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META-DATA FOR IN-SITU MONITORING OF LASER POWDER BED FUSION PROCESSES

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ABSTRACT

Increasingly, a wide range of in-situ sensors are being instrumented on additive manufacturing (AM) machines. These sensors collect a variety of data that is used to monitor process performance and part quality. The amount, type, and speed of the collected data are unprecedented. Consequently, several data-related, standards issues are impeding the use of both data analytics and tool integration. Those issues include registration, curation, organization, storage, and management. This paper focuses on registration. It proposes the use of meta-data as a foundation for new interface and exchange standards. Standards that will facilitate the use of several types of in-situ sensors that monitor laser powder bed fusion (L-PBF) processes. The paper also includes an example data model that captures the properties and relationships among those meta-data. The data elements in that model provide industrial users with the capabilities and formats to capture, exchange, and share L-PBF process data.

1. INTRODUCTION

The value of parts fabricated using additive manufacturing (AM) continues to grow. Current market projections estimate that by 2025 that value will be approximately \$7.65B in North America and \$21.5B worldwide [7]. However, there are still hurdles impeding the widespread acceptance of AM as a reliable and cost-effective production technology. These hurdles are due primarily to the high variability in the quality of AM-produced parts. Quality problems include undesired pores or cracks, dimensional inaccuracies, poor surface finish, and inhomogeneous mechanical properties.

Factors causing quality problems include variable material properties, improper process settings, and the dynamic build environment. Many ongoing research efforts are being conducted to understand the impacts of those factors both individually and collectively. These efforts typically focus on two tasks: 1) identifying the material-process-structure-property relationships and 2) using those relationships to improve both process control and part quality. Both tasks rely on a variety of in-situ monitoring sensors for their success. That variety includes imaging sensors, thermal sensors, video cameras, acoustic sensors, ultrasonic sensors, and vibration sensors. The data coming from those sensors are characterized by volume, variety, velocity, and veracity [13]. A systematic organization of that data is needed for both real-time monitoring and off-line design and planning. The benefits of registering data are 1) accessing validated data with known time, locations, and approvals, 2) data alignment and fusion, 3) detecting defects traceable to process, material, equipment parameters, and 4) validating AM process models using validated data.

This paper describes our efforts implementing one important aspect of meta-data for in-situ monitoring of laser powder bed fusion processes. Meta-data are data types that describe how data were collected, including scanning strategy, sensor types, sensor configuration, calibration, and setup parameters. Meta-data is for AM data registration. AM data registration involves 1) a data curation process by which the context of the data (i.e., meta-data) is captured as well as 2) a unique data object identifier. This identifier can be used for generation of a persistent object identifier from a trusted registration authority. Registration is necessary to compare and fuse multi-sensor, in-situ monitoring data.

Most of this paper focuses on data collected by four types of sensors during a powder bed fusion (PBF) process. The four sensor types are imaging, thermometry, acoustic emission, and acceleration. Although profilometry is another possible sensor type, it still being studied. It will be added to our categorization when more detailed studies are available. Details in meta-data are in data elements in this paper.

Our proposed data elements approach is to link the in-situ data with product, process, and resource information. This paper also provides the XML representations of several data elements related to the raw monitoring data we collected by the sensors.

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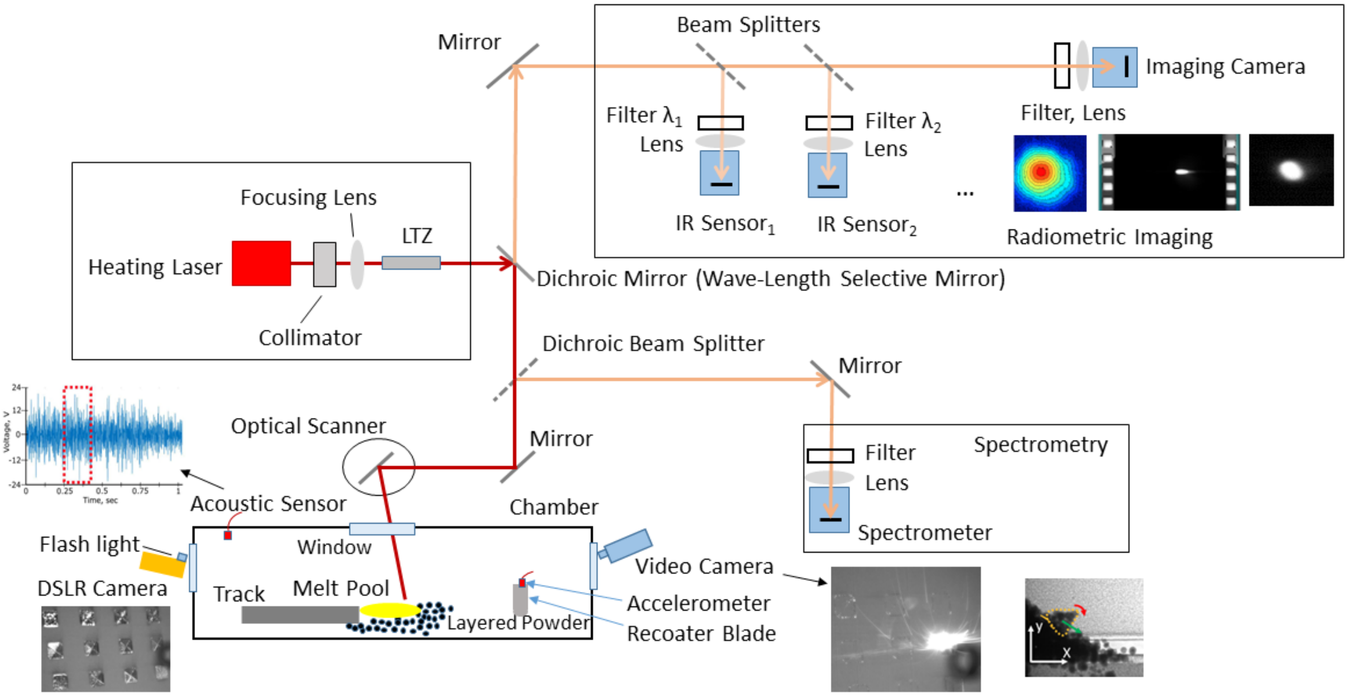

