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Methods for Mapping Empirical Data to Authoritative Definitions for Additive Manufacturing Part Validation

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ABSTRACT

Traditionally, inspection and geometric dimensioning and tolerancing (GD&T) are deployed at the macroscale, where complete parts are tested to meet geometric and functional requirements. The additive manufacturing (AM) process is unique in that it is a digital process where the fabrication of the part at the macroscale is the result of a series of operations at micro and mesoscales. Subsequently any additively manufactured part is the aggregation of many points of localized fabrication, and these parts uniquely expose themselves to full volumetric inspection during part fabrication and postprocessing. While new methods have been developed for designers to communicate process definitions used for the fabrication of an AM part, methods to validate these specifications are lacking. This work will explore challenges in the validating against advanced part and process definitions. Leveraging the concepts of "authoritative product definition," "digital twin," and "time stepped commands," novel methods, built on a "zero dimension" information model, will be proposed to validate AM parts at the macroscale using mesoscale and microscale measurements and observations. Specifically, new data representations in the Standard for the Exchange of Product model data Numerical Control (STEP-NC) are proposed for discretizing AM geometry and process definitions to achieve point-level controls. Through the facilitation of traceable information in authoritative data models, AM process qualification and part acceptance could be streamlined, and reliable and referential data for Digital Twin frameworks and real-time controls could be realized.

Keywords: Data exchange, data/information modeling, GD&T/tolerance modeling, intelligent manufacturing.

1. INTRODUCTION

Additive manufacturing (AM) produces and consumes large volumes of data throughout the lifecycle of a part. From design geometry and tolerance bounds to process plans and manufacturing commands, to post-process inspection and qualification, data occupy every stage of an AM lifecycle. However, current AM industry practices rely on data transformations along the chain of processes, which might result in geometrical inaccuracies or decoupling of valuable information such as product and manufacturing information. The continuation of a traceable information flow is essential for the evaluation of AM processes and the qualification of AM parts, which in turn results in reliable data for analytical, simulation, and Digital Twin frameworks.

The Standard for the Exchange of Product Model Data Numerically Control (STEP-NC) [1] is a standardized data model that combines part geometry and process in a uniform data format. This model extends traditional geometry information (e.g., STEP [2]) with additional manufacturing standards. As the STEP and STEP-NC models were developed to be direct interpretations of natively developed formats, in appropriate context they can also serve as authoritative models [1,2]. That is to say that these models can be used to provide geometry and manufacturing definitions that must be validated and verified against. In the context of AM, 3D parts are created from 2D layers that consist of 1D paths, and as a digital manufacturing process, AM 1D characteristics are inherently discretized further through digitization. No standardized mechanisms currently exist for facilitating the verification and validation of a process

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by comparing process observations to authoritative model definitions.

To establish an authoritative referential data model, this paper proposes a hierarchical-based approach that utilizes multi-dimensional scaling and discretized point-based representations for mapping process observations to authoritative part and process definitions. The proposed approach is influenced by fundamental research conducted at the National Institute of Standards and Technology (NIST) on the Additive Manufacturing Metrology Testbed (AMMT) [3,4]. The Time Stepped Digital Command (TSDC) was first defined by Yeung et al [5]. It has been used to implement the point-wise control on NIST AMMT [6–8] and generated numerous datasets for the AM research communities [9,10], including the AM-Bench 2022. The proposed approach in this paper uses point-wise AM process controls of TSDC [5] to act as a medium when aggregating heterogeneous data observations to AM process strategies. For a given slice, regional points are segmented and indexed relevant to the applied scan strategy and measurement frequency, and in--situ measurements and models can be directly or indirectly linked to the corresponding indexed points.

To effectively facilitate part and process validation by providing a medium between process definitions and process observations, the work outlined in this paper is based on the following premises:

a) AM is a localized process [11], that is to say the formation of a part and its properties does not occur as a single operation at the macroscale but instead a series of operations at smaller scales,
b) Measurements made at mesoscales and microscales, both in-situ and ex-situ, can be leveraged to provide insight into the quality and state of the process and part at the macro scale,
c) Discrete measurements taken during and after the process lend themselves well to the formation of a Digital Twin, where the Digital Twin is a temporally and spatially mapped representation of all measurements over time,
d) Verification and validation can be achieved by using a digital twin to establish pedigree/provenance of a part and facilitate part inspection, which in turn can be linked to the quality of the part.

