
America Makes Project 4039	
Title:	Open Source Process Control for Powder Bed Additive Manufacturing Research
Status:	Complete
Participants:	GE Research, GE Aviation, Lawrence Livermore National Laboratory
Dates:	March 2015 – August 2016
Summary:	Open-source computer programs for laser-based powder bed fusions systems were written for both scan path generation and machine control. The resulting software was implemented on multiple SLM machines.
Project #2:	
America Makes Project 4040	
Title:	An Open, Layered Protocol for Powder Bed Additive Manufacturing for Synchronizing Heterogeneous Sensors and High-Speed Data Acquisition
Status:	Complete
Participants:	Applied Research Lab at Penn State, Honeywell International Corporation, Northrop Grumman Corporation, 3D Systems
Dates:	February 2015 – February 2017
Summary:	A standard protocol was developed and demonstrated for specifying the behavior of SLM systems, including monitoring and control.
Project #3:	
America Makes Project 4051	
Title:	A Flexible Adaptive Open Architecture to Enable a Robust Third-Party Ecosystem for Metal Powder Bed Fusion Additive Manufacturing Systems
Status:	Complete
Participants:	GE Research, Rensselaer, MatterFab, Applied Research Lab at Penn State,
Dates:	February 2016 – July 2018
Summary:	An open-architecture control system for laser-based powder bed fusions systems was designed and demonstrated on two SLM machines using the software from the prior program.
Project #4:	
America Makes Project 3024	
Title:	Acceleration of Large Area Additive Manufacturing (ALSAM)
Status:	Ongoing
Participants:	GE Research, Applied Research Lab at Penn State
Dates:	Dec. 2018 – March 2022
Summary:	A commercially available 2-laser Concept Laser M2 machine will be modified to allow operation using *either* the OEM-supplied scan path generation and controls software *or* the America Makes open-source software. This system will be delivered to the Air Force, including the source code for all software, by the end of 2020.

<u>**Project #1: America Makes #4039**</u>

Open Source Process Control for Powder Bed Additive Manufacturing Research

March 2015 – August 2016

The objective of program was to develop protocol and open-source programs that would take any STL file as input and generate a machine-independent protocol for manufacturing the part on an SLM system. This protocol is termed the *SCAN* protocol. Another protocol, termed the *LAYER* protocol, was implemented as an intermediate step between the STL file and SCAN file. Both file protocols conform to the eXtensible Markup Language (XML) format. Demonstration software was written to generate both LAYER and SCAN files from STL files.

The sequence is illustrated in Figure 1, where computer programs are indicated as yellow boxes and protocols are indicated as blue boxes. The STereoLithography (STL) format and the Additive Manufacturing File (AMF) format are established file formats for representing geometric objects. At least one of these files is required as input for the LAYER generator. The LAYER protocol describes the physical attributes of all contours and regions comprising a specific layer. The SCAN protocol describes the laser scan parameters to fuse the layers in an SLM machine. Both protocols are independent of SLM machine type, with the goal of making them comprehensive, simple, scalable, and extensible.

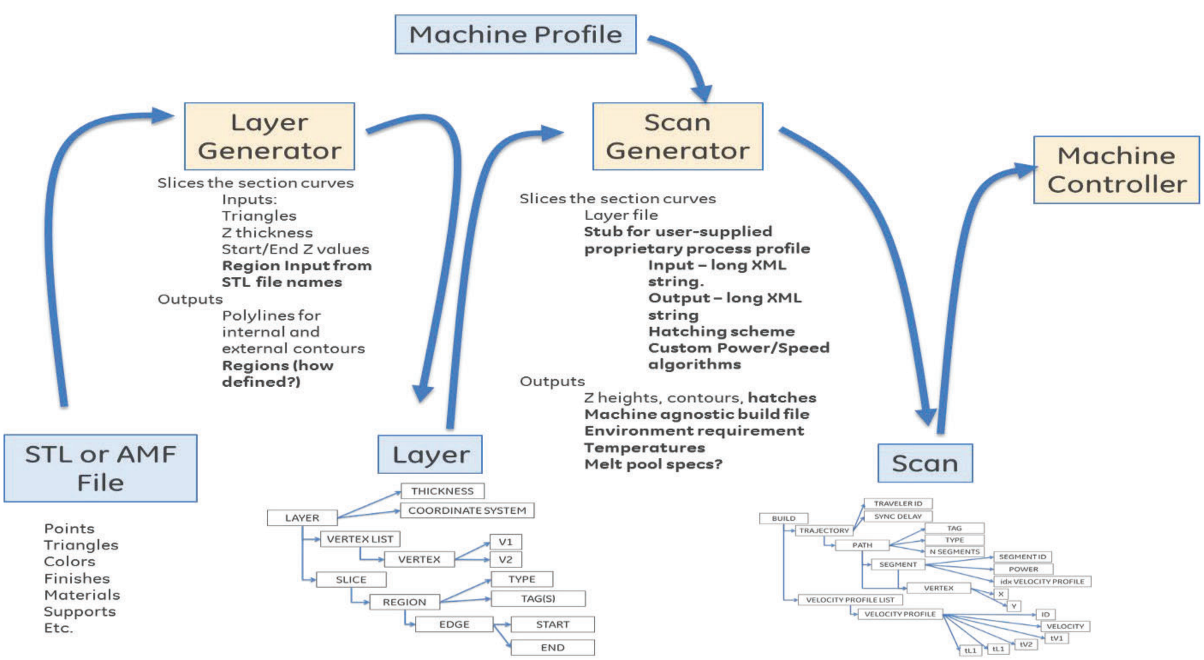

Figure 1. Scan Path Generation Sequence. Yellow boxes indicate computer programs and blue boxes indicate file formats.

LAYER Protocol

The LAYER protocol was designed during the project to be independent of SLM machine type and describes the physical attributes of a given layer. Multiple layers form a part and each LAYER is defined with a specified thickness. Regions can be tagged with feature types. For example, contours can be tagged with the part name and serial number. Additional tags are used to define regions of support material, bulk material, sidewalls, upward- or downward-facing surfaces, etc. Anticipating future improvements to SLM, regions may be tagged with differing materials. All the details within the LAYER protocol are in standard XML text files that can easily be inspected or modified. The protocol is illustrated in Figure 2.

Details of the LAYER schema are described in other publications by the authors [1]. In the context of the XML file, Types have elements and attributes. The elements in the LAYER XML file are described in this section. The elements in the LAYER file schema include VertexType, VertexListType, EdgeType, RegionType, SliceType, and LayerType.

