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A REAL-TIME COMMUNICATION ARCHITECTURE FOR METAL POWDER BED FUSION ADDITIVE MANUFACTURING

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Abstract

Recent advancements in the field of additive manufacturing continue to push its application deeper into commercial use. However, concerns persist regarding the consistency of part quality, methodologies for quality assurance, and cyber-physical system security. These concerns are exacerbated by the closed-system architecture implemented by most commercial powder bed fusion additive manufacturing (PBFAM) machine manufacturers. Though implementation of device and process monitoring equipment is often suggested to address these concerns, deployment is hampered by the inability to extract real-time information from closed systems during the build process, including scanner position, laser power, sensor data, etc. Here, a framework for an open and transparent communication protocol for PBFAM systems is developed and implemented on a 3DSystems ProX-200 machine. Real-time measurement of build process parameters and synchronization with an optical emission sensor is demonstrated. The utility of the protocol and real-time sensing for PBFAM are discussed.

Keywords: Monitoring, Powder bed fusion, Additive manufacturing

Introduction

Additive manufacturing (AM) is a method of part production wherein a component is built from the layer-by-layer deposition of material. Early forms of AM manufacturing have existed for decades, but these early forms of AM were limited to polymers and composites [1]. As a result of the limited available materials employed in early AM methods, its application was typically limited to prototypes, molds, and models. Recent advancements have led to a more widespread application of AM, especially in the field of manufacturing functional metal components [2]. One of the methods of AM that is industrially relevant is powder bed fusion (PBF). PBF is able to produce net shape parts by utilizing thin (~20-80 μm) layers and a smaller laser spot size (50-100 μm), than is typical in directed energy deposition additive manufacturing techniques [2]. In addition, powder bed fusion additive manufacturing (PBFAM) excels in its ability to create complex internal geometries previously unfeasible for manufacturing with conventional techniques.

While PBFAM does allow production of previously untenable geometries, complexity in part manufacture and high cost for metal powder currently hamper its implementation in industry. As with many new manufacturing technologies, there is a serious need for the development of techniques to qualify, certify and non-destructively evaluate AM components [3].

In addition to the complexity of the AM build process, there are additional factors that complicate both the certification and qualification of PBF built components. Typical commercial PBF machines are essentially black-box systems, which limit the end user's ability to monitor the build process, limit direct control of the manufacturing process, and allow the end user to manipulate only a subset of process settings. Restricted access to, and control of, process parameters (e.g. laser scan strategy and timing) inhibit the ability to conduct well-controlled experiments and thus to develop and validate theoretical and empirical models. Additionally, most commercial PBF systems provide no means for third-party sensor integration, hampering the development and implementation of in situ quality assessment tools and build failure mitigation techniques.

Currently, PBF end-users and researchers are left with insufficient tools to conduct controlled experiments or to develop generalizable conclusions across multiple machines and part builds. To enable controlled experimentation, assessment of process transferability between machines and builds, and development of in-process quality assessment tools, researchers and end-users must have two capabilities: (i) access to input process variables, including the build plan, and (ii) ability to measure and record process parameters, in real-time, during the course of a build. This work focuses on the development of a machine-to-machine communication method to transmit measured process information. Additionally, the integration and synchronization of the developed communication protocol with a sensor-based process monitoring system is detailed to demonstrate the feasibility and utility of such a system. Once the requirements and technology of the open-protocol communication system have been presented, verification and validation is completed to demonstrate its accuracy and reliability. Finally, the system is applied to full PBFAM build to highlight the utility of such a system for process monitoring and in PBFAM research. The primary goal of this work is to demonstrate the utility of an open-protocol measurement system for use in not only research, but industrial applications.

Dataflow in Powder Bed Fusion

Additive manufacturing can be categorized into three phases: design, planning, and production, schematically shown in Figure 1 [4]. The design phase is the most transparent of the three phases wherein a CAD package, such as Solidworks or AutoCAD, is used to design a part model. Next, the model is exported in an open-source format (e.g., *.stl, *.stp *.iges), to be loaded into another software package, where part orientation is determined, support structures are generated, and part slicing occurs. From this point forward, details within processing files become increasingly opaque.

In the Planning phase, process parameters are applied, including laser power, scan speed, hatch spacing, the laser scan paths for each layer, etc. Depending on the particular commercial machine, only a subset of process parameters may be accessible. Additionally, geometry specific process parameters may be applied at this point including specific process parameter sets for: contours, outlines, upskin, downskin regions. For some PBF machines, build plan information can be stored so that it can be reused for repeat builds regardless of location on the build plate while in other cases the build plan is not stored.