Figure 1 Schematic diagram of sensors for in-situ monitoring of L-PBF

These representations are key to 1) implementing and replicating our approach for data registration and 2) enabling the future standards on common data formats and data exchange.

The paper has six sections. Section 2 reviews related publications in in-situ monitoring. Section 3 describes data elements for in-situ process monitoring. Section 4 prescribes a data model based on the identified data elements to enable implementations. Section 5 provides an example and discuss the usage of the data model. Section 6 concludes the paper.

2. REVIEW OF IN-SITU MEASUREMENT RESEARCH

To develop a data model for data registration, we need to understand the current use of sensors for in-situ monitoring. The section provides a review of sensors, data fusion, sensor categorization, and research needs. Recently, researchers have been integrating L-PBF sensors and developing techniques to evaluate the data they provide.

2.1 Sensors for In-situ Process Monitoring

In-situ process monitoring, which is necessary for real-time control, is enabled by sensors and data analytics. In this paper, we focus on only four types of in-situ monitoring sensors: co-axial imagers, off-axis imagers, acoustic sensors, and accelerometers (see Figure 1). Co-axial sensors, which share the same axis as the laser beam, are optical sensors that can generate images of temperatures or melt-pool geometries. For the temperature measurement, a multi-wavelength pyrometer can provide more accurate temperature data. For the melt-pool geometry measurement, 2-D images are used to measure melt-pool dimensions. Moreover, a spectrometer can be used to analyze energy peaks and spatters in the melting process [2].

Off-axis sensors include Digital Single Lens Reflex (DSLR) cameras, acoustic sensors, and accelerometers. A DSLR camera can take images of the powder bed each time it is triggered. A combination of flashlights from different angles and illuminations can detect anomalies on each scanned layer [11]. A high-speed camera can record the laser-scanning process including melting, solidifying, and tracking. Acoustic sensors, which generate sound signatures in the frequency domain, can detect anomalies in the scanning process [15].

These different sensor types have different sensor capabilities. Lane et al. [9] characterized sensor capabilities using three metrics: spatial resolution, temporal resolution, and sensitivity. The authors' goal was to evaluate the capabilities of various sensors to determine how well they can detect defects and irregularities in AM processes. Yadroitsev et al. [19] described sensors used in the selective laser-melting process. The authors listed sensors to measure powder-material properties, process parameters, and their relationships to the instabilities in the process that can lead to defects. The same authors also characterized various defects on tracks and part surfaces.

Smith et al. [16] showed acoustic parameters used in spatially resolved, acoustic spectroscopy to detect near-surface defects such as pores, cracks, and voids. Depond et al. [3] developed a low-coherent, laser-scanning interferometry sensor and showed sensor parameters to measure powder layer-surface roughness. Bertoli et al. [1] estimated cooling rates using high-framerate video and multi-physics simulations. They reported consistency between the solidification shown in picture frames and the simulations. Heigel and Lane [8] measured melt-pool temperatures and dimensional characteristics using an infrared camera outside the chamber with temperature calibration. Hooper [9] demonstrated in-line measurements of melt-pool temperature and cooling rates using a coaxial laser and imaging design.

Fisher et al. [5] also used a coaxial sensor for monitoring melt pools. In the paper, the authors identified metrics for using the data from that sensor – including the cross-sectional area, the temperature changes, and the plate temperature. In addition to sensors for characterizing melt-pool temperatures, there are sensors for measuring individual parameters, such as melt-pool sizes. Tan et al. [17] listed specific material and process parameters to model the melting process. They also proposed a temperature-measuring technique using a pyrometer.