The structure of this paper is presented as follows. Section 2 covers a brief background. Section 3 describes the discretization of AM geometry and processes. Section 4 details the proposed methods to map AM process observations to authoritative, STEP-NC compliant data representations for pointwise AM operations. Section 5 discusses the approach to model the proposed pointwise AM operation through simulation and proof-of-concept build. Section 6 concludes this paper.

2. BACKGROUND

Traditional roles of geometric definition and product and manufacturing information (PMI) provide the basis for the creation of parts from conceptual designs to fabrication and inspection. General principles of design for manufacturing (DfM) adopt such roles with emphasis on fabrication optimization and cost reduction. On the other hand, design for AM (DfAM) combines traditional roles with material compositions and mechanical properties at micro-meso-macro structure levels to employ AM process competencies in realizing performance requirements and life-cycle goals [12]. However, AM technologies can significantly differ in their allowable designs, functional properties, process planning and controls, and material selection, which necessitate the categorization of design rules for different AM processes [13]. Furthermore, free-form geometry and process variability in AM parts often produce postprocess inspection and qualification issues pertaining conformance with geometric dimensioning and tolerancing (GD&T) specifications [14]. Investigations into root causes of GD&T nonconformity in AM parts revealed the absence of clear and consistent methods for communicating AM design and processing specifications, and the need for establishing adequate AM data packages [15]. Recently, the American Society of Mechanical Engineers (ASME) published an update of the Product Definition for Additive Manufacturing standard Y14.46 [16] based on fundamental research conducted by NIST. The updated standard provided uniform guidelines not only for AM designs, but also for process recommendations and methods to document AM specifications. Despite research progresses and standardization strides, it is not clear how much of the defined specifications are being communicated in common AM file formats? and whether the represented definitions are verifiable during AM implementations? To answer these questions, one must understand how information flow within AM technologies, and the common mediums that facilitate its communication and traceability from one phase of the process chain to another.

It is well known that the generation and consumption of digital information span the entire lifecycle of an additively manufactured part. Therefore, collecting, registering, and archiving data from each AM phase, and during phase-exchange, becomes an important task for asserting part acceptance and process evaluation [17]. Lately, the AM industry has been exploring ways to use such data in creating a Digital Twin of the manufactured part and addressing manufacturing challenges such as process verification, validation, and uncertainty quantification (VVUQ) [18]. In 2021, the International Organization for Standardization (ISO) published the ISO 23247 standard [19], which defined a framework that supports Digital Twin generation, monitoring, and assistance to achieve functional objectives and enhance manufacturing operation and business cooperation. While detailed descriptions and implementations of Digital Twin(s) for specific AM technologies are still a subject of ongoing research, current data models that're commonly used by the AM community are not capable of containing the geometry and processing information needed to drive the build of an AM part in a uniform file format. For example, popular AM files such as STereoLithography (STL) [20] only approximate the solid geometry in tessellated mesh of triangles, whereas advanced mesh-based files such as the Additive Manufacturing File (AMF) [21] add metadata regarding material, color, texture, and orientation. However, when considering AM process planning and control specifications, STL and AMF files alone do not convey

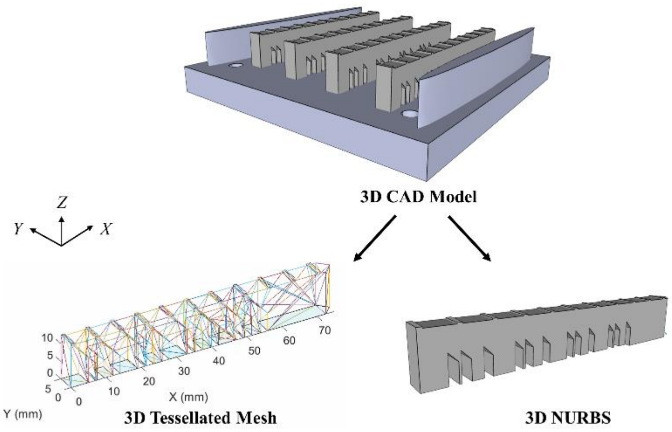


FIGURE 1: ADDITIVE MANUFACTURING GEOMETRY DISCRETIZATION.

