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GAPS ANALYSIS OF INTEGRATING PRODUCT DESIGN, MANUFACTURING, AND QUALITY DATA IN THE SUPPLY CHAIN USING MODEL-BASED DEFINITION

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ABSTRACT

Advances in information technology triggered a digital revolution that holds promise of reduced costs, improved productivity, and higher quality. To ride this wave of innovation, manufacturing enterprises are changing how product definitions are communicated – from paper to models. To achieve industry's vision of the Model-Based Enterprise (MBE), the MBE strategy must include model-based data interoperability from design to manufacturing and quality in the supply chain. The Model-Based Definition (MBD) is created by the original equipment manufacturer (OEM) using Computer-Aided Design (CAD) tools. This information is then shared with the supplier so that they can manufacture and inspect the physical parts. Today, suppliers predominantly use Computer-Aided Manufacturing (CAM) and Coordinate Measuring Machine (CMM) models for these tasks. Traditionally, the OEM has provided design data to the supplier in the form of two-dimensional (2D) drawings, but may also include a three-dimensional (3D)-shape-geometry model, often in a standards-based format such as ISO 10303-203:2011 (STEP AP203). The supplier then creates the respective CAM and CMM models and machine programs to produce and inspect the parts. In the MBE vision for model-based data exchange, the CAD model must include product-and-manufacturing information (PMI) in addition to the shape geometry. Today's CAD tools can generate models with embedded PMI. And, with the emergence of STEP AP242, a standards-based model with embedded PMI can now be shared downstream.

The on-going research detailed in this paper seeks to investigate three concepts. First, that the ability to utilize a STEP AP242 model with embedded PMI for CAD-to-CAM and CAD-to-CMM data exchange is possible and valuable to the overall goal of a more efficient process. Second, the research identifies gaps in tools, standards, and processes that inhibit industry's ability to cost-effectively achieve model-based-data interoperability in the pursuit of the MBE vision. Finally, it also seeks to explore the interaction between CAD and CMM processes and determine if the concept of feedback from CAM and CMM back to CAD is feasible. The main goal of our study is to test the hypothesis that model-based-data interoperability from CAD-to-CAM and CAD-to-CMM is feasible through standards-based integration. This paper presents several barriers to model-based-data interoperability. Overall, the project team demonstrated the exchange of product definition data between CAD, CAM, and CMM systems using standards-based methods. While gaps in standards coverage were identified, the gaps should not stop industry's progress toward MBE. The results of our study provide evidence in support of an open-standards method to model-based-data interoperability, which would provide maximum value and impact to industry.

INTRODUCTION

Information technology advances such as big data, service-oriented architectures, and networking have triggered a digital revolution [1] that holds promise of reduced costs, improved productivity, and higher quality. Modern manufacturing enterprises are both more globally distributed and digital than ever before, resulting in increasingly complex manufacturing system networks [2, 3]. Manufacturers are under mounting pressure to perform digital manufacturing more efficiently and effectively within these distributed manufacturing systems. To do so, industry is changing how product definitions are communicated – from paper to models. The transition to model-based enterprise (MBE) has introduced new requirements on data usage in the manufacturing systems. The need for automated methods to collect, transmit, analyze, and act on the most appropriate data is gaining attention in the literature [4-7]. In addition, the MBE strategy must ensure model-based-data interoperability between design activities (e.g., product and assembly design) and manufacturing activities (e.g., fabrication, assembly, and quality assurance).

Tool developers of model-based data exchange have primarily focused on computer-aided design (CAD)-to-CAD data interoperability and long-term data archival. While computer-aided manufacturing (CAM) and (coordinate measurement machine (CMM) systems[1] can also ingest model-geometry data and product-and-manufacturing information (PMI) through their respective application program interfaces (APIs), they do so through vendor-specific formats.