There is the fifth type of sensors: chamber environment sensors, e.g., inert gas flow meter, inert gas pressure sensor, and CO$_2$ concentration sensor. They are located outside the view shown in Figure 1 and not used to measure the melt pool or scanned layers.

2.2 Sensor Fusion In-Process Monitoring Data

As a new attempt at monitoring AM fabrication processes, researchers are now using several different sensor technologies simultaneously and fusing the resulting data. Foster et al. [6] used staring-video cameras and coaxial cameras to collect data for monitoring melt-pool characteristics. Additionally, in that same paper, the authors surveyed existing, ultrasonic, in-process sensors that can be used to detect pores and delamination. In a survey focused on direct energy-deposition processes, Reutzel et al. [14] described measurements of melt-pool geometry and temperature. The authors made geometric measurements based on images taken by a single-color camera in the infrared (IR) range. Temperature measurements, however, were based on images taken from a dual-color camera. The authors aligned the images with built-in reference marks in addition to the part design.

Table 1 (a) Sensor categories and defect detection – photogrammetry

		Photogrammetry (still image or video)	
		Unstructured light (CMOS, CCD cameras)	Structured light (CMOS, CCD cameras)
Meltpool		Meltpool shape irregularities, e.g., key hole and size too small. Track irregularities, e.g., under melting, over melting, metal balls, and discontinuity	N/A
Layer	**Freshly coated**	Waviness, voids	Same as left with more contrast
	Scanned	Track discontinuity, cracks, voids, and spatters. Coated powder layer irregularities, e.g., streaks, waviness, and metal obtrusion	
Workpiece		N/A	N/A
Chamber		Plume, spatter, spark	N/A
Blade		N/A	N/A

Everton et al. [4] described specific sensors and sensing techniques for monitoring part buildup, layer-by-layer, in L-PBF processes. Purtonen et al. [12] focused on optical sensors and acoustic sensors. Optical sensors included photodiodes, spectrometers, Charged Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) imaging sensors, acoustic sensors, pyrometers, and infrared cameras. Acoustic sensors included microphone and signal analysis software in the frequency domain for detecting anomalies in melting. Sensor fusion has been increasingly a research topic for better understanding of AM processes.

2.3 Sensor Categorization

In this paper, we aggregate currently available sensors developed for in-situ, L-PBF monitoring as shown in Tables 1 (a), (b), and (c). The leftmost column lists what is being monitored. Items in the list includes the entire melt pool, a freshly coated layer, a newly scanned layer, workpiece, chamber, and blade. The top row in each table lists available sensor types. The list includes still image cameras, video cameras, infrared cameras, pyrometers, thermocouples, sonic sensors, ultrasonic sensors, strain gages, accelerometers, CO2 sensors, air-pressure gages, and air-flow meters. These sensors belong to the following five types: photogrammetry, thermometry, acoustic emission, mechanical sensing, and chamber environment sensing.

2.4 Research Needs for Data Elements for Registration

Clearly, a variety of sensors are being used for in-situ monitoring of different AM processes. Those sensors provide a plethora of data, including images, video clips, temperature data, and acoustic signals. While the data from individual sensors are important, correlations among those data can be extremely valuable. Sensor data must be registered in a data repository providing metadata before the data can be applied for analysis and correlated for decision making. The data correlations are necessary to determine the state of the powder-fusion process, the material microstructure, and the fabricated part. For example, without correctly aligning measurements in the spatial and temporal domains, conflicting predictions can be made on the part quality

Table 1 (b) Sensor categories and defect detection – thermometry

		Thermometry				
		Radiometry			**Non-radiometry**	
		Infrared imaging IR camera with filter (still or video)	**Pyrometry**		**Thermocouple**	**Thermometer**
			Single bandwidth (Pyrometer)	**Multi-bandwidth (multi-bandwidth pyrometer)**		
Meltpool		Melt pool temperature profile	Melt pool temperature (with correction of emissivity) to detect under/overheating problems	Same as left, but calibrated with near true temperature black body	N/A	N/A
Layer	**Freshly coated**	N/A	Powder bed temperature	Temperature monitoring	N/A	
	Scanned	N/A	Powder bed temperature	Same as left		
Workpiece		N/A	N/A	N/A	Temperature monitoring	N/A
Chamber		N/A	N/A	N/A	N/A	Temperature monitoring
Blade		N/A	N/A	N/A	N/A	N/A

Table 1 (c) Sensor categories and defect detection – acoustic emission, mechanical sensing, and chamber environment sensing