descriptions for technology-specific process parameters, fabrication commands or GD&T information for downstream postprocessing and inspection. Alternatively, STEP-NC is an ISO standard [1] that provides geometry and tolerance models, as well as process control and machining models, and enables their exchange across software vendors in a system-neutral format. STEP-NC definitions are represented in an object-oriented manner using the EXPRESS language [22]. The introduction of ISO 14649-17 [23], or part-17, enabled STEP-NC to describe data representations for general AM modeling and processes. For powder bed fusion (PBF) manufacturing, Milaat et al. [24] proposed STEP-NC compliant data representations and process plans that provided volumetric, three-dimensional (3D) operation parameters such as hatch space and interlayer rotation, as well as parameters for scan strategies and technology specifications such as beam diameter size, power output, and scan speed. Despite the feasibility of detailed representations for AM geometry, process, and technology specifications in STEP-NC, over specifying AM data representations might lead to the creation of unique formats that're tightly coupled with vendor-specific instruments. Therefore, there is a need for a process control method that serves as a medium between in-process controls and sampled measurements at the micro and mesoscales, and the desired near-net-shape finish at the macro scale. The pointwise AM controls [5] for the NIST AMMT [25] discretizes AM scan strategies into time-spaced points of commanded controls, as opposed to line-based controls, and provide geometric alignment and synchronization between the AM instruments and the measured observations. By defining pointwise controls [5] in authoritative STEP-NC models, one could develop novel evaluation methods that would unlock the potential for streamlining AM process qualification and the systemization of AM part acceptant.

3. AM GEOMETRY AND PROCESS DISCRETIZATION

AM parts are digitally designed as solid models using computer-aided design (CAD) software, where geometrical properties and tolerances of such parts are specified according to their corresponding DfAM rules [13]. On the other hand, the fabrication of an AM part is executed in successive steps, layer upon layer, until the physical 3D part is constructed. Therefore, transforming a digital 3D model into a physical 3D part requires discretizing the solid AM model into manageable geometric features and processing steps that comply with the designated AM technology, achieve the desired material and mechanical properties, reduce the occurrence of part defects, and maintain a balance between near-net-shape and build time. This section describes two categories of AM discretization, namely geometry and processing, as well as exploring the benefits and shortcomings in their application.

3.1 AM Geometry Discretization

Discretizing the geometry of an AM part involves transforming the 3D solid model into a format that abstracts geometric features into surfaces covering the inner and outer boundaries of the part, see Figure 1. The 3D surface transformation is a fundamental step towards simplifying the dimensional analysis of newly designed, modified, or consolidated AM parts and establishing the delineation of first article inspection. To this end, practitioners in the AM industry commonly subdivide continuous 3D surfaces of a part into a mesh of geometric and topological primitives. The STL file format, also referred to as Standard Tessellation Language, is a widely popular file format that describes 3D surfaces as a mesh of triangle facets of unstructured planar forms, where each facet consists of a facet normal and three vertices in a 3D coordinate system [20]. Similarly, the AMF format [21] represents a geometric surface as a curved triangle mesh, while specifying both the material and the color of each volume, as well as the color of each triangle in the mesh [26]. Modern computers are optimized to render 3D mesh geometries, which allow for quick visualization of 3D parts and simplify the inspection of rendered models. However, a tessellated mesh geometry is only an approximate representation of a part's CAD model, and therefore require additional steps to deal with inconsistencies such as geometric misalignments, open loops, and voids. In addition, formats such as STL and AMF have been established to remain independent of 3D model resolution and lack GD&T attributes that support postprocessing inspection and qualification of AM parts and processes [27]. Another form of 3D geometry discretization deduces the geometric shape of an AM part directly from a CAD model. This approach uses non-uniform rational basis spline (NURBS) to mathematically represent curves and surfaces for both standard analytic shapes and complex free-form shapes [28]. Previous studies investigated NURBS to represent AM features in STEP data models [27, 29]. Standardized STEP definitions allow detailed geometric, topological, and PMI specifications to be communicated from a 3D CAD model, and therefore provide valuable information for part qualification [30]. Such detailed specifications cannot be realized with tessellated models alone. Nevertheless, STEP data models should be inspected and optimized during file translations to ensure compatibility between different CAD software vendors [31].