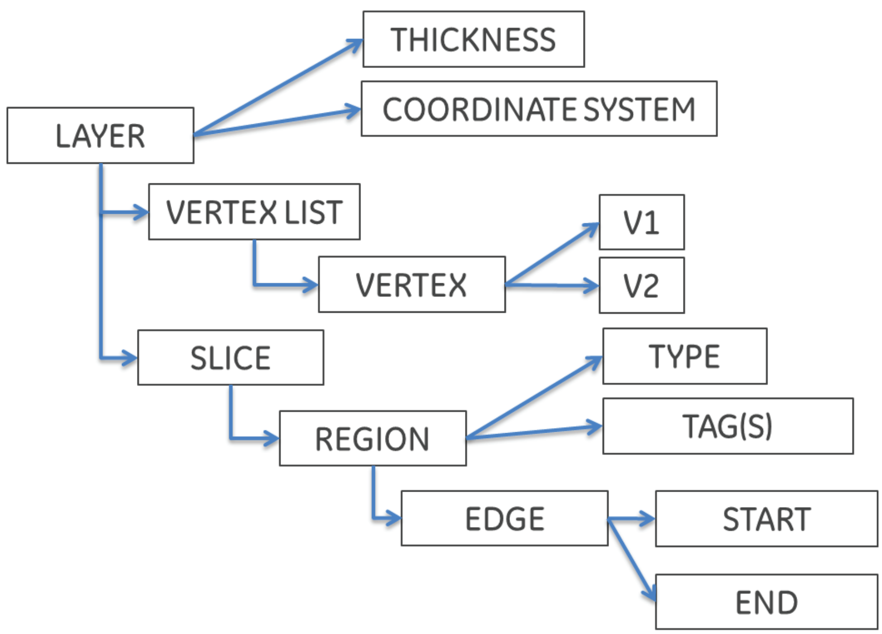

Figure 2. The LAYER Protocol Hierarchy.

SCAN Protocol

The SCAN protocol was designed during the project to be independent of SLM machine type and is used to direct a Machine Controller. The file describes the laser position, speed, and directions, and scan parameters for each layer. Each beam path represents one continuous translation of the beam relative to the powder bed and consists of a set of parameters that are indexed in time. The parameters represent any adjustable property of the SLM process such as coordinates, laser power, beam size, etc. Additionally, they can contain diagnostic cues for information that needs to be recorded at specific points in time such as camera image, stage position, or temperature. The SCAN file is stored in the XML (eXtensible Markup Language) format because the file is intended to be both human and machine readable and the visualizers and editors for this format may be readily developed. The team developed the detailed technical requirements for the SCAN protocol with the understanding that a successful protocol will continue to evolve long after the completion of the program. The content of the SCAN file is illustrated in Figure 3.

An interesting benefit of the machine-independent approach taken here is that, in addition to providing a standard seamless interface to SLM machines, the protocol can be used to set boundary conditions for finite element analysis (FEA). This will involve communicating the beam paths to finite element software through a file format or software automation interface, for instance ActiveX/COM. This advantage has already been exploited by a NASA-funded team at Rensselaer [2]. By leveraging these simulations, optimal beam paths may be developed over time.

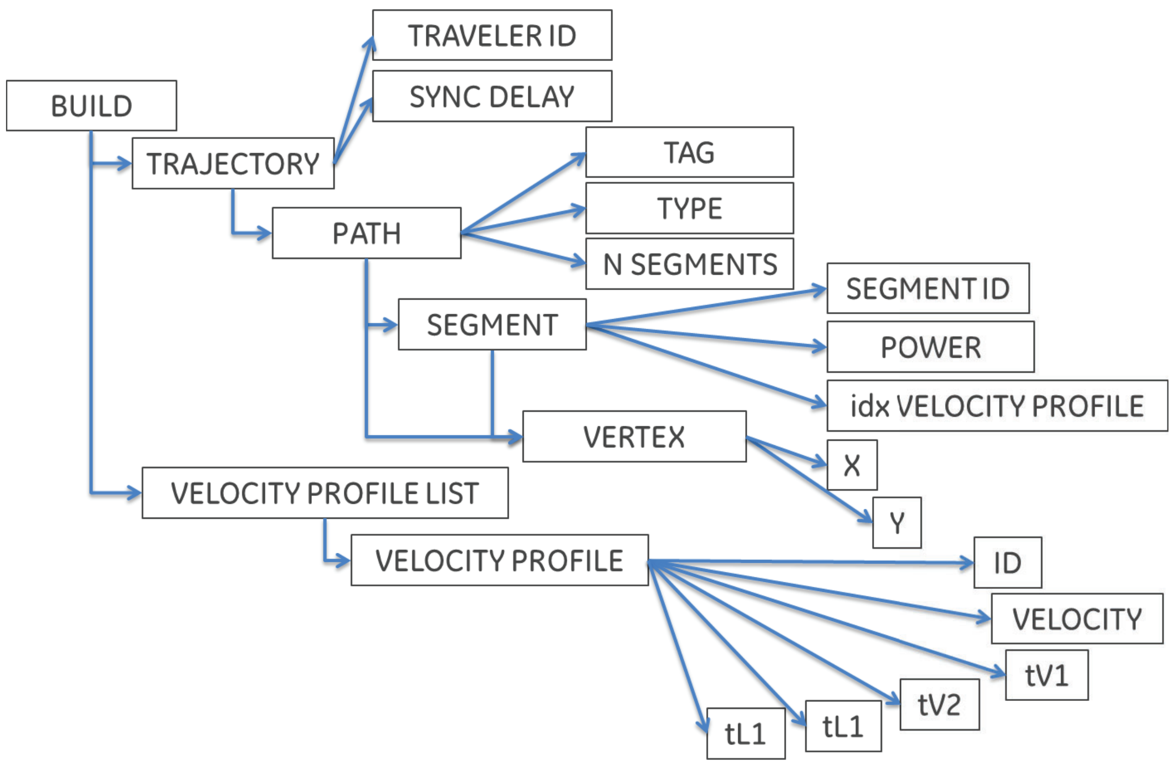

Figure 3. SCAN data and geometry hierarchy

Further details of the SCAN schema are described in other publications by the authors [1]. In the XML schema, types have elements and attributes. The elements used in the SCAN XML file are described in this section. The elements used in the SCAN file schema include BuildType, VelocityProfile, ListType, VelocityProfileType, TrajectoryType, PathType, Vertex, and SegmentType

LAYER and SCAN Generator Programs

A program written in C++, called *LAYER Generator*, was developed to demonstrate the conversion of STL files into a series of slice layer descriptions per the file format of the LAYER protocol. The slicing of the STL file itself is a well-established capability and it was not our intention to reinvent these algorithms. An open-source program, *Slic3r*, was used to perform this task during execution of the layer generator. Slic3r is free software developed by Ranellucci [3] with help of contributors in the open source community. This program is primarily aimed at fused deposition modeling; only the slicing portion of the code is used here. The required executables can be downloaded from the web. No source code of Slic3r is required, though available in the open community through GitHub.com.