	Acoustic emission		**Mechanical sensing**		**Chamber environment sensing**		
	Sonic (microphone)	**Ultrasonic (Ultrasonic sensor)**	**Strain (Strain gage)**	**Acceleration (Accelometer)**	**CO_2 concentration gaging**	**Air pressure gaging**	**Air flow metering**
Meltpool	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Layer	Sparking anomalies	N/A	N/A	N/A	N/A	N/A	N/A
Workpiece	Cracking	Crack, void detection	Thermal and residual stresses	N/A	N/A	N/A	N/A
Chamber	N/A	N/A	N/A	N/A	CO_2 concentration	Air pressure	Air flow
Blade	N/A	N/A	N/A	Waviness on the powder layer, Metal Obtrusion due to lamination	N/A	N/A	N/A

Metadata for capturing the 'context' of that data, both in the product development lifecycle and in the material and equipment supply chains, is also needed for qualification. That context should include three types of information related to individual sensors and their configuration, to the design, build, post-process, and inspection activities, and to material, equipment and personnel. This information is necessary for downstream applications, such as data analytics, and will enable users to analyze the data correctly. Data correctness reduces wrong decisions to be reached during and after L-PBF.

AM dataset registration as a research topic continues to expand. Nevertheless, the current limitations of that research are still impeding the use of advanced data analytics, which can be used to accelerate the understanding and control of AM processes. Current limitations include both a missing data identifier for tracing raw data objects and a lack of meta-data for data fusion and analytics. First, raw data objects from in-situ sensors are often stored in isolation: either on local computers, laboratory servers, or mobile drives. Since these data objects lack standardized syntax or semantics, each data object may not have a persistent identifier assigned. This makes it very difficult to trace the origins of the data objects where they are located. This, in turn, impedes the fusion of data objects collected from different monitoring systems and stakeholders.

Second, estimating the correlations among various sensor-data types is very difficult since there is no information to link the data correctly in both time and space. In the following sections, we present a data registration approach to contextualize AM in-situ data sets. The approach has the potential for standardization that will facilitate the integration of AM lifecycle data integration. Lastly, there is no contextual information for the product's lifecycle. This is one of major barriers for part qualification and verification to ensure AM product quality.

Multi-modal, nondestructive sensors collect a variety of data objects for monitoring AM processes. Comparing, fusing, and correlating these data objects to the original AM design, the current microstructure, and the final part quality is a major problem. The quantity and quality of different data types are also causing curation, organization, and administration problems that can limit the usage of those data objects. In our view, data registration is focused on contextualizing data in time and space (see Figure 2) for capturing the meta information necessary.

Figure 2 shows a picture of how in-situ data can be registered geometrically onto a voxel model. The additional data necessary to do this are shown on the right-hand side of Figure 2. For example, the laser-scanning strategies are critical since the scanner-motion control and laser-control commands provide fundamental references to contextualize in-situ data sets both spatially and temporally. The rest of the Section describes data elements that are needed for registering in-situ monitoring data, including scanning paths, melt-pool monitoring (MPM) images and videos, layer-wise images, and signals in acoustic emission.

Unfortunately, registering spatial-temporal data is not enough to guarantee better process control. Control requires a transformation of the raw sensor and calibration data into the same coordinate system. Control also requires linking all in-situ data to the design, geometry, tolerance, material, and inspection information.

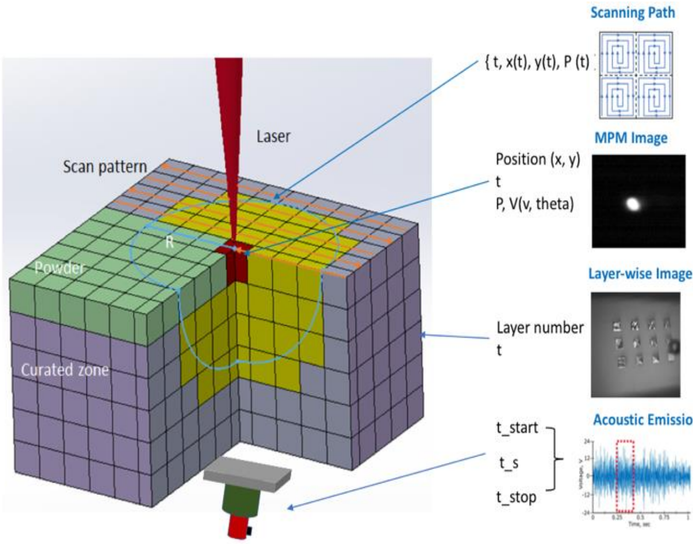

Figure 2 Registering AM data using a voxel model

3 Data Elements for In-situ Process Monitoring

3.1 Laser-scanning-strategy Data Elements

Laser-scanning strategies can provide both temporal and spatial references for the spatiotemporal alignment of in-situ measurements from different sensors. The scanning-strategy registration method is process-oriented, based on the xy2-100 protocol used in some open AM systems. The xy2-100 files provide the laser-spot positions, laser power, and camera-trigger timing [20]. This method is used primarily to register the position and the time when the image is taken by a camera. Required data elements are shown in Table 2. The scan starting time can be used as the temporal reference to align the data in the time domain, e.g., acoustic data.

