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A Collaborative Data Management System for Additive Manufacturing

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ABSTRACT
As additive manufacturing (AM) continues to mature as a production technology, the limiting factors that have hindered its adoption in the past still exist, for example, process repeatability and material availability issues. Overcoming many of these production hurdles requires a further understanding of geometry-process-structure-property relationships for additively manufactured parts. In smaller sample sizes, empirical approaches that seek to harness data have proven to be effective in identifying material process-structure-property relationships. This paper presents a collaborative AM data management system developed at the National Institute of Standards and Technology (NIST). This data management system is built with NoSQL (Not Only Structured Query Language) database technology and provides a Representational State Transfer (REST) interface for application integration. In addition, a web interface is provided for data curating, exploring, and downloading. An AM data schema is provided by NIST for an alpha release, as well as a set of data generated from an interlaboratory study of additively manufactured nickel alloy (IN625) parts. For data exploration, the data management system provides a mechanism for customized web graphic user interfaces configurable through a visualization ontology. As a collaboration platform, the data management system is set to evolve through sharing of both the AM schema and AM development data among the stakeholders in the AM community. As data sets continue to accumulate, it becomes possible to establish new correlations between processes, materials, and parts. The functionality of the data management system is demonstrated through the curation and querying of the curated AM datasets.

1 INTRODUCTION
Additive manufacturing (AM) is a process capable of building up complex shapes layer upon layer directly from a three-dimensional digital representation. As a production technology, AM minimizes the time lag between design and realization of a part while enabling novel design opportunities. However, since both the shape and the material properties of parts are formed during the AM process, manufacturers and end users have difficulty in predicting whether parts will meet specifications (shape, surface and material properties) and ensuring repeatability, consistency, and reliability across different AM machines and locations. Qualification of additively manufactured parts is one of the most serious hurdles to the broad adoption of additive manufacturing [1]. A key step in overcoming these hurdles is to characterize AM materials and geometry- -process-structure-property relationships.

To develop such relationships, sufficient information about feedstock materials, processes, machines, and final part performance tests must be collected and analyzed accordingly. Such an effort requires a well-populated database containing the necessary pedigreed information. This task is difficult and extremely expensive for any single company, especially given the limitation of currently available standard methods and protocols for AM feedstock material characterization and AM part property testing [2].

Several data system development efforts have been reported for AM. For example, the Senvol Database [3] provides researchers and manufacturers with open access to industrial AM machines and materials information. A search on the Senvol Database finds properties of most industrial additive manufacturing machines and materials, and information on their compatibility. Granta, a material information management technology provider, has collaborated in several European Framework Seven projects in the field of material information management. The results from those projects are not currently available for public access, and the underlying data structure ('schema') is proprietary to Granta users. The Materials Selection an Analysis Tool (MSAT) database led by Department of Defense (DOD) was built based on GRANTA:MI [4], which captured some data from NASA and it is available to approved users[5]. None of the existing AM databases are publicly accessible, and none provide a sufficient amount of reliable material property data for much of the necessary AM analytics. These two hurdles are significant barriers to adoption of this emerging transformative technology as a viable production alternative to traditional manufacturing methods, especially for small manufacturers.

To obtain the multitude of data sets rich enough for AM geometry-material-process–structure-property relationship identification, the full processing history of thousands of samples and parts must be monitored and captured. This creates a significant challenge for any individual organization. For a community, however, the matter becomes more realizable. The AM community expects that, with appropriate data driven modeling methods, heterogeneous data sets with a multitude of geometries, material types, and processes can be mined to develop empirical correlations between material properties, microstructure, part geometry and process parameters. Such advancements promise to speed up AM process, material, part qualification and to lead to new AM material discoveries.

This paper discusses our effort to develop a collaborative AM data management system. This data management system is built on the latest NoSQL database technology, providing data storage in clouds structured by an AM lifecycle data schema. The collaborative data management system provides a REST interface for application integration as well as a user-friendly web interface for data curating, exploring, and downloading. Regular users can explore the database through customized web GUIs. Authorized users can contribute to the database population by populating an agreed upon AM schema. Initially, an AM data schema is provided by NIST [6], while iterative improvements are planned through collaborative community development. The first section of this paper presents the overall collaborative AM data management system architecture. Then the second section introduces the initial data model designed for AM lifecycle data management. In the third section, data curation methods are introduced, and a mechanism to develop customizable data exploration views is shown. The final section summarizes the paper, our current development status, and discusses future work.