The GE Global Research team developed a C++ program, called *SCAN Generator*, to demonstrate the conversion of LAYER files into SCAN files. The program is a command-line driven executable that allows an organization to store a library of laser velocity profiles and assign the velocity profiles to regions of a specific type defined by a tag. Scalable Vector Graphics (SVG) files can be generated for scan path visualization using conventional programs, or they may be viewed in the LabVIEW™-based Machine Controller (in virtual machine mode) discussed below.

<u>Project #2: America Makes #4040</u>
An Open, Layered Protocol for Powder Bed Additive Manufacturing for Synchronizing Heterogeneous Sensors and High-Speed Data Acquisition
February 2015 – February 2017

Under this America Makes program, referred to as Open Protocol program for short, communication methods were developed and demonstrated for SLM systems. This work was led by the Applied Research Laboratory at Pennsylvania State University in collaboration with Honeywell International Inc., Northrop Grumman Corporation and 3D Systems, Inc. The developed hybrid open protocol system consisted of three components: open transmission of build-plan data, low-speed (10 Hz) communication of machine conditions, and high-speed (100 kHz) communication of laser beam position and status.

The developed protocol enabled specification and extraction of scan path and communication between a SLM system and heterogeneous systems for condition monitoring, data acquisitions, and in-process sensing. In particular, the developed methods provided

- access to critical data required for process modeling and optimization,
- synchronization of the process state with sensors for in-process monitoring, and
- monitoring and recording of machine condition and status.

Under the original America Makes program, all components of the open protocol system were demonstrated on a commercial 3D Systems ProX-200 SLM machine. Later, the framework was extended to other SLM systems including 3D Systems ProX-320, EOS M280, and Concept Laser M2 systems.

High-speed and Low-speed protocols

Two separate methods were utilized for transmission of real-time process data at 100 kHz and machine monitoring data at 1-10 Hz, respectively. High-speed transfer was carried out using a protocol similar to XY2-100 protocol to provide real-time, synchronous, digital transmission. Lower speed measurements are better suited for transmission using an Ethernet-based protocol, where they may be monitored remotely by networked systems. Thus, an MTConnect-like protocol was adapted for transfer of machine and management-level data. An illustration of the physical protocol implementations is provided in Figure 4.

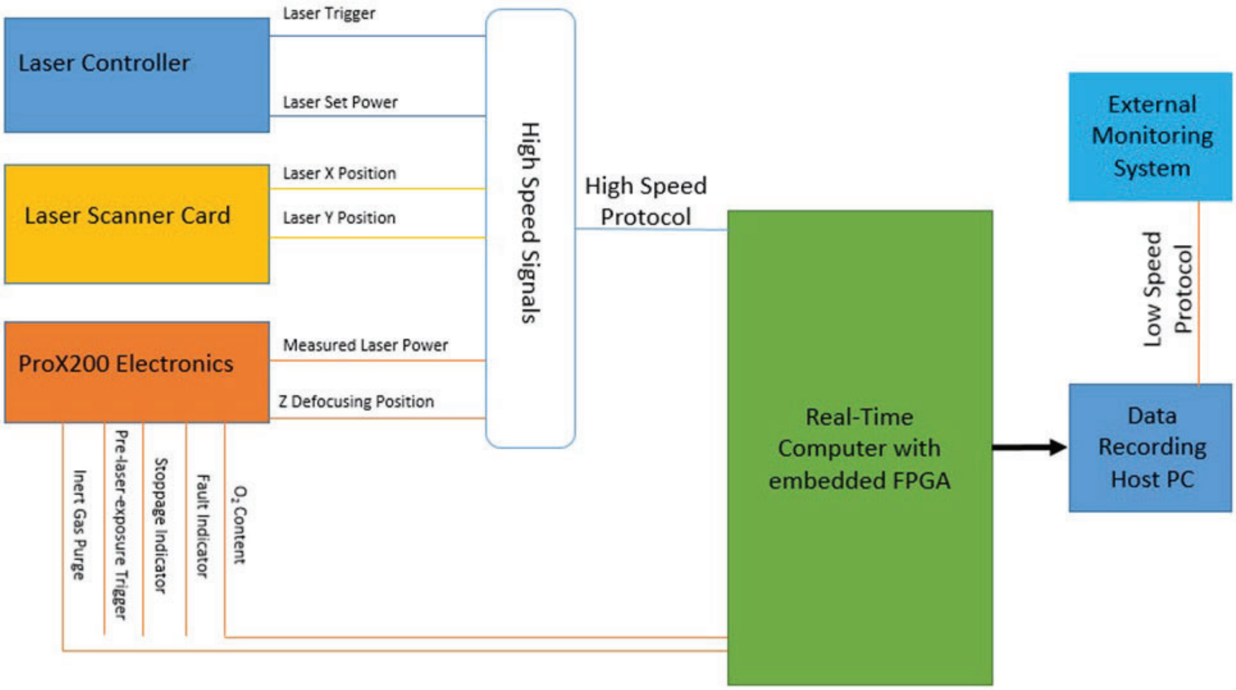

Figure 4. Schematic layout of the high and low-speed measured signals

During the SLM process, both high-speed and low-speed data are buffered and saved to disk. Network-shared variables are utilized to synchronize the high-speed and low-speed data streams via a sampling loop executed at 10 Hz. This enables the extension of the system across a network with separate computers capturing high-speed and low speed data. All data are saved to separate files in a local or networked location.

High-speed data are made available to heterogeneous sensors interfaced to a real-time data acquisition (DAQ) system while low-speed data are available to sensors interfaced with a Windows-based computer (PC). Sensor outputs (typically analog voltages) can be connected to available inputs on the real-time DAQ system in parallel with high-speed data. Both sensor and high-speed data are buffered and transmitted to the host PC for storage. For additional details, see [4].