Table 2 Process-oriented Data Elements

Data Element	Description
Build ID	unique identification of the associated build
Part ID	unique identification of the associated part
Scanning ID	unique identification of the data element
Layer number	the powder layer number
Command time (t)	the time that a position command is sent
Scan position (x, y)	the commanded location of the laser beam
Laser power (P)	the power of the laser beam
Scanning speed (V)	the scanning speed of the laser beam

The metadata shown in Table 2 can be provided by an open-architecture AM system, e.g., the AM Metrology Test Bed from the National Institute of Standards and Technology[2]. For commercial AM systems, part-oriented scanning strategies are used to scan the layer with minimized scanning time with acceptable part quality. The strategy specifies scan paths and process parameters based on partitions of the layer and is vendor-dependent and proprietary, so the registration of this kind of scan strategies is not discussed here.

3.2 Layer-wise images

Layer-wise images are dominating the current datatypes used in monitoring AM processes. There are two methods for registering layer-wise images: an individual image or a folder of images. The two methods are described below.

3.2.1 Registering an Individual File

When there is a limited number of individual images on a pre-scanned or post-scanned powder layer, each image can be registered with the data elements in Table 3 to provide the necessary meta information.

Table 3 Image Data Elements

Data Element	Description	
Image (or Movie) Name	the name of the image or movie	
Image (or Movie) ID	a unique identification (ID) number of the image or movie	
Build ID	the ID of the build for the part	
Layer number	the layer number of this image	
Time	the time it was taken	
Folder Path	the directory path for locating the folder that this image or movie was saved	
Flash condition	if flash lights are used, a description of the flash light angle relative to the layer	
Sensor ID	the identification of the image sensor	
Sensor description	sensor type (e.g., InSb, CMOS, Photoiode), purchase data, wavelength ranges, lens distortion information, and other specifications, including filters.	
Sensor configuration ID	Sensor configuration description must have the following tags	
	Original window size in pixels	mm x mm
	Cropped	(y/n)
	Pixel pitch	(µm/pixel)
	Magnification	magnification factor
	Viewing angle	(degree)
	Bit depth	the number of levels on grayscale or color scale
	Shutter Speed	the amount of time that the shutter is open for taking an image (s)
	Optical filter bandwidth	minimum and maximum wavelengths in nm
	Sensor calibration information	the date of calibration, the method of calibration, and person who performed the calibration

3.2.2 Registering a Folder of Images

When there is a large number of individual images on a pre-scanned or post-scanned powder layer, the images may be organized in a file folder. In this case, users should register all the folders with all the optical images from the first layer to the last layer. Data elements are in Table 4.

Table 4 Image Folder Data Elements

Data Element	Description
Build ID	the ID of the build
Folder path	the path of the file directory of the folder
Layer range	the start layer and the end layer included in the folder
Start time	the time that the first image was taken
Stop time	the time that the last image was taken
Flash configuration enumeration	the enumeration of the index of flash lights and their configuration descriptions
Image prefix	the prefix of an image in the folder
Flash condition	the condition of an indexed flash light
Sensor ID	the ID of the sensor
Sensor description	the description should include the type of sensor, the purchased date, sensor specification, and the information on lens distortion
Sensor installation	the view angle
Sensor setting and configuration	description of settings and configuration of the sensor
Configuration ID	ID of a sensor configuration
Image size in both X and Y directions	pixel by pixel
Cropped	(y/n)
Pixel pitch	(µm/pixel)
Magnification	the magnification factor
Viewing angle	the angle relative to the build plate normal
Bit depth	the number of levels in grayscale or color scale
Shutter Speed	the amount of time that the shutter is open for taking an image (s)
Optical Filter Bandwidth	minimum and maximum wavelength in nm
Sensor calibration information	the description of sensor calibration

3.3 MPM Data Elements

In this section, we focus on registering still images and video files since they are used by metrologists for process monitoring.

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[2] https://www.nist.gov/el/ammt-temps

Since melt-pool monitoring often requires high-speed cameras, which can capture thousands of images per layer, we recommend users register images in a folder. Data elements are in Table 5.