2 ARCHITECTURE

The top requirements on the collaborative AM data management system are data curation and sharing by multiple types of stakeholders. The open database system will be freely accessible to the AM community including vendors, manufacturers, and researchers. Consistent information should be provided to all stakeholders. Changes made on the database should be validated and relevant stakeholders are notified of any changes. Active and prior schemas will be available to the AM community, accompanied with clear definitions and descriptions of the data attributes. Users are encouraged to participate in improvement and optimization of the common AM schema. To enable these, a friendly GUI is needed with an effective navigation and data browsing scheme. A standard Application Programming Interface (API) will be made available for integration with other applications. For example, loading data into data analytics software such as R and Matlab will help the AM community to develop process-structure-property relationships for AM materials. Finally, it is desired that the system, to the greatest extent possible, be developed on proven technology.

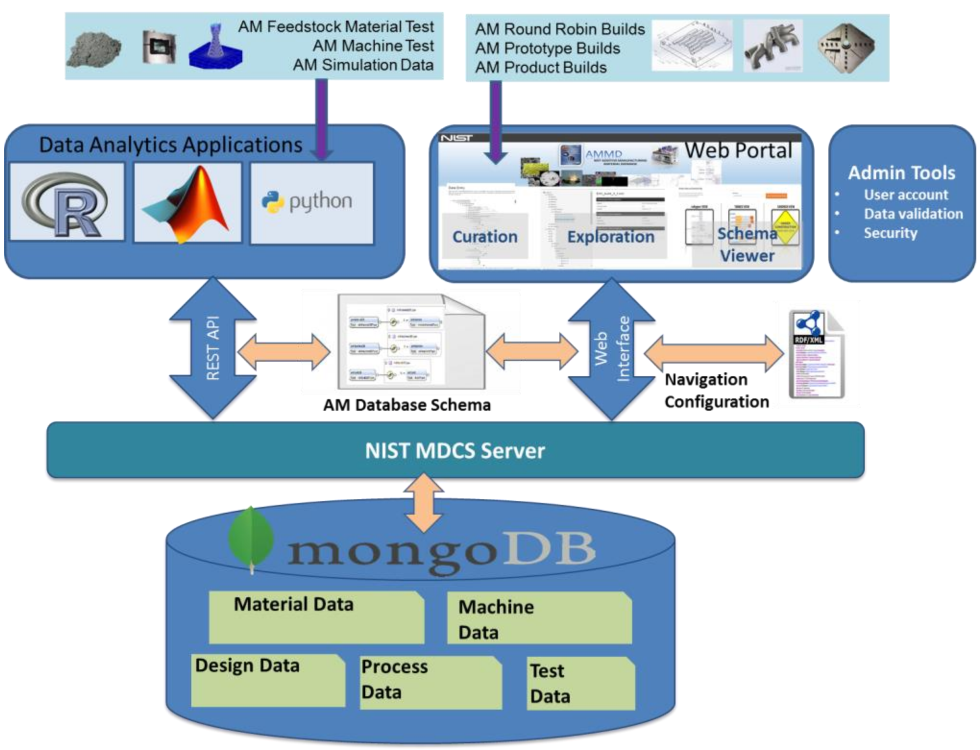


Figure 1: A collaborative data management system architecture

Based on the requirements, several conceptual designs were investigated, including those using commercially available software. However, to avoid the use of proprietary software technologies and proprietary data models, we turn to NIST's own Material Data Curation System (MDCS), a product of the Material Genome Initiative [7][10]. The core of MDCS, the MDCS Server, was identified as a foundational system on which to build our data management system. The NIST MDCS server provides a means for wrapping MongoDB, an open source NoSQL database, and capturing, sharing, and transforming data into a structured Extensible Markup Language (XML)-based format. The server allows users to curate data with user-selected templates encoded in XML. These templates provide data entry forms that can be saved in a MongoDB database to be queried, explored and exported as XML files.