Sensors operating at or less than 10 Hz or which require a windows-based interface are synchronized to the high-speed measurements on a PC. Published low-speed data along with sampled high-speed data are synchronized using network shared variables. The low-speed protocol is independent of the update rate of attached sensor. However, low-speed sensors are continuously sampled at a fixed (10 Hz) rate on the on the host PC. Data collected across a layer is saved locally or to a networked location to a separate file.

Implementation, Extensions and Technology Transitions

Under the Open Protocol program r, the protocol was demonstrated on a 3DSystems ProX-200 machine. Two sensing systems were also interfaced with the high-speed and low-speed protocols: An Ocean Optics HR2000+ES spectrometer and an ARL Penn State proprietary multi-spectral sensor [5]. Because all data streams were indexed and synchronized, sensor data could be easily overlapped for later comparison with post-process computed tomography scans (Figure 5).

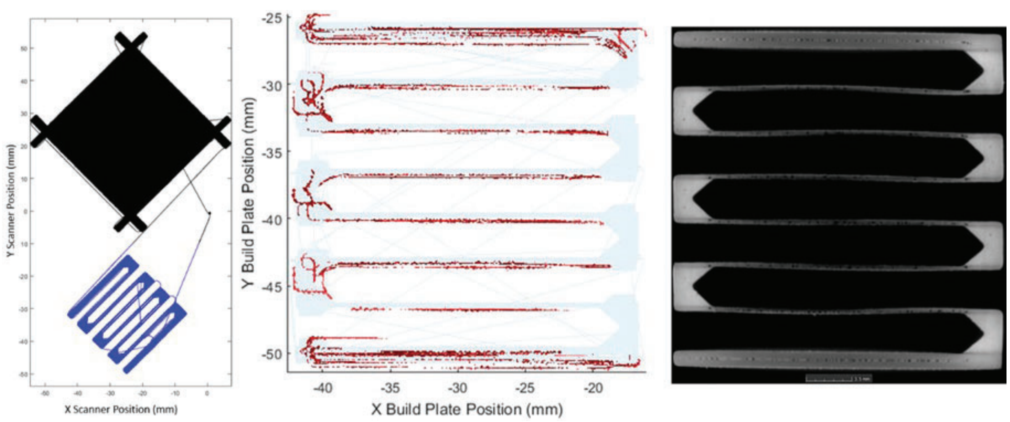

Figure 5. Results of the ARL PSU Open Protocol System. Scanner position captured by the system (Left). Multi-spectral sensor data layer with potential flaws identified (Middle). Computed tomography scan showing lack of fusion defects in same build layer (Right).

Following the completion of the America Makes program, a follow-on effort funded by Sandia National Laboratory and in collaboration with 3D Systems, Inc. enabled transition and installation of the Open Protocol system on a ProX-200 system at Sandia National Laboratory. The system included the ARL Penn State multi-spectral sensor and an optical emission spectrometer. The system is still operational. An illustration of the sensor layout and a GUI used for operation of the Open Protocol system is provided in Figure 6.

A parallel effort, funded by DARPA also enabled extension of the Open Protocol System to a wider class of SLM systems, including the 3D Systems ProX-320, EOS M280, and Concept Laser M2 system. All efforts utilized the implementation framework developed under original

America Makes funded effort, though these later efforts focused primarily on data acquisition from high-speed sensors at a reduced rate of 50 kHz. These efforts also captured commanded, rather than actual scanner positions to reduce the need for post-process data filtering.

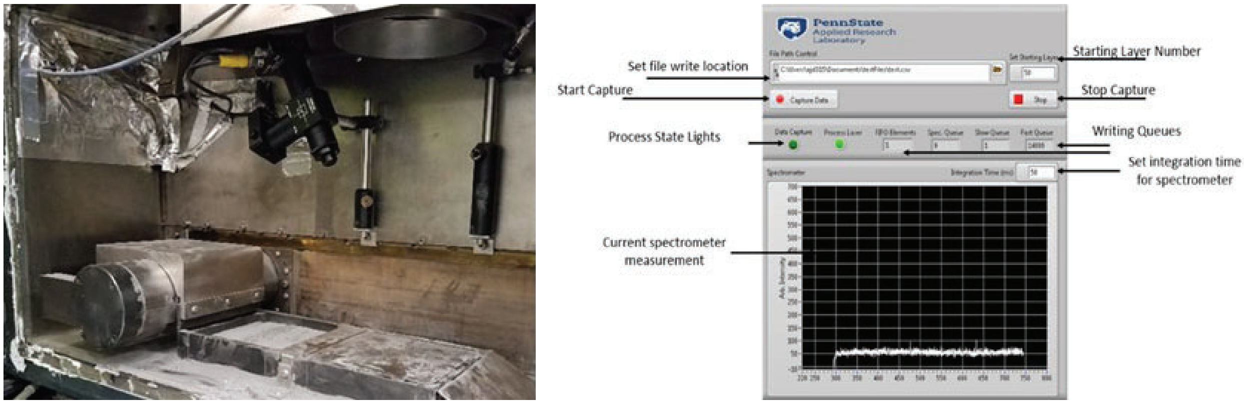

Figure 6. Layout of Sensors installed (Left) and simple GUI developed for open protocol system for use by Sandia National Laboratory (Right).

<u>Project #3: America Makes #4051</u>
A Flexible Adaptive Open Architecture to Enable a Robust Third-Party Ecosystem for Metal Powder Bed Fusion Additive Manufacturing Systems
February 2016 – July 2018

Under this 28-month research program completed in 2018, GE and Rensselaer formed a team that developed, demonstrated, and documented a fully open-architecture control system for SLM. The control system includes subsystems that were tested and integrated into a research SLM machine at Rensselaer's Center for Automation Technologies and Systems [6]. Demonstration parts were generated to show the full applicability of the open-source software, working on the open-architecture control system, with full control of laser scan paths to generate SLM parts.