The final step of the PBF AM build process is the production phase, during which the designed component is constructed. Monitoring of the build process at this point is limited to manufacturer-provided and user-designed sensors. Manufacturer- provided sensors are typically limited to system monitoring (e.g., build time, current layer, build time till completion), build interrupts (e.g., machine faults, errors in production, jammed components), and environment sensors (e.g., oxygen content, chamber temperature). These sensors may be useful to end users, but access to other measurements during the build process is limited, and automatic storage of these measurements is constrained to regular time or layer intervals. Machine manufacturers have announced development of additional sensors for monitoring of the melt-pool and laser [5, 6], but their algorithms are closed, and little information regarding their utility has been published. Extensive work has been completed regarding the addition of sensing equipment to PBF systems [7], but the synchronization and implementation of such tools on commercial systems is inhibited by the closed-type architecture of PBF machines.

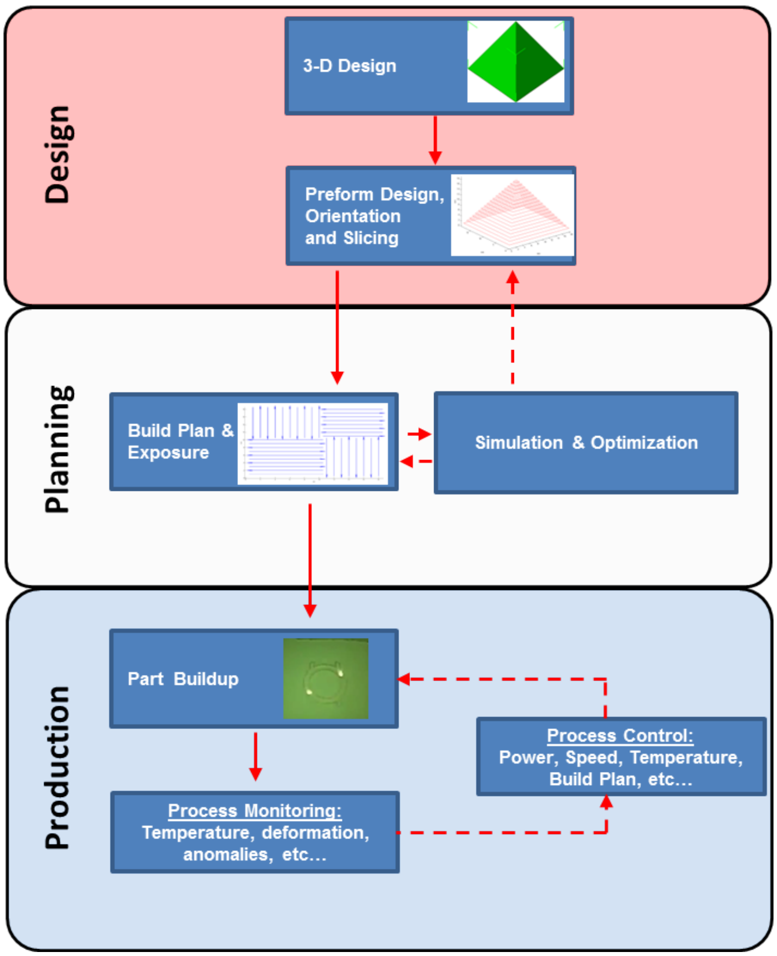

Figure 1. The three phases of the AM process along with potential additions (dashed-arrows) enabled by an open protocol

To address the hindrances to research from the closed-type architecture of PBF systems, an open-protocol communication system was developed. The open-protocol system comprises two components: a system monitoring toolset and a communication platform to transmit data. As developed, the system provides information regarding build plan, laser scan paths, laser trigger events, and data from other built-in (or user-added) sensors throughout the build process. The system monitoring toolset can be implemented in conjunction with user-designed sensing equipment to provide synchronized measurements of the build process. Using the open-protocol system, external measurements can now be presented alongside information regarding the current state of the PBF system including: laser on/off status, laser scanner location, current layer, O_2 content and laser power.

Measurement Requirements for Powder Bed Fusion

To provide appropriate resolution on measurements for PBFAM systems, consideration of the time scale for each signal is required. For example, PBFAM is typically performed with rapid laser scan rates that can exceed 2.5 m/s when scanning and up to 5 m/s when traversing to a new location. In contrast, 0_2 content in the chamber is unlikely to change rapidly within one second. For a typical scan speed (on the order of 1-5 m/s), it is necessary to provide measurements at a frequency on the order of 100 kHz to ensure consecutive measurement are spaced by less than one beam diameter (~75 µm). For other signals, such as oxygen content, chamber temperature, and layer number, measurement frequency need not exceed 1-2 Hz. Given the large disparity in timescales, the open-protocol measurement system is separated into two types of data capture and transmission, (i) high-speed (e.g. laser scanner position, laser trigger), and (ii) low-speed (e.g. machine faults, oxygen content, chamber temperature).

Development of a Hybrid Communication Protocol for Powder Bed Fusion

To address both the high-speed and low-speed measurements, a hybrid 2-level communication platform is developed that uses the XY2-100 high-speed digital encoding to transmit high-speed signals and the MTConnect XML format [8] for the transmission of low-speed signals. A schematic system diagram is shown in Figure 2.