Figure 1 shows the final design of our open access and open structure database system architecture. The system can be summarized as an aggregation of seven main components in five layers. Proceeding from the bottom of the figure up the components are as follows:

1. *Layer 1 - a MongoDB database:* The document-based database stores AM material data and provides scalability for the accumulation of data sets. It can be deployed in a private or public cloud.
2. *Layer 2 - NIST MDCS Server:* The NIST MDCS server wraps MongoDB by providing XML-based templates for data population. It provides basic functions for material data curation, exploration, query, and template composition. In addition, it provides a REST API for application integration.
3. *Layer 3 - NIST AM Database Schema:* The schema is developed to model the data sets in the AM data management system. The schema template is uploaded to the MDCS server for data population. It can be modified in any XML tool, and active and prior schemas can also be viewed and downloaded by end users.
4. *Layer 3 – Data Navigation Configuration:* To enable a user friendly and customizable GUI, an ontology based data exploration mechanism is employed for effective web-based data navigation and browsing by different end users. The navigation configuration file is a Resource Description Framework (RDF)/XML file. The entity annotations defined in the RDF/XML are used to describe specific views and create links to the database items that will automatically be queried. The navigation schema can be automatically updated when the data schema changes. Access to development of this function is limited to the developer role.
5. *Layer 4 - A NIST-hosted web portal:* A web portal is developed for AM data curating, exploring, and downloading. AM material data, AM machine data, build data, and test data can be explored through a customizable navigation schema. In addition, an AM-specific data query capability is provided for searching data records. New data can be curated and added to the database. (This feature is limited to those with appropriate administrative rights.)
6. *Layer 4 - Data Analytics Application Integration:* Using the REST application interfaces, data analytics capabilities provided by Matlab, R, and Python applications can be integrated into the collaborative data management system. Data analysis functions provided by the software can be fully utilized to analyze material properties and mine process-structure-property relationships.
7. *Layer 5 - AM Build, Material, and Test Data:* AM material data, AM machine data, and the complete process history of AM builds can be curated into the data management system through the web user interface or through software tools (e.g. customized Python applications). AM feedstock test data, AM simulation data, and data generated from AM testbeds can be captured into the data system as well. Fusion of these data sets will facilitate AM material characterization, process characterization, and part qualification.

The next several sections elaborate on the main functional components of the NIST collaborative data management system.

3 AM DATABASE SCHEMA

The collaborative data management system is designed for collaborations among AM stakeholders including manufacturers, material vendors, machine builders and the AM research community. The system should capture, store, and manage the data through the entire AM lifecycle and value chains, including part/specimen design, feedstock material data, AM machine data, process parameters, process monitoring and control data, part/material test data, and other pedigreed information. Each of these factors potentially contribute to qualifying the process, as-built parts, materials, and identifying process-structure-property relationships. For example, to highlight possible challenges, process parameters, the feedstock material handling, and even the design of the component can all cause differing thermal properties from layer to layer, leading to excessive internal stresses and build failures. Hence, in addition to feedstock material data, the full processing history of manufactured parts must be captured, stored, and linked in attempt to relate materials, designs, and process parameters with process outcomes. The individual AM machine calibration and maintenance history, as well as their geographic locations, can also contribute to variability of part properties.

The data structure, or schema, provides the backbone of the collaborative data management system. The relationships created by the structure are essential to supporting meaningful data curation and data retrieval. As the collaborative data management system matures through iterations, it is the data structure that will need to evolve to support the development of meaningful relationships that can be used to query and analyze the database.

As part design information and test data are linked to individual builds, we structure the data sets into four types of main entities, as shown in Figure 2. The first entity type "amMaterial" captures vendor material information and vendor provided material properties. The second entity type "amMaterialTest" captures feedstock material properties, e.g., flowability, spreadability etc., provided by the AM community. The third type of entity "amMachine" captures AM machine information. The data captured by these three types are independent of specific builds and can be provided by material vendors, material researchers and machine owners. The fourth type of database entity "amBuild" captures the information related to a specific AM build, including part and specimen design, pre-process, in-process and post process information, as well as test information. Figure 3 shows the data structures of an AM build record in an XML tree structure. These structures are representative of the initial data structure of the database.