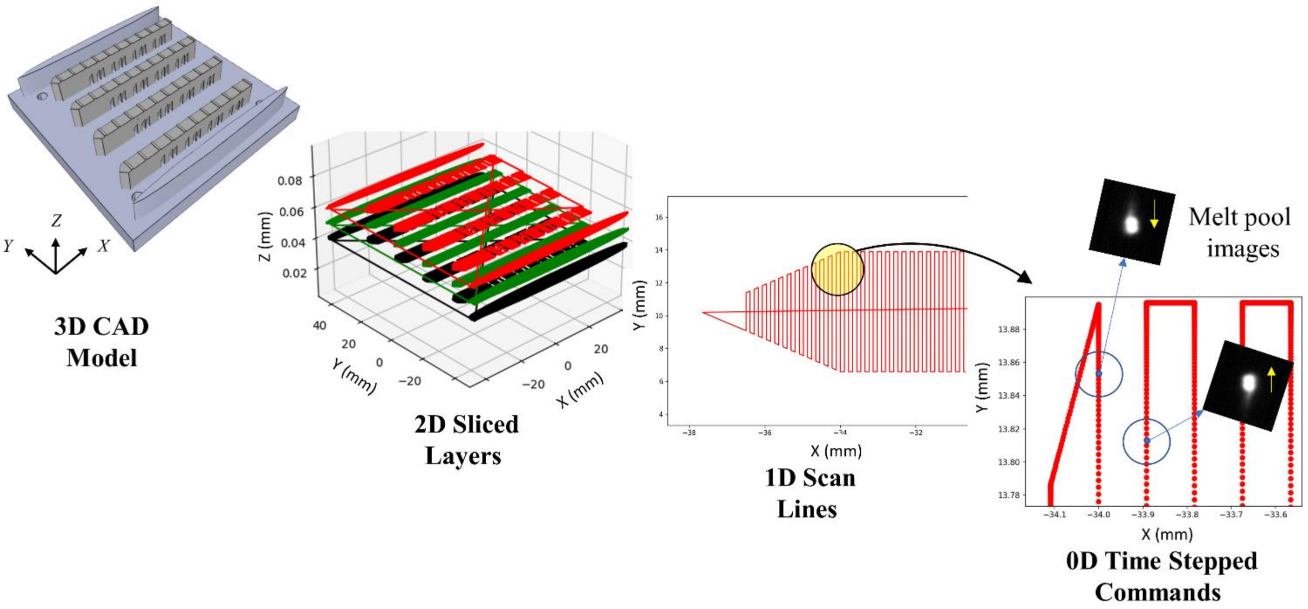


FIGURE 2: ADDITIVE MANUFACTURING PROCESS DISCRETIZATION.

3.2 AM Process Discretization

AM parts are built using additive, layer-by-layer, fabrication processes that adhere to their discretized 3D geometry specifications and their manufacturing requirements based on the selected AM technology. Before processing an AM part, few steps must be pursued. Initially, engineers identify the orientation of the 3D modeled part relative to the build plate and the instruments of the AM machine. In addition, support structures could be generated for the AM part where appropriately needed. After describing the part's orientation and generating the necessary support structures, the AM process discretization could be accomplished as follow:

From 3D to 2D: The first step in discretizing an AM process involves slicing the 3D volume of the modeled part into two-dimensional (2D) layers, each with a specified layer thickness relative to the selected material and AM technology specifications, see Figure 2. Slicing a tessellated mesh of a 3D shape into 2D layers is typically achieved either by uniform contour cross sections with constant layer thickness, or by adaptive cross sections with varying layer thicknesses depending on desired features or AM machine capabilities [32]. Note that the layer thickness, PMI, and GD&T specifications are externally defined relative to the 3D tessellated mesh, which require additional software tools to retain such information along the AM process chain. On the other hand, a NURBS geometry in STEP AP242 format could be directly sliced using the STEP-NC `AM_operation` entities shown in Figure 3. The `AM_operation` entity describes the process parameters attributed to the manufacturing of an additive geometry feature that is defined in an `AM_feature` entity [23]. When slicing is considered, the `AM_threed_operation` entity provides volumetric, 3D operation through describing the rotation angle of the scan strategy or in-fill pattern for each sliced layer. In addition, the `AM_twod_operation` entity expresses the 2D operation on the surface geometry of a layer and specifies the layer thickness when given the normal direction [23]. Therefore, discretizing the AM processes from 3D volumes to 2D slices could be applied directly onto the NURBS geometry in standardized, authoritative definitions and aligned with PMI and GD&T data.