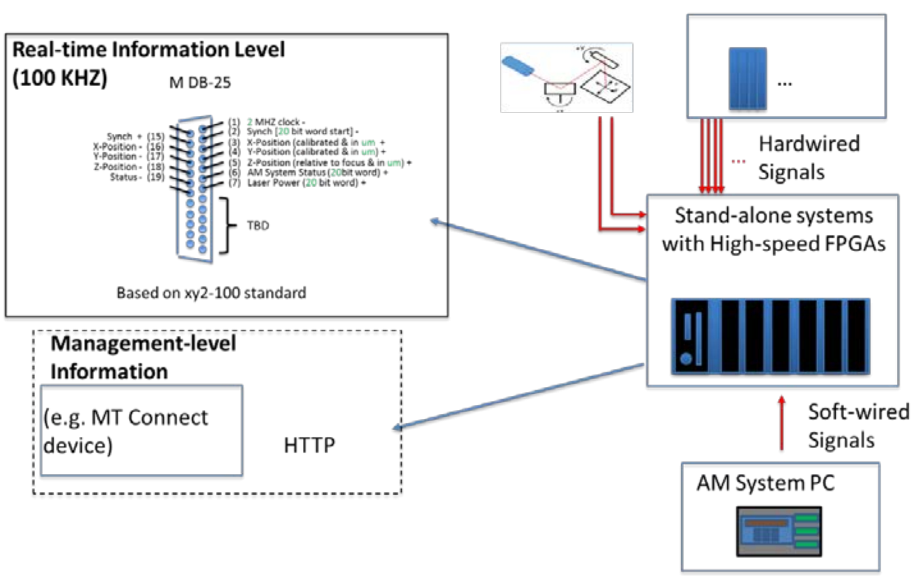

Figure 2. The developed two-level protocol for transmission of high-speed and low-speed PBF data

The XY2-100 is a commonly used industrial protocol designed for high-speed laser scanners [9]. Using this protocol, separate signals are sent over a 25P-D connector using serial transmission. . Data packets consist of 20 bit words that are made up of a 1 bit trigger signal, 3 bit control signal and 16 bit word. A clock and trigger signals are transmitted over separate lines. An illustration of the protocol is shown in Figure 3. Digital signals allow for transmission over long lines without loss of accuracy. However, there is some loss of accuracy in converting any measured analog signals to digital (i.e. when converting signals from an analog scanner). Table 1 shows the loss of accuracy of each high-speed signal measured as part of this protocol, highlighting the size of the discrete steps in the digital signal. Due to the high accuracy of the 16 bit data storage for each signal, error in the analog to digital conversion is eclipsed by measured signal noise and error. For the XY2-100 protocol, the 20 bits are sent with a timing of 500 nanoseconds between each bit, resulting in signal measurement frequency of 100 kHz.

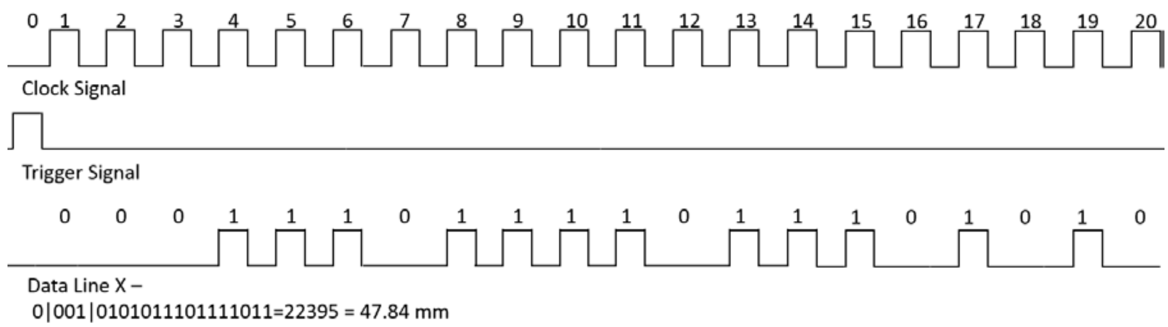

Figure 3: Example XY2-100 based protocol 20 bit envelope for the clock, trigger and laser scanner X position.

Table 1: Definition of measurement range and digital step size for each of the high-speed measurement signals

	Measurement Range	**Digital step size (Δ)**
Laser Power	0 - 100%	0.0015%
Laser Trigger	On/Off	NA (BOOLEAN)
Laser Set Power	0 - 100%	0.0015%
Defocusing Position	-10 – 10 mm	0.0003 mm
Laser Scanner Position X	0 - 140	0.0021 mm
Laser Scanner Position Y	0 - 140	0.0021 mm