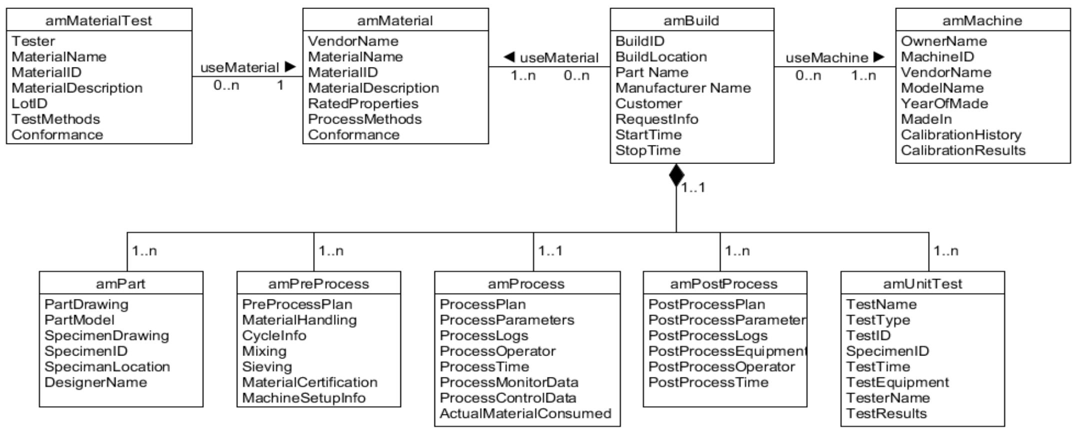


Figure 2: Database Concept Model

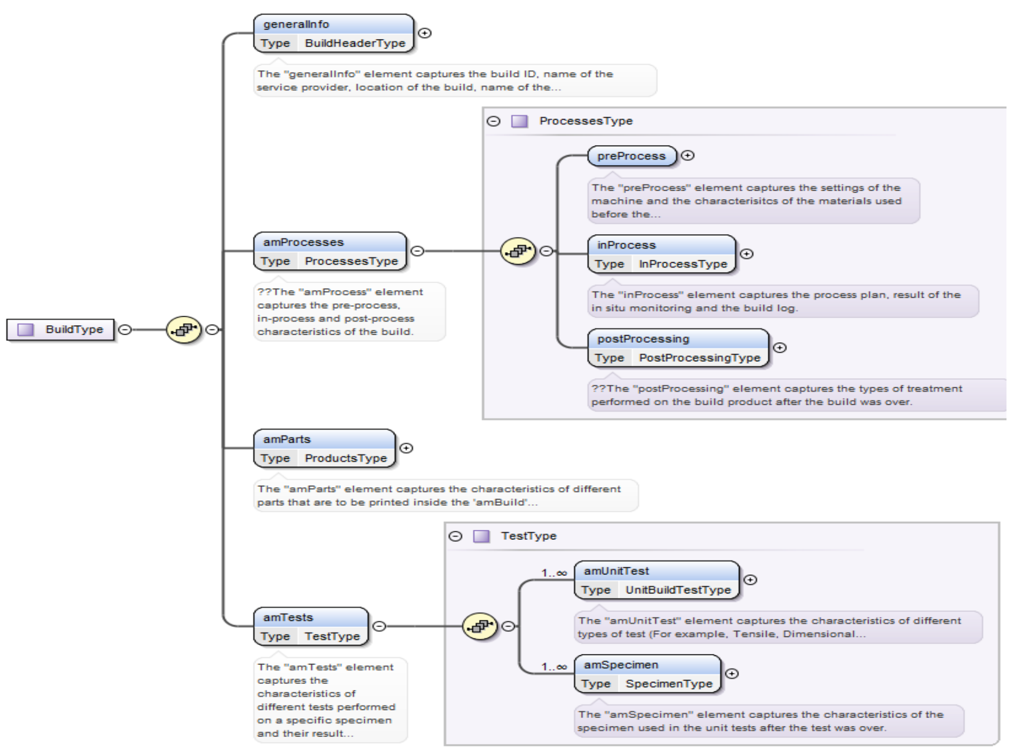


Figure 3: AM Build XML schema.