From 2D to 1D: The second step in AM process discretization is to populate each sliced 2D layer with scan strategies that partition the 2D layer into smaller regions. As shown in Figure 2, each region would contain a set of one-dimensional (1D) scan lines, which are arranged in patterns according to specified process parameters such as hatch space, power outputs, and so on. The arrangement of AM scan strategies requires clear understanding of material and mechanical properties, AM technology and printer capabilities, microstructure formation and in-process controls among others [33]. Therefore, computer-aided manufacturing (CAM) software tools are typically used for automating the AM process discretization from 2D slices to 1D scan lines, and producing numerical control (NC) codes such as G-code (RS274 [34]) to execute the build in the AM machine. However, one of the major disadvantages of this approach is that the collection of AM process definitions (e.g., process planning, scan strategies, process parameters, etc.) are specified exclusively in the software environment, and not in the data models of the actual geometry, topology, or PMI of the AM part. For example, applying a scan strategy on a mesh sliced 2D layer would require process parameters and controls of 1D scan lines to be explicitly defined in the CAM software and made available for the end-user to configure. Alternatively, slices of 2D layers in STEP-based NURBS could be directly discretized into 1D scan lines by employing the STEP-NC "AM_oned_operation" entity, see Figure 3. This entity performs a freeform operation that repeats

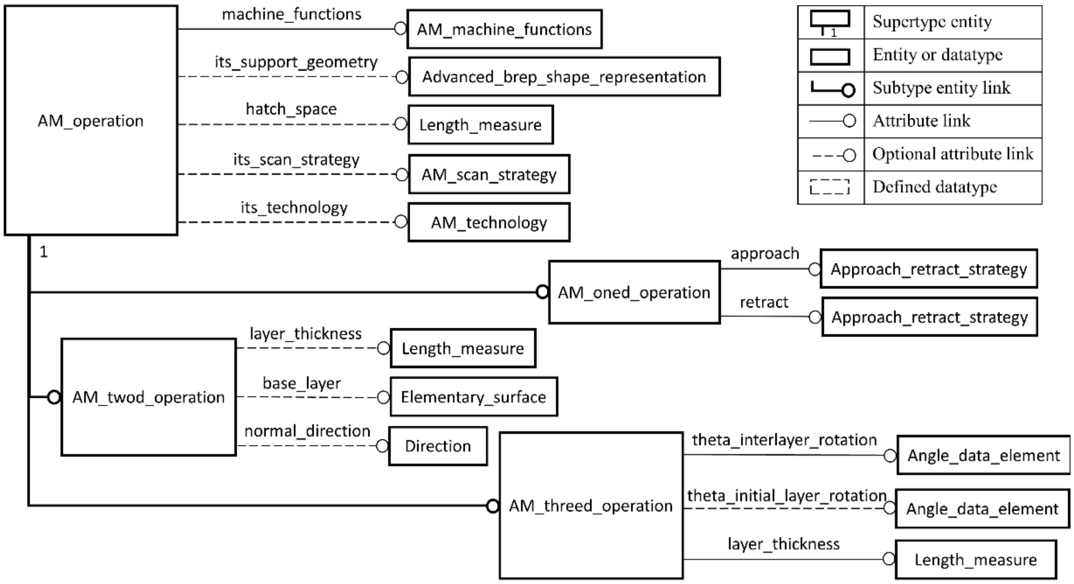


FIGURE 3: A DIAGRAM REPRESENTATION OF ISO 14649-17 "AM_OPERATION" ENTITIES WITH ADDED "AM_THREED_OPERATION" ENTITY [24].

the deposition of one path of material each time [23]. In [24], proposed STEP-NC representations further extended the process parameters and controls for 1D scan lines with scan strategies and technology specifications that're commonly used in PBF manufacturing. As the demand for qualifiable AM processes increases, it becomes critical to preserve AM process control specifications from 1D scan lines to 2D sliced layers, and maintain their associations with 3D geometric features in system neutral, standardized representations.