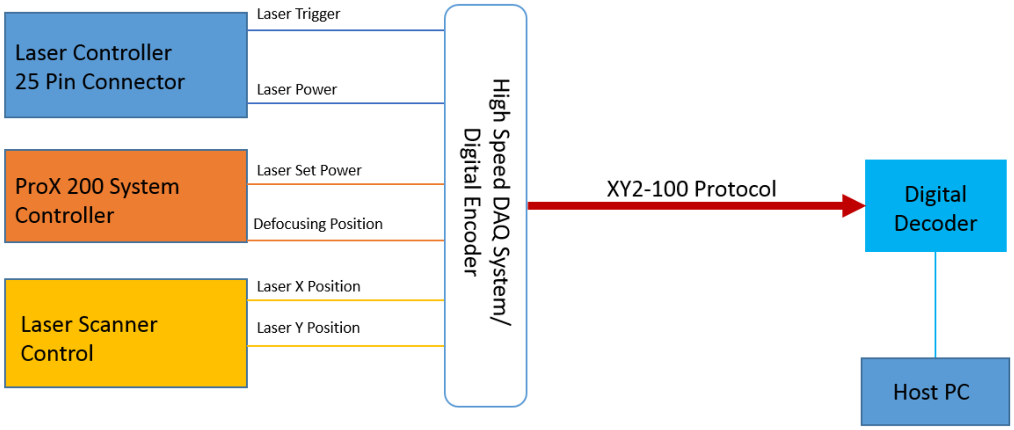

Figure 4: Schematic of the XY2-100 protocol implementation for the transmission of high-speed signals for the 3D Systems ProX200 PBF machine

The MTConnect protocol is chosen as a framework to transmit the low-speed signals. The MTConnect protocol was designed for the remote monitoring of computer controlled manufacturing equipment such and CNC mills and lathes [8]. MTConnect also provides the user with the ability to remotely monitor multiple installations of manufacturing equipment. The developed low-speed protocol mimics the MTConnect protocol defines a structure, which specifies a device ID which contains series of components. Components can contain further sub-components or contain the pertinent information for the user. A sample schematic for the low-speed protocol organizational structure used in this work is shown in Figure 5.

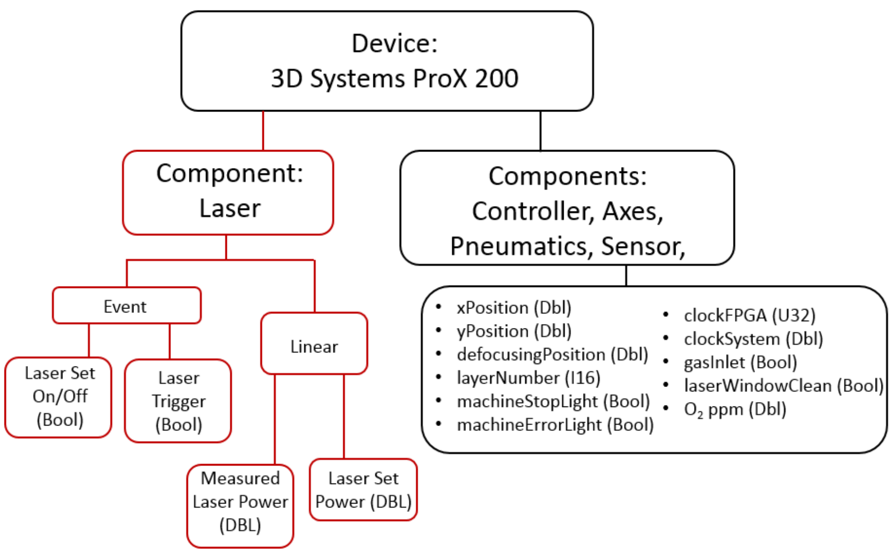

Figure 5: Schematic demonstrating the tiered structure of the low-speed measurement protocol. An example component substructure is shown on the left (red), additional components and measured signals are shown on the right (black).

Results and Discussion

Verification and Validation

Verification and validation of the high-speed protocol first required testing the encoding and decoding analog-to-digital values. For the verification of the high-speed protocol, constant values were encoded in to the digital protocol and then decoded. Measured signals were found to have been decoded properly with the only error resulting from the conversion from analog to digital, 0.0002% of the set measurement range. For validation of the entire system, a single layer scan comprised of a circle and a cross hatch pattern was designed. A schematic of the as designed laser scan path for the validation case is shown in Figure 6. The validation case is a single layer with process parameters shown in Table 2. Build files were generated using 3D Systems Phenix Manufacturing software. The software outputs proprietary build plan files which were then converted, with permission, using in-house developed software.