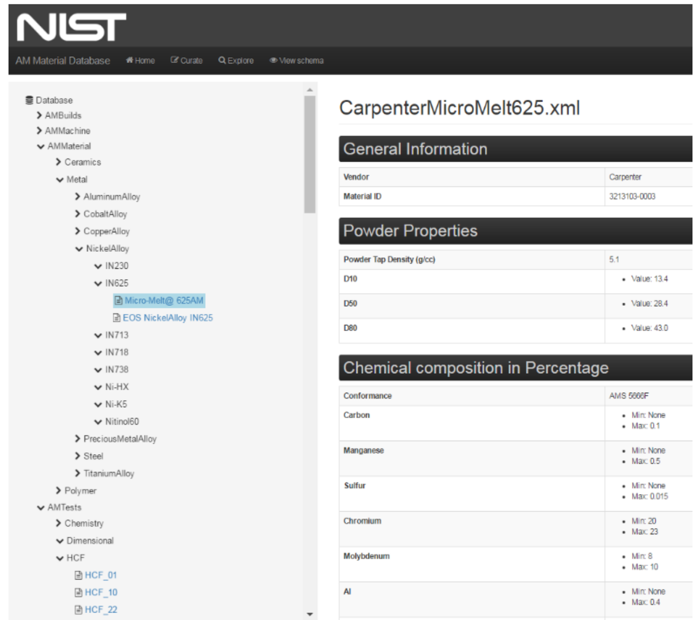
AM Data Curation

Curation of pedigreed data about feedstock material, build process and built-material testing and results is done through a XML-based template. To ensure data integrity, the current instantiation of the curation system only allows data entry by users with appropriate credentials. Figure 4 shows the current design of the template used to instantiate the amMaterial entity in the web portal. An alternative entry mechanism is to curate and edit data by using a POST request as provided by the MDCS REST API. The documents of the REST API are accessible through the web portal as well.

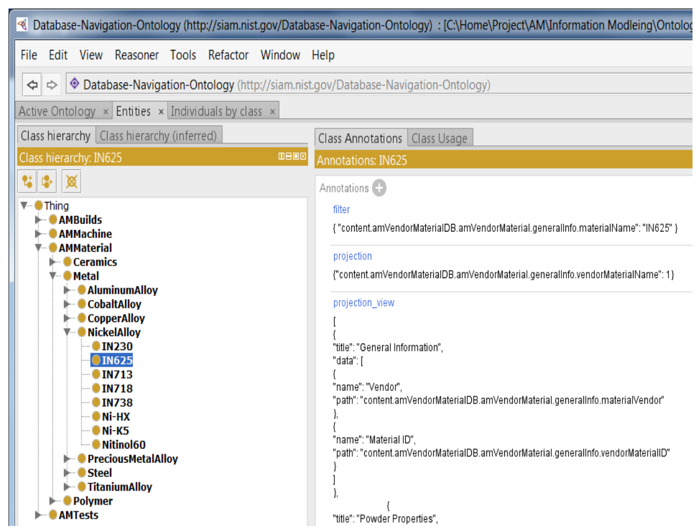
Figure 4: AM vendor provided material data curation.

4 DATA NAVIGATION CONFIGURATION

The functionality and ease-of-use of the data management system is heavily dependent on the abilities and appearance of the Navigation Pane. Custom navigation can help improve efficiency by grouping, highlighting, or hiding objects. The flexibilty of the Navigation Pane allows us to continuously improve usability by making it easier for users to continue to identify the database objects they require as the schema evolves. As shown in Figure 5, The NIST collaborative AM data management system navigation Pane and Views can be customized through an ontology based configuration tool. Here, Protégé, a free, open-source platform is used to construct the collaborative data management system data navigation schemas. Figure 5 shows the current design of the data exploration view and the corresponding ontology configurations.