Table 5 An Image in the Folder (Data Elements)

Data Element	Description	
Image Name	the name of the image	
Image ID	a unique identification number of the image	
Build ID	the ID of the build	
Triggering Time	the time when the camera is being triggered to take the picture based on the scanning program in xy2-100	
Instant laser power	the laser powder (W) at the time of image taken	
Frame Rate	frame per second (fps) if it is a movie	
Folder Path	the directory path for locating the folder that this image was saved	
Sensor ID	the identification of the image sensor	
Sensor description	sensor type, purchase data, specifications, lens distortion information, etc.	
Sensor installation	installed date, installer	
Sensor configuration ID	Sensor configuration description must have the following tags	
	Original window size in pixels	mm x mm
	Cropped	(y/n)
	Pixel pitch	(nm/pixel)
	Magnification	magnification factor
	Bit depth	the number of levels in grayscale or color scale
	Shutter Speed	the amount of time that the shutter is open for taking an image (s)
	Optical filter bandwidth	minimum and maximum wavelengths in nm
	Sensor calibration information	The date of calibration, the method of calibration, person who performed the calibration, and the calibration data

3.4 Acoustic Emission Data Elements

Acoustic sensors can capture the sparking and cracking sound generated in L-PBF. That sparking sound is generated by laser heating. Metal cracking is due to thermal stress. The acoustic emission data is a time series of signals. The file elements can be found in Table 6.

Table 6 Acoustic Emission Data Elements

Data Element	Description
File name	the name of the file
Uniquely generated ID	ID of the data
Start Time	Time of recording started
Stop Time	Time of recording stopped
Sampling interval	Time interval between two samples
Sensor location	The location of the acoustic sensor in the chamber
Setting	Acoustic sensor setting information

3.5 In-situ Measurement Uncertainty Quantification

There is always uncertainty in the data collected from sensors. Knowing the sources of that uncertainty is critical to applications such as data analysis and model validation. Uncertainty sources can be registered in categories in Table 7.

Table 7 Uncertainty Sources

Sensor Type	Uncertainty Source
Camera	• view angle variation due to installation • magnification factor variation due to the viewing angle • instantaneous Field Of View (iFOV) due to viewing angle • FOV due to viewing angle • Variation in the focus of lens
Laser spot	• The location relative to the build plate coordinates in the X and Y directions
Galvo Scanner	• The actual laser spot position in the X and Y directions relative to the build plate coordinates in the X and Y directions can deviate from the command position.
Image	• The laser (spot) is moving while the camera is taking a picture. Melt pool keeps changing during the exposure. Uncertainty is embedded in the shape and size of the measured melt pool.

4 Data Model for Meta-Data

To implement the identified data elements in Section 3, we developed a data model using the XML Schema language [18]. XML Schema was chosen based on the following reasons: (1) data structures in XML enabling efficient search/query, (2) predefined data types satisfying a variety of our modeling needs, (3) XML files validation using XML schema, and (4) available tools for implementation. The user community can implement the data registration method using XML tools with the schema described in this Section. Our choice does not imply that XML Schema is the best language for data modeling. Every modeling language has its capabilities and shortcomings.