Table 2. Description of experimental test cases

POWER (W)	210
MARK SPEED (MM/S)	2500
JUMP SPEED (MM/S)	5000

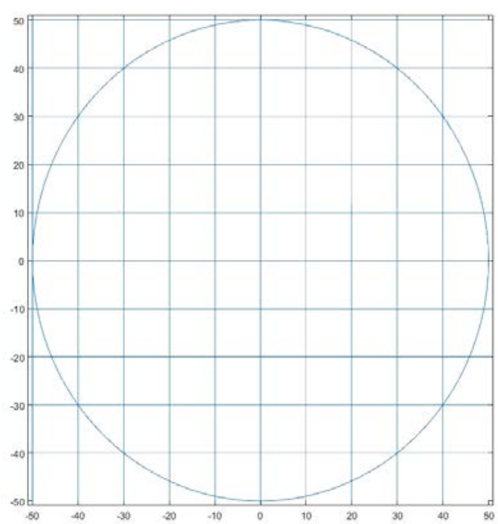

Figure 6: Schematic of validation cases for the open protocol measurement system

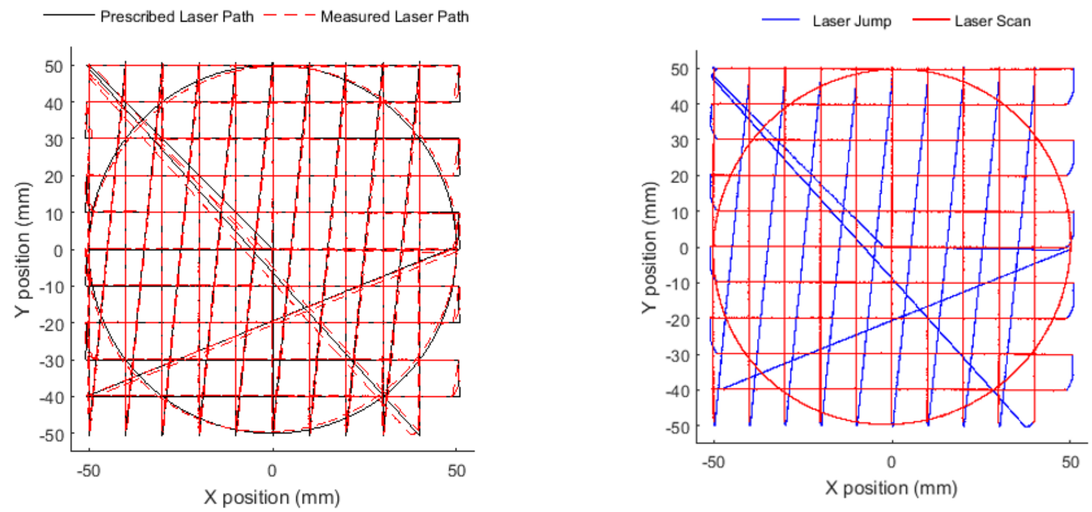

Figure 7: Comparison between the prescribed and measured laser scan paths shown on the left. Denotation of both laser jump (laser off) and laser scan (laser on) shown on the right.

Figure 7 shows the measured build plan identifying laser jump (blue) and scan regions (red) of the laser tool path. The greatest deviation from the prescribed laser path occurs during laser jumps, so it does not affect the actual build, but deviations from the prescribed path demonstrate why the open-protocol monitoring system may be useful when limited control of the build process is available. For further validation, comparisons between the prescribed and measured laser scan paths for the X and Y laser positions versus time are shown in Figure 8. Overall, measured magnitude and positional information matches well.

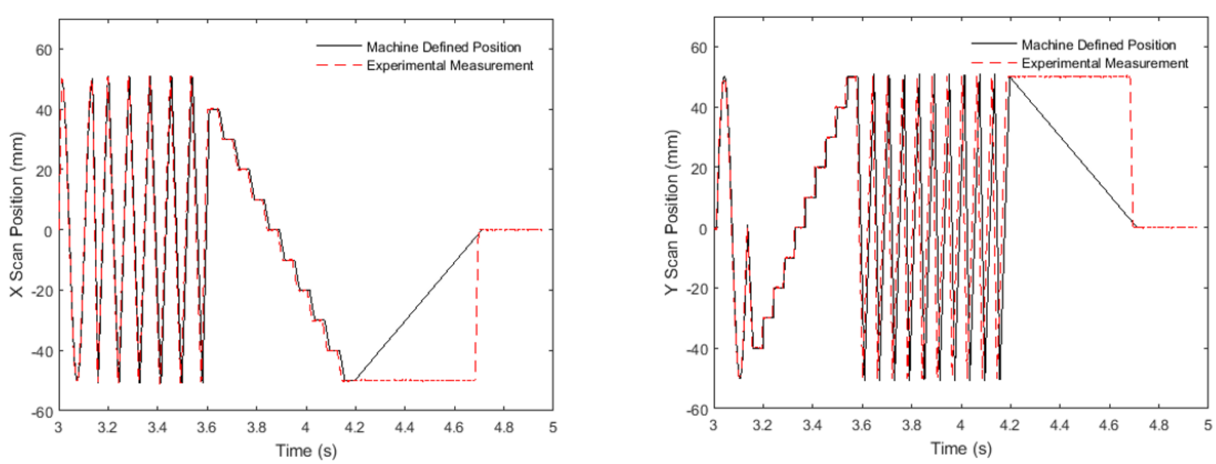

Figure 8: Measured laser scan path for validation case: Laser scan position X versus time for both measured and machine defined positions (left), Laser scan position Y versus time for both measured and machine defined positions (right)

Case Study

Once validated, the open-protocol hybrid system was implemented in conjunction with an Ocean Optics HR2000-ES spectrometer mounted at a fixed location within the build chamber to provide real-time build parameters alongside measurements of optical emissions. The experimental build presented in this section is intended to test the effects of the defocusing parameter for the 3D systems ProX200 machine. The defocusing parameter allows for minor adjustments to the Z position (direction of build height) during a layer. The focus of this analysis is the series of squares placed diagonally across the build plate, shown in Figure 9. The blocks are designed to have dimensions of 15 mm x 15 mm x 10 mm. Dimensions marked on the build layout, shown in Figure 10, represent the difference from the default 0 defocusing position (default build location) position for each set of squares. Squares that are side-by-side (matching colors) are built at the same height with the dark colors representing solid squares and the pastel colors representing hollow squares.