Hardware Elements

The SLM process must be carried out in an inert atmosphere under controlled temperature and pressure. Further, SLM systems must contain safety interconnects, alarms and lighting as basic features. The fundamental hardware subsystems of a SLM machine (shown in Figure 7) are listed below:

1. Optical System consisting of laser, scanning system, and focusing system
2. Motion Control consisting of build platform motion control, recoater motion control, and powder hopper motion control
3. Environment Control consisting of gas flow control (O_2 / N_2 / Ar / Air) and water cooling
4. Safety System consisting of door lock and interconnect, alarm and Lights

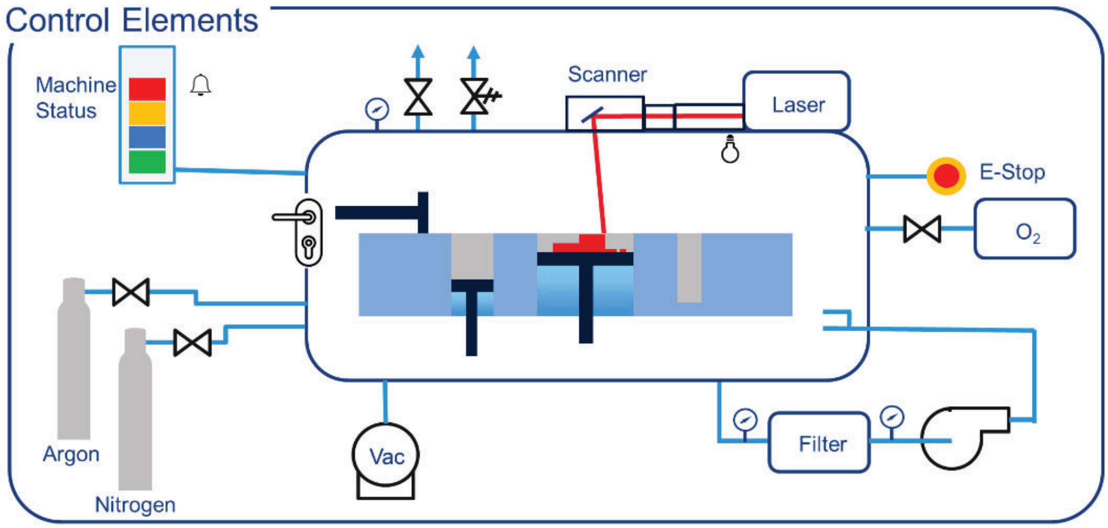

Figure 7. Schematic of a Typical SLM Machine.

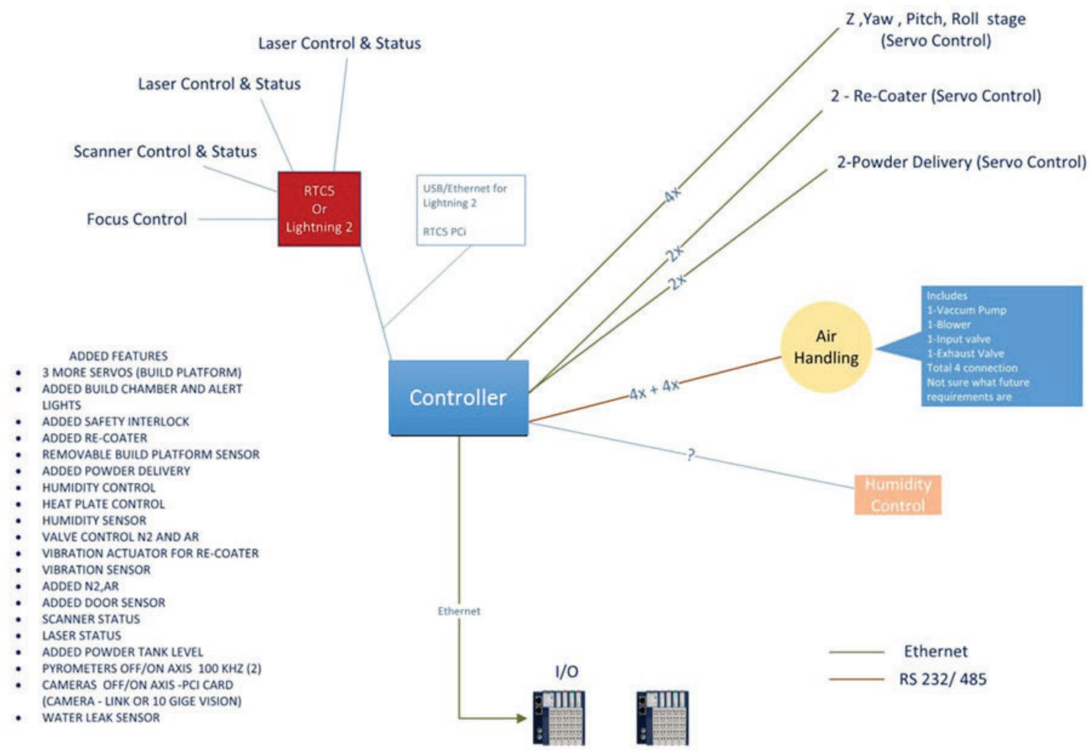

Figure 8. Control hardware architecture for SLM machine. Features for an advanced machine are listed on the lower left-hand side. Without these features, the figure illustrates a basic SLM machine. I/O refers to Digital/Analog Input/output.

A schematic of the control system along with the hardware interface of actuators and sensors is shown in Figure 8. At the heart of this hardware schematic is a controller, which can be a PC, an IPC (Industrial PC) or a programmable logic controller (PLC). The various hardware elements (actuators and sensors) of SLM machine are controlled via their respective interfaces. This approach lends itself to an open and adaptable hardware architecture by allowing for interfacing sensors and actuators from any OEM, if they support the provided interface. It should be noted, that most of the components feature an Ethernet or USB-based interface, which can be easily expanded using the features of the controller.

Open Machine Control Software

As a demonstration of the efficacy of the new protocols developed in the first program, the research team developed a tool to interpret the SCAN file and stream commands over a communication interface to run actual SLM machines per the protocol. The controller program, called *Machine Controller*, is based on the LabVIEW™ software programming environment from National Instruments. LabVIEW™ is a ubiquitous programming environment that greatly enhances interoperability, which will be key to enabling software exchange between researchers using differing physical hardware in the future. Members of the Lawrence Livermore National Lab team developed the Machine Controller and ran it on an SLM machined purchased from Aconity3D. The extended team demonstrated the use of this code on several commercial and proprietary machines during program. In addition, the Machine Controller can run a virtual machine, which is useful for visualizing scan paths, predicting build time, etc. Some specific features of the controller:

- It reads SCAN protocol files and generates commands specific to hardware
- It uses a plugin architecture supporting multiple commercial machines
- It has built-in design flexibility to allow future plugins for new machines
- It has start, pause and abort controls
- It displays the progress of the build, any errors, and hardware specific information that indicates the real-time quality of the build
- It runs unattended for periods exceeding
- It generates a log file
- It has controls for manual changes of machine parameters for test and setup
- It displays real-time process information received from the hardware
- It allows on-the-fly changes of parameters during the build process

The program can be launched from within LabVIEW™ as a "Virtual Interface," or a precompiled version can be run directly from Windows. Data from the input files flows to the machine through various interfaces, as illustrated in Figure 9. The modules that transfer data between the interfaces can be upgraded with new modules that support new machine actions, for instance diagnostics, without disturbing old modules. An example LabVIEW™ user interface is shown in Figure 10. A single human interface was developed with relatively easy transfer to other machines. Machine-specific code for a new machine component, or an entirely new machine, can be easily implemented by a user.