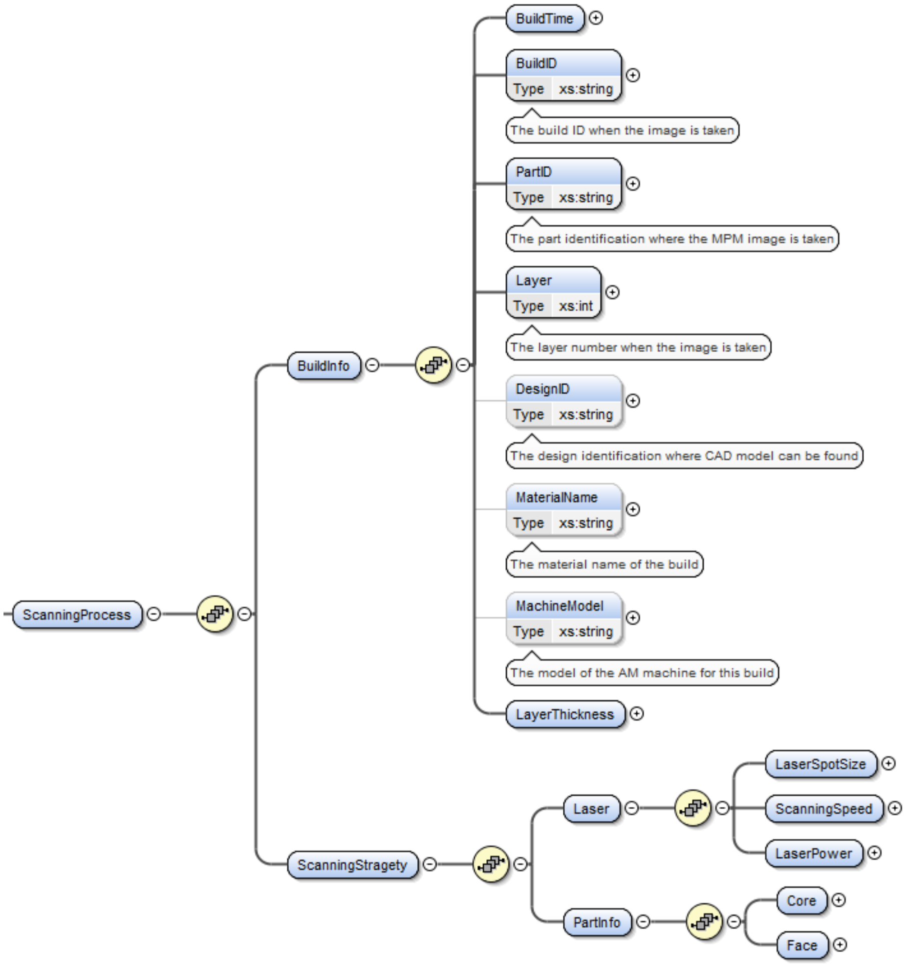

Figure 3 Data schema for scanning process

The data elements and attributes in the schema are based on the classification and data elements described in Section 4. In-Situ_Monitoring is the root element. It has four sub-elements: Scanning_Process, Layer_Imaging, Melt_Pool_Imaging, and Acoustic_Singnals. In the paper, we only describe a group of data elements for scanning process (Section 5.1) and another group for layer imaging (Section 5.2) as two examples. We create attributes to uniquely identify the data element. Note that attributes are not shown due to the limitation of the paper length. We create sub-elements to describe details of the data element.

4.1 Scanning Process Data Elements

As described in Section 3.1, a scanning process is for a specific build with a scanning strategy. The main data element is Scanning_Process, and it thus has two sub-elements: Build_Info and Scanning_Strategy. Figure 3 shows a graphical representation of Scanning_Process elements and its two sub-elements. Build_Info has two attributes, BuildID and Total_Number_of_Layers (not shown). Two sub-elements, Build_Time and Layer_Thickness provide detailed descriptions of Build_Info. Similarly, Scanning_Strategy has attributes to uniquely describe the data element. Three sub-elements to provide detailed information on Scanning_Strategy: Laser, Part_info, and G-code. Furthermore, Laser and the Part_info have attributes and sub-elements.

4.2 Layer Imaging Data Elements

As described in Section 4.2, Layer_Imaging is the main element for layerwise images registration and six attributes and three sub-elements, as shown in Figure 4. Like the description in the previous section, attributes uniquely describe a data element. The data element can have one or more sub-elements that provide detailed information about the data element. Six attributes (not shown) are Image_Name, Image_ID, Time_Taken (the time when the image was taken), Folder_Path (the path to locate the folder where the image is saved), Flashing_Condition (a description of flash lighting, including number flash lights and their locations and flashing directions), and Still_Image_of_Movie (to indicate the registered item is a set of images or a movie).

Layer_Imaging_Sensor is one of three sub-elements and has two attributes and three sub-elements. Two attributes are Sensor_ID and Sensor_Description. Three sub-elements are Pixel_Pitch, Bit_Depth, and Sensor_Size. They all have quantity and unit as their attributes.

Layer_Imaging_Sensor_Configuration has three attributes (not shown) and six sub-elements. Three attributes are Sensor_Configuration_ID, Sensor_Configuration_Description, and Cropped_or_not (for indicating whether the image is cropped or not). Six sub-elements are Magnification (the magnification factor of the lens), Shutter_Speed (camera shutter speed), View_Angle, Optical_Filter_Bandwidth, Original_Window_Size_in_Pixel, and Cropped_Window (an indication whether the window is cropped or not). Layer_Imaging_Sensor_Calibration_Info (to provide relevant information on the calibration of the sensor).

5 Sample Use Case

The data schema presented in Figure 3 and 4 were instantiated to capture the meta data which describe the scan command and in-situ tower camera based layerwise monitoring data set generated from a 3d build using an open architecture powder bed fusion system- NIST AMMT[3]. A Python program is created to register the layerwise image against the galvo position. Figure 5 shows a function diagram of the program.