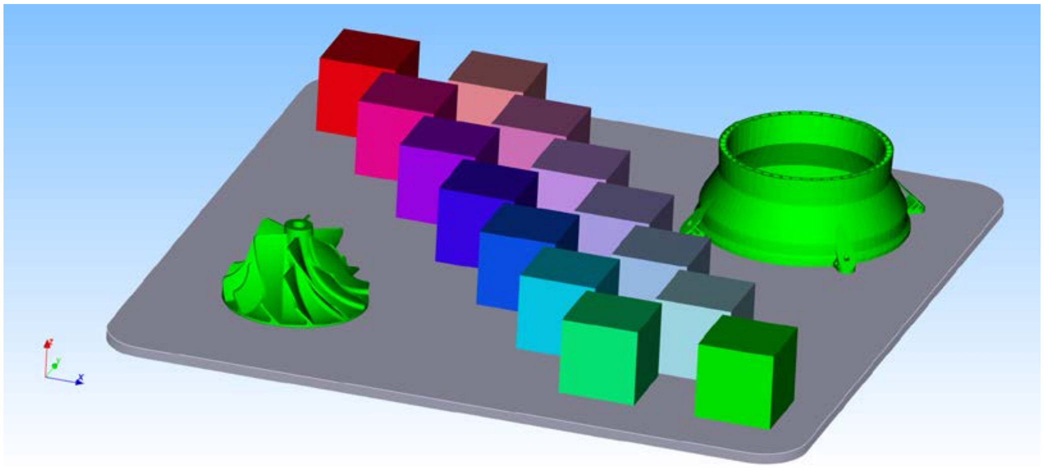

Figure 9: Isometric view of experimental build layout

Using the high-speed portion of the open-protocol, the laser scan path was captured and is shown in Figure 10. Different defocusing positions are measured using the high-speed protocol and are separated in Figure 10 using different colors for different heights and black for the laser jump vectors. The difference between the solid and outlined squares is more obvious on the right side of Figure 10, where solid squares are on the left and squares that are outlines are on the right.

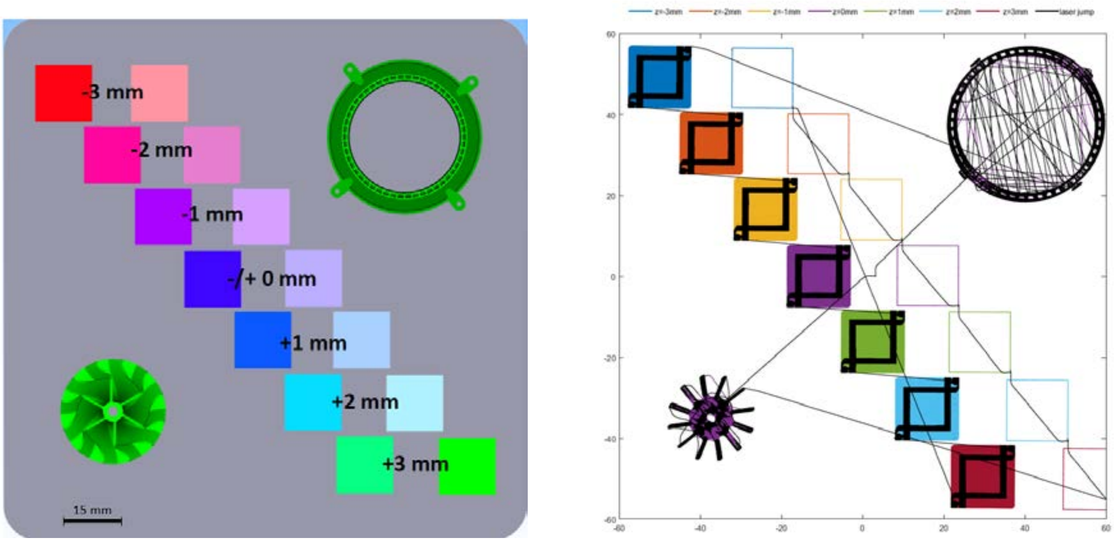

Figure 10: Build layout, XY plane, for experiment with denotations of +/- represent displacement from the default laser scan position (left) Build plan as measured by the high-speed measurement system with denotations for different build heights and laser jump vectors (right).