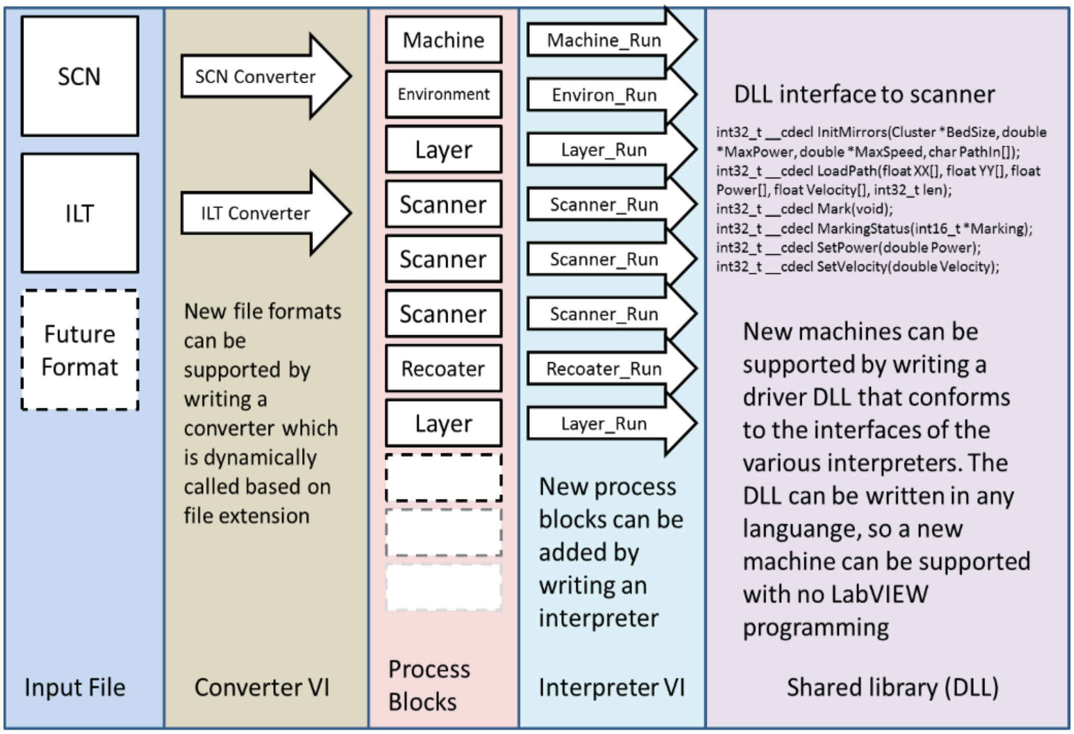

Figure 9. Data Flow in the Machine Controller.

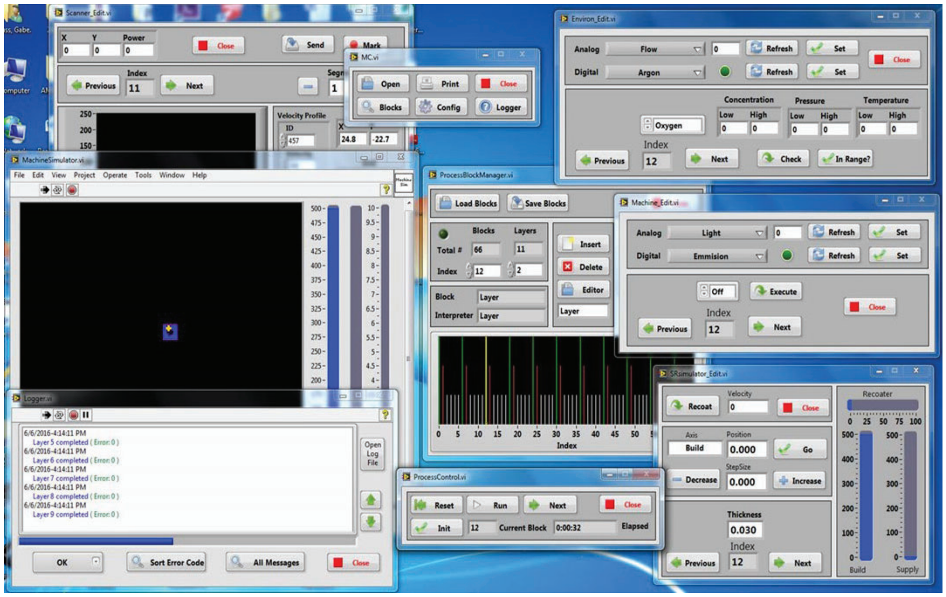

Figure 10. Example LabVIEW™ Virtual Interface. This custom control was developed at LLNL for microsecond pulse laser machining incorporating real-time sensing, FPGA control, and galvanometer-scanned laser beam motion.

Controller Demonstration

A research SLM system developed at Rensselaer is an exemplary platform for demonstrating the versatility of the control architecture. The system is a combination of repurposed and new components and is thought to be representative of what many institutions would be capable of developing to advance research in additive manufacturing. Application of the open controller architecture to this machine showcases its ability to integrate a variety of devices over many interfaces. Implementation of these interfaces will facilitate the controller's further development and application to other machines, much as the open source community is expected to do.