From 1D to 0D: The third step is to translate AM processes into machine-executable commands for implementing the fabrication of the desired part. This involves the use of an interpreter software [35], which ingests NC codes that're produced by CAM software and generates a set of calls that manipulate the instruments of an AM machine. There are a few limiting factors for how an interpreter software could be used in AM applications. For instance, popular NC codes such as G-code generate line-based commands, meaning that they can represent the start and finish of 1D scan lines or curves, one line at a time, for each 2D layer. This is relatively sufficient for general purpose AM parts. However, interpreting line-based NC commands might become inefficient when manufacturing AM parts with specific design features such as overhanging structures and thin walls, which necessitate further discretization of 1D scan lines and AM process controls. In recognition of the opportunities in fully defined AM scan strategies, Yeung et al. [5,25] proposed a pointwise TSDC framework, which discretizes custom G-codes of individual 1D scan lines into zero-dimensional (0D) AM control points with 10 µs incremental time steps, see Figure 2. Developed for precision metal AM applications, the TSDC provided full customization of AM scan strategies at the 0D level through controlling the position of each commanded point, the speed of movement between points, and the synchronization between the commanded points and the AM machine instruments [5]. With granular 0D process controls, the tasks of qualifying AM processes and certifying AM parts could be supported with pointwise validation through data registration of in-situ and ex-situ observations [36], defect reduction [6], and material and mechanical properties simulation [6-8].

4. METHOD TO MAP PROCESS OBSERVATIONS TO AUTHORITATIVE DEFINITIONS

This section describes two methods for mapping data observations to authoritative definitions for AM part validation. The first method introduces STEP-NC compliant data representations for pointwise AM operation with 0D controls. The second method utilizes 0D operation capabilities for AM data grouping of in-situ measurements and ex-situ observations. The following discussions detail the functions of the outlined methods.

4.1 Pointwise Additive Manufacturing Operation

Figure 4 shows the proposed `AM_zerod_operation`, which is a subtype entity to be contained in the `AM_operation` entity. Here, the proposed `AM_zerod_operation` entity includes five attributes, which are the `time_step`, the `time_step_file`, the `registration_start`, the `registration_end`, and the `triggers`. Each of the proposed attributes could be specified to achieve the desired 0D operation. For instance, the `time_step` attribute defines a time value using the `time_unit` datatype, which specifies the duration for executing an additive 0D operation. Similarly, the `time_step_file` attribute provides a method for reading a TSDC file from an external source. On the other hand, the `registration_start` and `registration_end` attributes allow a start and stop capability when registering the Cartesian coordinates of a sequence of pointwise operations. Finally, the `triggers` attribute specifies a list of monitoring instruments

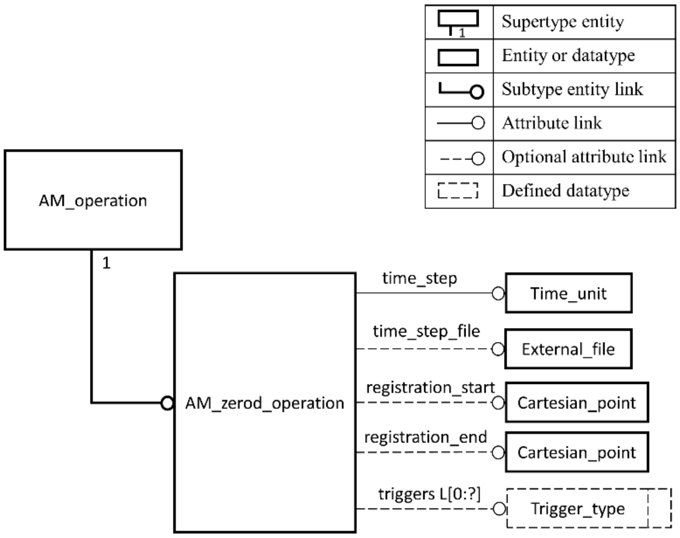


FIGURE 4: A DIAGRAM REPRESENTATION OF THE PROPOSED AM_ZEROD_OPERATION ENTITY.

that could be triggered while executing a point operation. The `triggers` value could be set to `none` when not in use, otherwise it could be set to a predefined value that corresponds to a monitoring instrument in the list. For instance, when implementing pointwise control on NIST AMMT [4–6], the types of monitoring instruments specified in the `triggers` list were `coaxial camera`, `staring camera`, and `pulsing light` among others [5]. As a result, the proposed STEP-NC data representations for `AM_zerod_operation` provide system neutral capabilities when specifying AM process controls at the 0D granularity. Such standardized representations could be implemented in CAM software and AM machine firmware to realize advanced point controls in AM with PMI and GD&T definitions that support the qualification of AM parts.