Using the spectrometer in conjunction with the high-speed protocol, measurements can be separated into different groups based on build location and defocusing position. By identifying the defocusing position, analyses can be performed to identify effects on the emission spectra from the defocusing of laser. During the experiment the spectrometer was placed off-axis and signals were normalized for direct comparison. Data for the -3 mm, -2 mm and +3 mm off-focal positions had a high signal-to-noise ratio and are not shown.

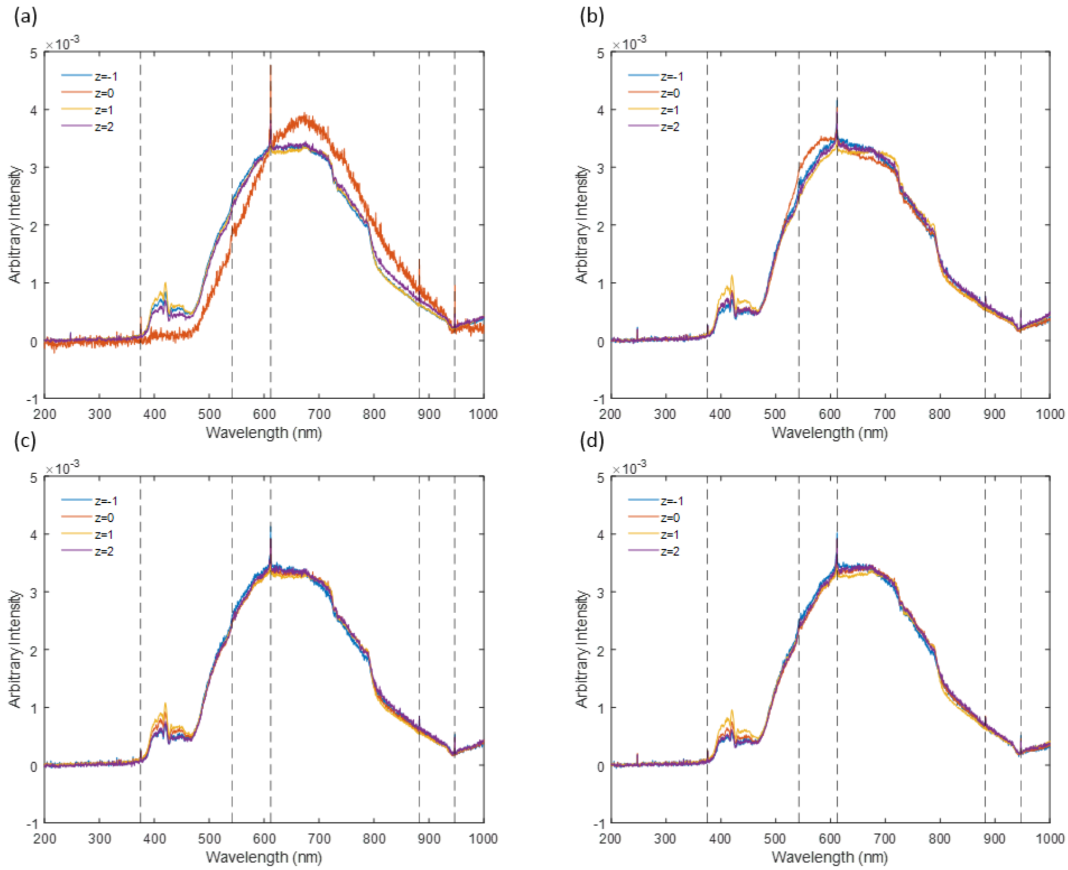

Figure 11: Spectra emissions for differing defocusing positions for: (a) Layer 0, (b) Layer 1, (c) Layer 2, and (d) Layer 3.

It is clear from Figure 11 and Figure 12 that emission show a relationship between the relative intensity of near-UV to visible emission. The emission not only affected by defocusing offset, the layer number may also have an effect on the emission spectra as well. In particular, comparing the spectra of zero offset on layer zero and layer one seems to demonstrate the largest discrepancy, shown in Figure 12-(b). Future work includes further analysis of the emission spectra, tracking specifically what species show greatest variations, how process conditions (e.g. layer or focal position) may affect the these emissions, and the physical underpinning of spectral variations. Additionally, determination of the relationship between spectral emissions and build quality, as has been done for directed energy deposition [10], is planned.