The major components of Rensselaer's research SLM machine are shown in Figure 11 and the assembled system is shown in Figure 12. The SLM process takes place inside a vacuum chamber that was repurposed from another lab. This allows replacement of the atmosphere, as the ambient air can be vacuumed out and back-filled with an inert gas, such as argon. The build plate and powder supply are moved on piston-style axes, while the recoater blade is driven along linear axes inside the chamber. A 400-watt fiber laser is used to provide energy to the process, which is focused by an F-theta lens and steered onto the powder bed by means of a galvanometric scanner. Sensors are used to monitor the machine and the process, which provide additional data to the controller for use in real-time and in post-processing and analysis. Redundant safety features, such as emergency stops and door interlocks, ensure the safety of the operator and bystanders during operation

The control cabinet has two main compartments (Figure 12). There are standard 19” rack mounts, attachment rails, and a shelf for placing equipment. The top component contains a shelf but can be modified to suit various needs. All the discrete power distribution and control components can be mounted on DIN rails that are accessible from the rear of the cabinet. An emergency stop button and machine status indicator lights are mounted on top of the cabinet. The lower compartment can be locked to prevent unauthorized access to the laser and other sensitive components.

A coin was chosen for the Rensselaer demonstration part. This coin has the GE Monogram on one side, the Rensselaer seal on the other side, and the America Makes seal on the edge. The scan file preparation (see Figure 13) followed the sequence described above for SCAN file generation, and a resulting part, a coin, also shown in the figure.

Typical process trials are shown in Figure 14. “Bead-on-Plate” trials, where, the system is exercised without metal powder are very common when debugging an SLM machine. The width of the weld pool can be measured easily from the top down with a microscope. Often the sample is cut, polished and placed under a microscope to measure the depth of the weld pool. Bead-on-plate trials are critically important for setting the scanner and laser synchronization delay parameters. Process parameter trials are extremely common. Here, samples are made at various laser speeds, powers, hatch spacings, etc., to determine an optimal set for a given material. This kind of parameter trial is exactly what the America Makes control system was designed to enable.

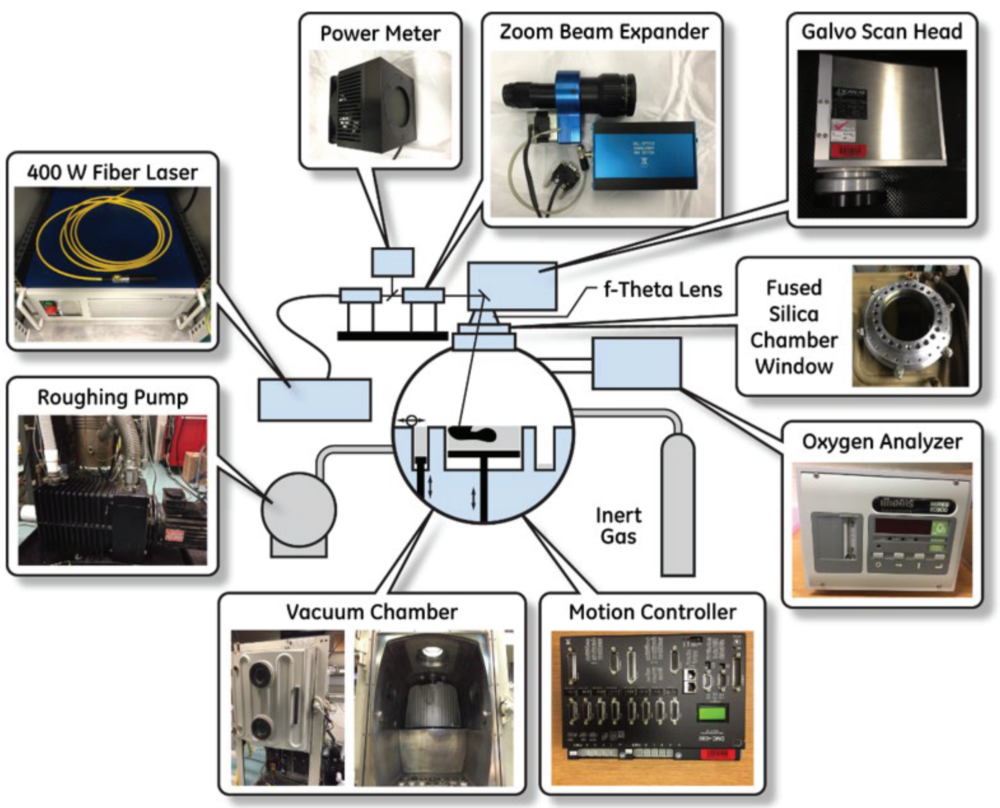

Figure 11. Major components of the Rensselaer SLM system.

Figure 12. Rensselaer's research SLM system. The mechanical components are housed in the repurposed vacuum vessel to the left. The controller is housed in the cabinet to the right.

Figure 13. Build File Preparation Sequence for Demonstration Coin. The final coin is shown on the lower right.

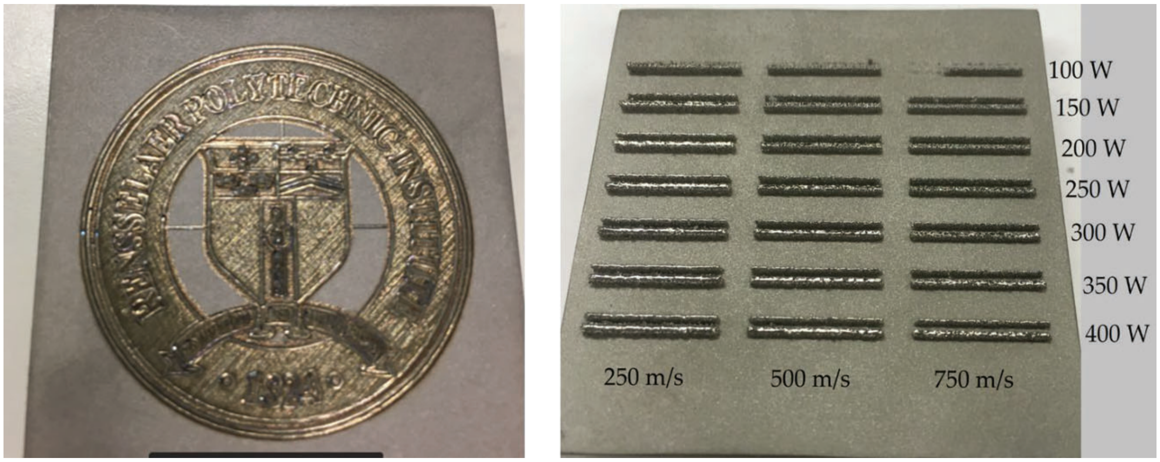

Figure 14. SLM Trials on the Rensselaer Machine. Bead on plate trials on the left, and process parameter trials on the right.