(a) Data Exploration view



(b) Data navigation configuration using Protégé

Figure 5: Customizable AM data navigation

As shown in Figure 5(b), the class hierarchy defined in the ontology dictates the data navigation pane, as shown in Figure 5(a). The annotations of the leaf nodes as highlighted in the class hierarchy of the ontology define the document types to be searched for, the instances to be shown, and the information of the instances to be displayed. The annotation 'filter' constrains the search path. The annotation 'project' defines the instance to be listed and displayed in the left side navigation pane, and the annotation 'projection_view' defines the information to be displayed for all the instances.

The ontology is modeled in the RDF/XML format and uploaded to our data management system to configure the data exploration view. The navigation schema can be designed based on end-user's requests.

5 RESULTS AND FUTURE WORK

The NIST collaborative data management system has successfully gone through a series of functional tests and security tests both on a local server and in a cloud. Currently an instance of such a data management system is deployed on a NIST public server.

The first batch of data was captured and curated in this server, including a set of round robin test data from a NIST MSAM (Measurement Science for Additive Manufacturing Program) [8] sponsored project. The project investigated four nickel alloy 625 builds produced on three different Laser Powder Bed Fusion machines in argon or nitrogen environments. Except for the machine serial number and build environment, all other conditions of the four builds were specified, including: build geometry, powder lot, process parameter sets, and heat treatment. Each build produced 13 coupons for tensile, high-cycle fatigue (HCF), low cycle fatigue (LCF) and metallurgy tests. The samples cut from mechanical test coupons include both XY build orientation and Z direction orientation. Figure 6 shows the coupon drawing.

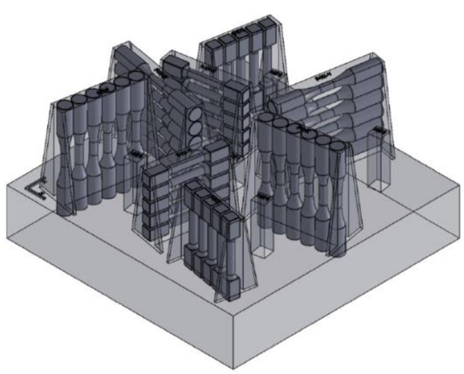


Figure 6: NIST-EWI round robin test coupon drawings

All the build coupons, except those two for chemical analysis, received a stress relief at 1038°C, followed by a hot isostatic pressure thermal treatment at 1121°C. Test samples were cut from the post-processed coupons and mechanical tests were conducted by a third party lab. There are total 40 tensile test reports, 24 HCF reports, 24 LCF reports, two chemical analysis results, 4 hardness test reports, and 8 grain size analysis results available.

Large volumes of structured and unstructured data were generated during the processes, and in various formats, such as CAD models, STL files, excel data sheets and pdf documents. In addition, AM machine data was collected from the machine vendor. All of the stated data was captured in our data management system through manual curation. The first build data was manually entered though the web portal. The other three build data sets were edited on top of the first build data set offline and curated using the REST API. In total, the first set of data instantiation included one AM material document for Carpenter micro-melt 625, three AM machine documents capturing the information about three different EOS M 270 machines, and four AM build documents. The data is instantiated and can be explored based on current navigation schema, as shown in Figure 5 (a).

At its initial release, our system aims to provide a mechanism that will allow AM users to view and download the NIST schema as well as view the first batch of data sets. Its setup allows the AM community to provide feedback on the suitability of the data types, definitions, content, and structure. As the collaborative data management system is meant to support changes in needs and priorities, the tool will easily be able to update schema variations while preserving the previous schema in its archives. While our initial success was based on the demonstration of remote access and data retrieval, we have also demonstrated that the direct integration of Matlab with the AM data management system through the RESTful API simplified any repeatability analysis of the NIST Round Robin data.

After initial Alpha and Beta releases, the next phase of our open data effort will incorporate vetted AM data submitted by the AM community. We look to expand the open data management into a comprehensive collaboration platform, and provide an additional analytical framework for data management with data analytics tools and simulation engines. This effort aligns with NIST's goal for open data to expand public access to NIST research results while maintaining the quality and integrity of NIST data resources. Progress and updates on the NIST-hosted AMMD data management system can be found at https://ammd.nist.gov. The locally-downloadable version of the AMMD data management system software can be found at https://github.com/usnistgov/SIAM-Project.

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DISCLAIMER

Certain commercial equipment, or materials, suppliers, or software are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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