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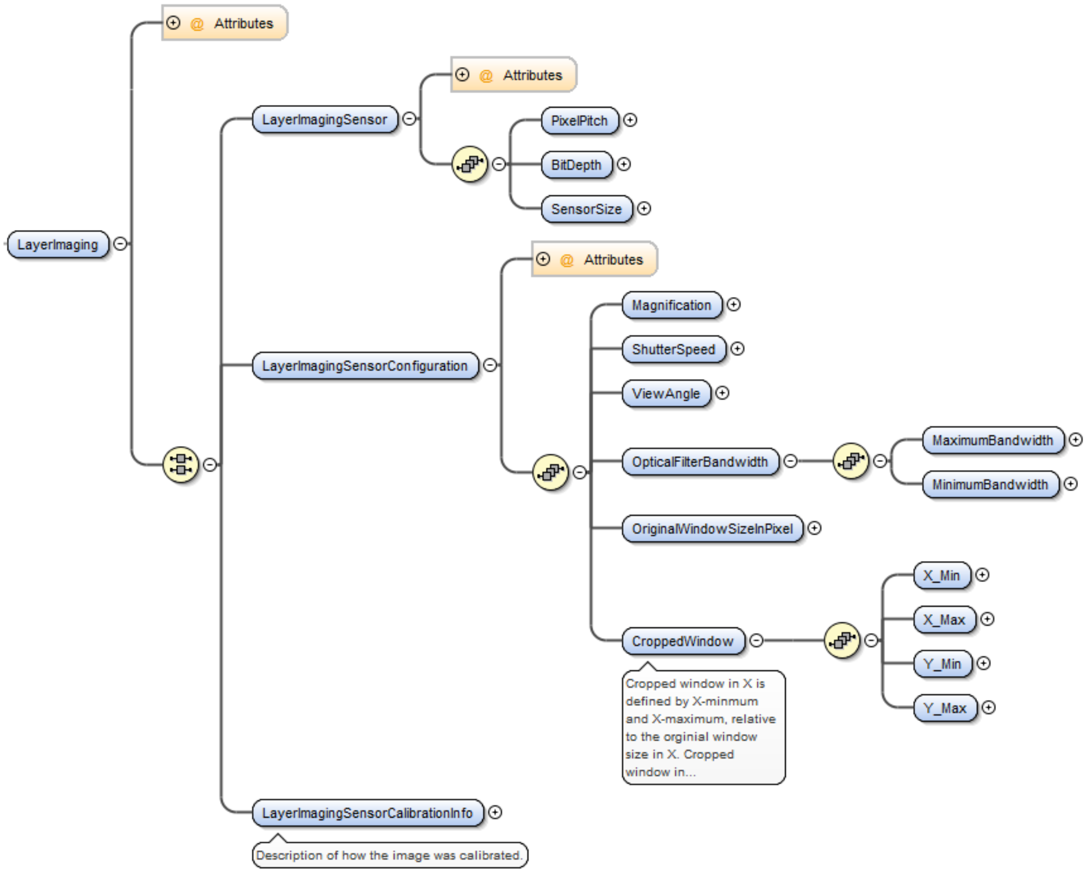
[3] https://www.nist.gov/el/ammt-temps



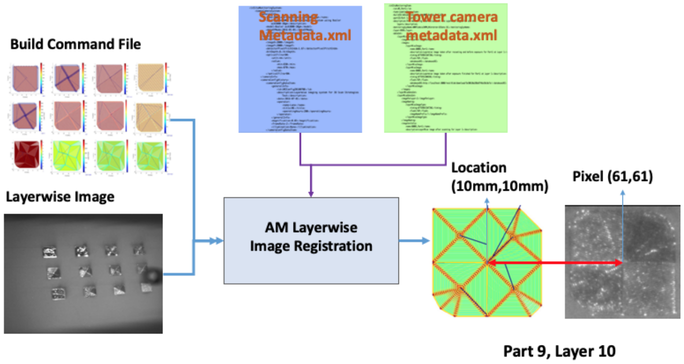


Figure 5 Use case for XML-based meta data

The tower camera metadata.xml file provides camera intrinsic and extrinsic parameters to remove the projection from the layerwise images and convert the image to the build platform coordinates. The Scanning Metadata.xml deciphers the build command data from which the contours of each part are extracted and used to segment the parts and convert the pixels of the image into galvo positions. The output of the functions are the registered after-exposure images of each part. Figure 5 shows the registered Part 9 layerwise image at Layer 10. Pixel (61, 61) corresponding galvo location at (10mm, 10mm).

6 Conclusion and Future Work

The use of laser powder bed fusion, L-PBF, technology to fabricate complex, metal parts in several industries has been steadily growing. As a result, the demands on both the quality and reliability of those parts have increased. Academic researchers and real-world manufacturers have implemented in-situ sensors to monitor L-PBF processes and to detect potential anomalies in the part.

The target audience of the paper are the practitioners who rely heavily on standards, interfaces and tools to integrate different systems and data. The work in this paper enables the future standards on common data exchange formats which will play critical role in implementing the scientific results from the academia and integrating and analyzing AM sensor data.

This paper focuses on defining a key element of those standards: meta-data. Specifically, this paper proposes new data elements, which can be used to characterize the properties and relationships among the data types captured by those sensors. Characterizing those properties and relationships requires a schema model; we have included a small number of examples of such a model.

Future work will be in three areas. One is to include other types of in-situ sensors emerging in the future, such as pyrometer and ultrasonic sensor. Second is to extend the number of schema model, standardize the resulting models, and integrate them with other existing schemas, such as powder material and machine schemas. We expect that these standards will lead to better implementations in the L-PBF user community. Third is to characterize data and meta data on image calibrations and define data elements. Specifically, a data model on methods and calibration instruments needs to be included in the developed data model. The data model will enable users of the data to compensate distortions in an image and quantify uncertainties in measured data.

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