4.2 Additive Manufacturing Data Registration and Grouping

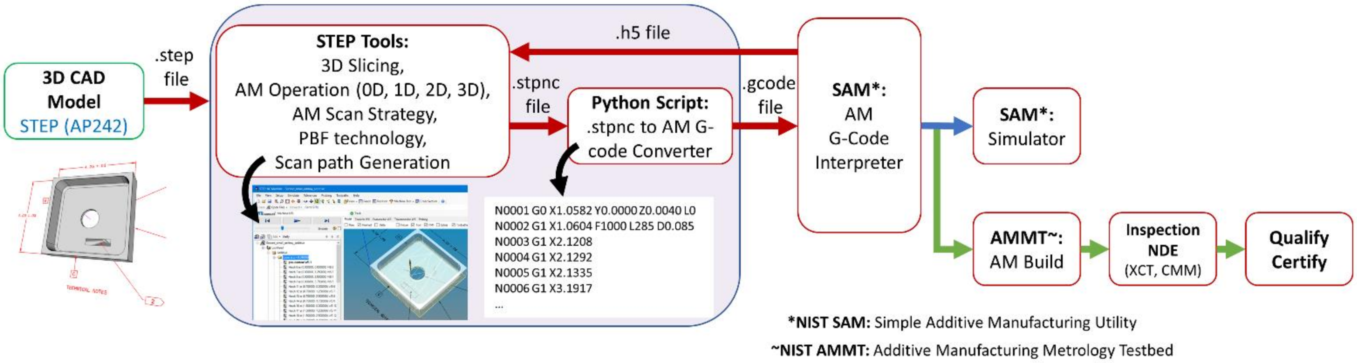
Data collection is an essential element of AM operations with 0D controls. The ability to make in-situ observations of material state transformations and morphology, as well as ex-situ measurements through nondestructive testing (NDT), provide important insights and analytics for achieving qualifiable, near-net-shape AM parts. However, when empirical data observations of AM point controls are collected, their position and orientation require alignment relative to the AM machine's coordinate system as specified in ISO 17295 [37]. In addition, the association of AM data observations across different datasets, or different collection phases, necessitates a referential mechanism. By employing pointwise AM controls [5], the tasks of data alignment and data association could be facilitated through data registration and data grouping, respectively.

Data registration concerns the consolidation of diverse data observations into a common coordinate system [38,39]. For AM applications, pointwise controls [5] provide the necessary positional coordinates for each commanded operation, which could then be associated with the data observation from a monitoring instrument. In laser-based PBF, Lu et al. [38] presented data registration methods for camera-based coaxial melt pool monitoring, where algorithms of the proposed methods were verified on both open architecture and closed 3rd party monitoring systems. On the other hand, the challenge of registering data observations from multiple sources to the same pointwise command persists. To address this challenge, Feng et al. [39] developed a general method to register images of in-situ and ex-situ observations for AM parts and processes, where images from multiple monitoring sources were aligned. Nevertheless, coordinating and aggregating multiple observation data sources that correspond to a specific time interval for a set of pointwise AM operations remain outstanding. Building on foundational work in [38, 39], the attribute definitions of the proposed `AM_zerod_operation` entity are leveraged to enable the grouping of data observations for a sequence of point operations. The term “data grouping” is defined in ISO 20005 [40] as the “process of identifying a time interval common among different data sources and grouping data obtained in the time interval”. By instantiating the `time_step`, `registration_start`, and `registration_end` attributes, the `AM_zerod_operation` entity could be specified to execute a sequence of 0D operations and retain the positional coordinates of `triggers` data observations. In addition, the identified time interval for the 0D operations sequence can be tagged with key values such as universally unique identifier (UUID) [19] prior to the execution of the commanded controls. Here, key values serve as referential key values that indirectly link data observations to their corresponding spatiotemporal location in the geometry and processing of an AM part. As a result, the proposed `AM_zerod_operation` entity facilitates the grouping of in-situ and ex-situ data to a common time interval of pointwise AM operations.

5. DISCUSSION

In this section, the steps taken to model the proposed pointwise STEP-NC data representations for AM are discussed. The NIST AMMT system, as well as the NIST Simple Additive Manufacturing (SAM) utility developed by Yeung et al. [5,25], played a critical role in the development of the proposed STEP-NC representations. In what follows, a brief illustration of the information flow for authoritative definitions will be covered, followed by a simulation evaluation and proof of concept determination. Finally, several challenges while conducting this investigation are highlighted.