<u>Project #4: America Makes #3024</u>
Acceleration of Large Area Additive Manufacturing (ALSAM)
Dec. 2018 – March 2022

The fourth program, ongoing, is a culmination of the prior three. During this program, a commercially available Concept Laser M2 machine will be modified to allow operation using *either* the OEM-supplied scan path generation and controls software *or* the America Makes open-source controls system for multi-laser control. The resulting "M2-Open" system will be supplied to the Air Force Research Lab, including the source code for all software, by the end of 2020. The program overcomes research barriers by providing an open-architecture machine that runs open-source software. Researchers will have access to all the parameters and scan path software necessary to fully explore solution space. This capability will speed the maturity of additive manufacturing processes and facilitate widespread adoption.

Control of the M2-Open is illustrated in Figure 15. When operated in "OEM-mode," the system will use commercially available scan path generation software, and the standard OEM-supplied operating system known as *CL WRX*, with no changes. When operated in "open-mode," the system will require an input file conforming to the SCAN protocol, and the LabVIEW™ system controller will drive all functions of the machine including the laser and scanner. Penn State is participating in the program by refining the spectroscopy-based sensors and analytics from Program #2 for use on both lasers of the M2-Open.

A major contribution of this program will be to adapt and develop the SCAN protocol and the open-controller to support multiple lasers. The updated SCAN protocol is designed to enable customizable scan path generation routines, whether based on the open-source software described above or 3rd party software. In addition, the synchronized multi-laser control will allow for the development and evaluation of scan strategies optimized for various objectives, such as maximum throughput or tailored thermal profiles. Several options for multi-laser build which will be added enable either faster build rates [7] or more even control of heating along the build direction [8]. Designed experiments to address overhangs and surface roughness [9] [10] [11] will be enabled. In addition, segment-by-segment control of power, speed and focus will be enabled to allow delicate or frequently trouble-prone build areas to be fine-tuned [12] [5].

In addition to multi-laser control, the revised SCAN protocol will incorporate new features such as build “styles", which describe entire parameter sets covering power, speed, focus and such. This will enable the SCAN files to be greatly condensed, while still permitting optional segment-by-segment control of build parameters. The LAYER and SCAN file protocols will be modified to enable these new features.

Most of the machine operations are handled through secondary controls. For example, the scanners controller (SCANLAB *RTC5* units) are control cards for the laser scanners. These cards sit in the OEM-supplied industrial PC which serves as the supervisory controller and are software addressable from LabVIEW™. Standard motion of actuators, valves, gauges, and other items is handled by an OEM-supplied PLC which is software-addressable from the supervisory controller via LabVIEW™. To allow extensibility of the M2-Open to future possible enhancements, as set of digital and analog I/O cards, also software-addressable through LabVIEW™, will be supplied as *RSTi EP Slice* modules. A key concern is operator safety. The original M2 machine uses a separate PLC to monitor all safety-related aspects of the machine including laser operation, door status, oxygen level, etc. to prevent inadvertent dangerous operation by the operator. This Safety PLC will be left unmodified in the M2-Open. The LabVIEW™ controller can read from the Safety PLC but cannot write to it. This will ensure that all factory-installed safety features remain uncompromised when the system is operated in either mode.

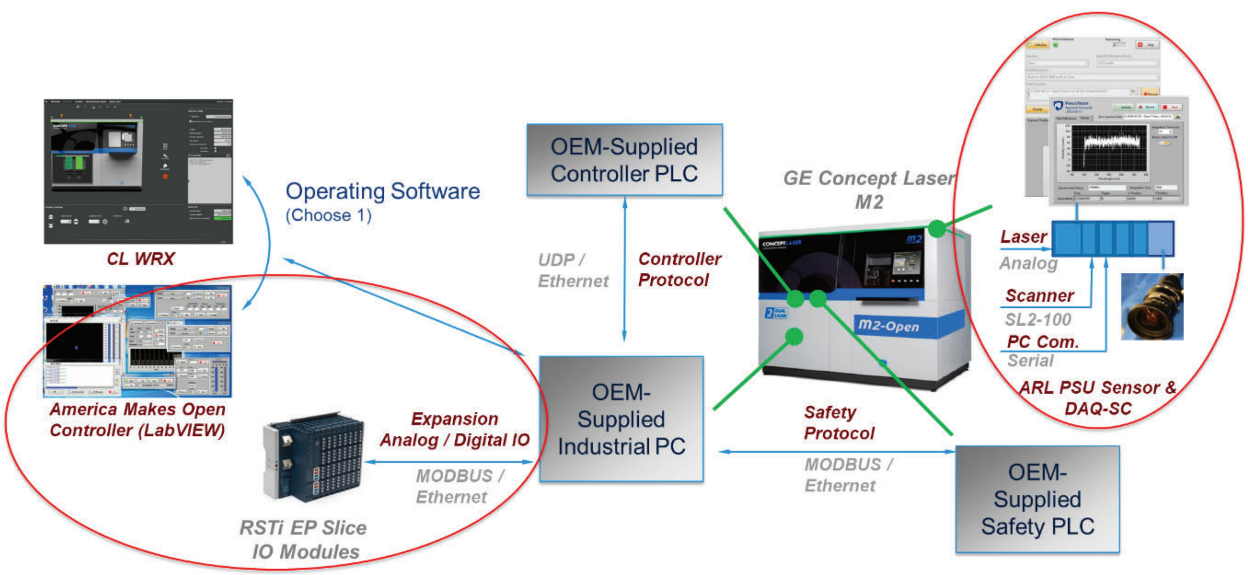

Figure 15. Concept Laser M2-Open. Items circled in red indicate the modifications to the controls system to implemented during the ALSAM project.

Conclusions

The research community, which includes academia, national laboratories, industrial research laboratories, and independent researchers have long voiced frustration with "closed" OEM manufacturing equipment that hampers their ability to perform independent research beyond the design intent of the original equipment manufacturer. This is true in many research fields, though the series of research programs discussed in this paper addresses concerns restricted to the SLM field. The programs discussed here have generated a set of software and hardware that allows complete access to SLM machines through an "open" approach. This open approach includes source code file generation and machine control, extensible hardware for easy system modification, and advanced sensors for monitoring the process with the goal of improving the SLM process.

Acknowledgements

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At Rensselaer, special thanks to Dr. Steven Rock and his students for their work on implementing the control system on the RPI DMLM machine.

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At America Makes, special thanks to John Wilczynski, Scott Crynock, and Rick Fowler for their ongoing enthusiasm and support.

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