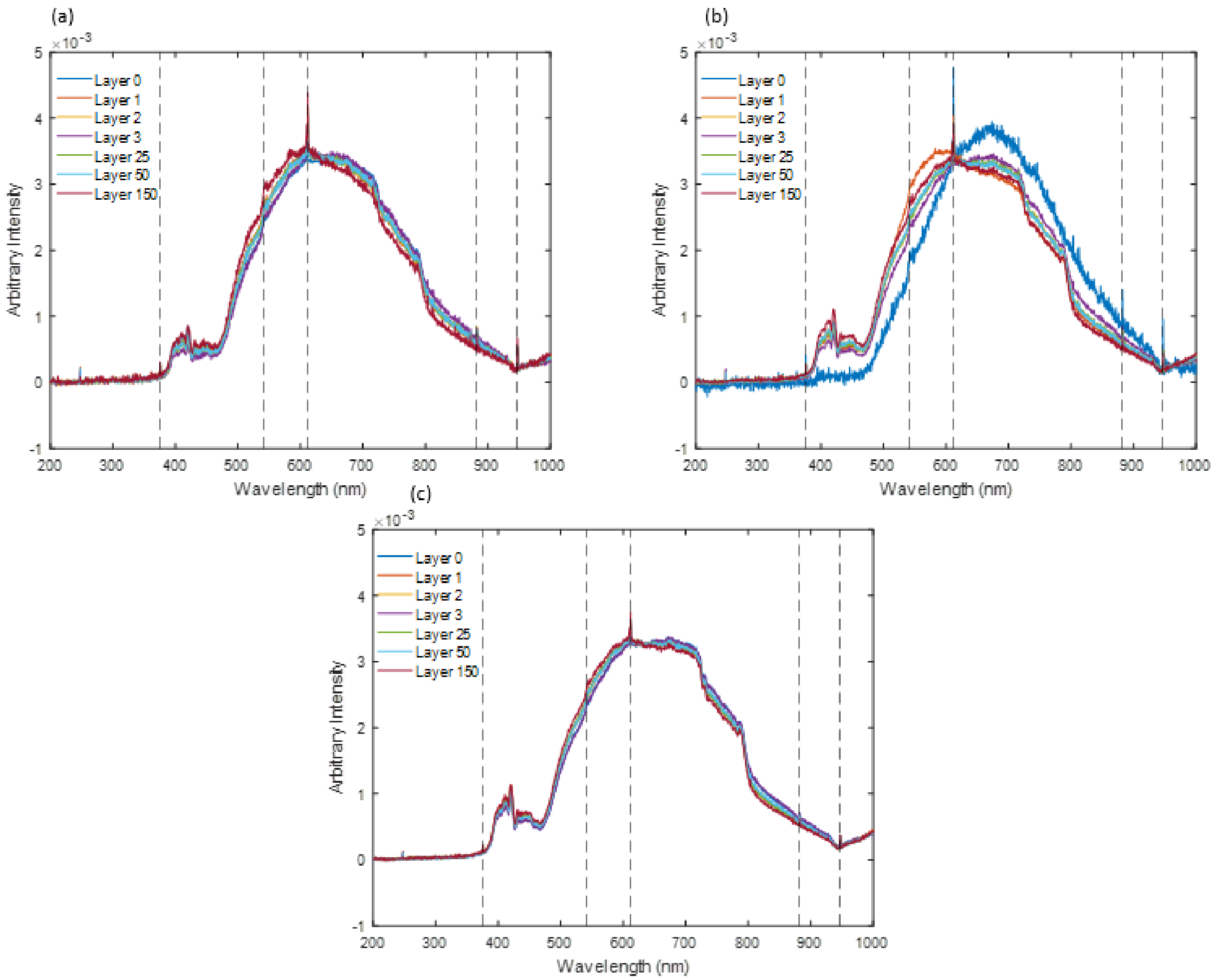

Figure 12: Comparison of spectra emissions for different layers for specific defocusing offsets: (a) Z= -1 mm, (b) Z= 0 mm, (c) Z= +1 mm

Conclusion

The closed system architecture of current PBF systems hinders both experimental study of the process, as well as its implementation in industry. In order to produce reliable PBFAM components, sufficient process monitoring capabilities must be available to ensure reliability in manufacturing. The hybrid open-protocol system demonstrated herein identifies the utility of an in situ process monitoring system for PBF AM. The developments made on the open-protocol measurements system were enabled through a collaboration with 3DSystems, the developer of the ProX200 machine. Future advancements to this system should include feedback control based on in situ system measurements and improved system monitoring of additional variables. The system demonstrated herein represents the first open-protocol measurement system for PBFAM, capturing both build parameters as well as synchronous external sensor measurements. Through the future analysis of measurements mad e using this system we hope to incentivize of this system we hope demonstrate the utility of such a system.

In addition to increasing confidence in industrial implementation of PBF by enabling direct access to process parameters by end-users and 3rd-party sensor developers, the open-protocol system developed herein demonstrates a novel utility for further research of PBF. Using the open-protocol system, laser position, laser status, build platform position and scanner position can all be provided at 100 kHz and synchronized with external measurement equipment allowing for increased precision in the analysis of the PBF build process. To demonstrate this, emission spectra were isolated part by part allowing for measurements to be collected for specific defocusing positions. By isolating spectrometer measurements by defocusing position, we were able to provide comparisons of emission spectra for different focal positions. Future work includes further analysis of the emission spectra to identify what effects the defocusing position may have on emissions during the build process, and to correlate this to build quality. Wide-spread implementation and adoption of this or similar, open communication paradigms for PBF will enable researches to advance the science of additive manufacturing, end-users to integrate third-party quality monitoring systems, and enable the development of manufacturer and third-party add-on tools.

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