Figure 5 demonstrates the information flow used in evaluating the proposed AM definitions for laser-based PBF manufacturing. First, a 3D CAD model of a test part is discretized into 3D NURBS representation in STEP file format. Next, the STEP Tools software [41] is used to slice the 3D model into 2D layers with specified layer thickness. After that, an AM scan strategy is applied on each layer, further discretizing 2D layers into regions of 1D scan lines with specified process parameters. Once the AM scan strategies are created for all layers, a corresponding STEP-NC file is generated.



```
N0001 G0 X1.0582 Y0.0000 Z0.0040 L0
N0002 G1 X1.0604 F1000 L285 D0.085
N0003 G1 X2.1208
N0004 G1 X2.1292
N0005 G1 X2.1335
N0006 G1 X3.1917
...
```

FIGURE 5: A DIAGRAM REPRESENTATION FOR THE FLOW OF INFORMATION USING AUTHORITATIVE DEFINITIONS.

For implementation purposes, a Python script converts the STEP-NC file into an AM G-code file. This AM G-code file is then interpreted by the NIST SAM utility [5] to generate a pointwise TSDC [5,25] file, which the `AM_zerod_operation` entity could read using the `time_step_file` attribute. During the building phase of an AM part, in-situ data measurements and observations of 0D operations are collected and grouped relative to their specified intervals. Following the fabrication and post-processing of an AM part, ex-situ data inspections and testing are collected and grouped in correspondence to their spatiotemporal relevance to 0D operations. Finally, the qualification and certification of the finished AM part are supported with authoritative definitions and detailed referential information spanning from microscale to mesoscale and macroscale. Figure 6 shows a simulation of a 0D AM operations on a sliced 2D layer of a 3D model with AM scan strategy and process parameter specifications for L-PBF manufacturing. To validate the simulated results, a proof-of-concept AM build of 5 layers was executed directly on a stainless steel build plate as shown on the right side of Figure 6. At this stage, processing in-situ measurements and ex-situ observations from the conducted experiments remain in the pipeline and their evaluations will be considered in subsequent fundings.

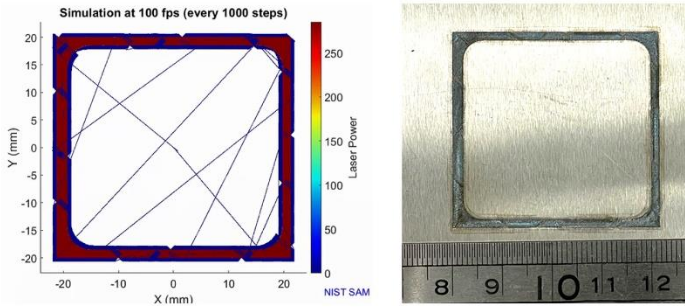


FIGURE 6: SIMULATION OF L-PBF PROCESS PLAN AT 100 FRAMES/SECOND (LEFT) AND PROOF OF CONCEPT 5 LAYER BUILD (RIGHT).

Following the development of the STEP-NC representation for point AM operations, several challenges have been realized. When defining data representations for the STEP-NC compliant `AM_zerod_operation` entity, many combinations of attributes and datatypes could be formulated to achieve similar definitions or processes. In addition, the proposed attributes of the STEP-NC compliant pointwise AM operation have been designed to be neutral of AM vendors specifications. However, the proposed representations assume that an AM machine and its instruments meet functional requirements such as AM machine instrument calibration and command control synchronization. Furthermore, the design of definitions that're associated with specific AM technologies might lead to overspecification of parameters that require explicit declarations, which could also impact other parameters that derive their values from other parameters. Therefore, defining an attribute should satisfy not only the syntax of the definition, but also the semantics that represent its purpose and function.

6. CONCLUSION

This paper proposed hierarchical methods for establishing authoritative, referential data models in AM. First, STEP-NC compliant definitions were developed to represent the discretization of AM processes with pointwise control [5] capabilities. Second, multi-dimensional scaling and discretized point-based representations were utilized for mapping process observations to authoritative part and process definitions. Simulation results and proof-of-concept fabrication demonstrated the viability of the proposed STEP-NC definitions, and the potential for linking AM process and post-process observations to their corresponding authoritative definitions over spatial and temporal domains. Therefore, the facilitation of traceable information through authoritative definitions streamlines AM process qualification and part acceptance, and maintain reliable and referential data for Digital Twin frameworks as well as intelligent analytics and real-time control opportunities.

DISCLAIMER

Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST; nor does it imply that the products identified are necessarily the best available for the purpose. Further, any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NIST or any other supporting U.S. government or corporate organizations.

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