A team of Aerospace and Defense industry sector members, software solution providers, and researchers from the National Institute of Standards and Technology (NIST) conducted a study of model-based-data interoperability across the product lifecycle – focusing on design, manufacturing, and inspection.

Our objective was to test the hypothesis that model-based-data interoperability from CAD-to-CAM and CAD-to-CMM is feasible through standards-based integration.

The project team used the recently published STandard for the Exchange of Product (STEP) model data, ISO 10303-242:2014 [8] titled "Managed Model Based 3D Engineering," or STEP AP242, as our standards-based format exported from the CAD system. Many CAM and CMM solution providers use either the ACIS or Parasolid geometric-modeling kernels, so the project team considered these geometric-modeling kernels to be defacto standards. In the research, the project team translated native 3D-CAD models with PMI to the STEP AP242 standards-based format and exchanged the validated translations with a Parasolid-based CAM system and ACIS-based CMM system.

Now, with the introduction of STEP AP242, the project team asked if industry has the tools it needs to move toward the MBE vision. Can industry achieve a vision that includes model-based-data interoperability when going from design to manufacturing and inspection across the supply chain?

The project team identified, in our study, several barriers to model-based-data interoperability. The first barrier is that the majority of industry still considers the two-dimensional (2D) drawing the legal master data record, versus the three-dimensional (3D) model. There is also a significant learning curve for data authors to effectively enrich a 3D-CAD model with the 3D annotations and data that are needed to support downstream processes. Also, in the context of automation, many APIs do not adequately support reading and writing of standards-based PMI. In addition, easy data exchange through standards-based implementations threatens to upend the business model of major product-lifecycle management (PLM) tools. Lastly, the CAM and CMM markets are distributed across many small-to-medium enterprise (SME) manufacturers, which lack industry's ability to drive CAM and CMM solution providers to implement standards-based solutions.

BACKGROUND

In the United States, the manufacturing supply base consists significantly of SME manufacturers. Today, suppliers predominantly use CAM and CMM models to conduct manufacturing and inspection activities. An OEM typically sends the product definition to suppliers in the form of full-detail 2D drawings, which are in most cases the legal master data form. Thus, suppliers spend considerable time converting 2D product-definition data back to usable 3D product definition. Research supports the business case and benefits of MBE [9]. The widespread adoption of MBE would eliminate these manual conversions, which are time consuming and may introduce error.

More recently, the product-definition data delivered to suppliers also includes a 3D-shape-geometry model. This shape-geometry model is often provided in a standards-based format, typically ISO 10303-214:2010 (STEP AP214) [10] and ISO 10303-203:2011 (STEP AP203) [11]. However, in addition to shape geometry, the CAM and CMM processes require additional, non-geometric information (PMI) to fabricate and inspect the part. This information may be presented for human consumption in the STEP AP203 exchange, but it is not available in a computer-processable form.

MBE strategy must include model-based-data interoperability for design to manufacturing and quality in the supply chain. In MBE, data authors use computer-aided-design (CAD) tools to create a model-based definition (MBD). A MBD is a 3D digital-product model that defines the requirements and specifications of the product – including computer-processable PMI in the form of 3D annotations and data. Figure 1 presents an example of a MBD. After releasing the MBD, an original-equipment manufacturer (OEM) sends the MBD to a supplier to manufacture and inspect the physical parts.

Despite the industry MBE vision to become model-based, there is still a reliance on 2D drawings. A survey [12] of SME suppliers showed that many of those surveyed still receive design data from their OEM customers in the form of full-detail-2D drawings. Another large group receives a 3D-shape-geometry model combined with a 2D drawing containing the PMI. Only a small percentage of the SME manufacturers

[1] NOTE: The term "Coordinate Measurement System" (CMS) is gaining in popularity to describe the evolution of the metrology domain towards an integrated system of both coordinate measurement software and hardware.

receive just a 3D model with embedded PMI. The design to manufacturing process is still very much drawing-based. The few data exchanges that are model-based with embedded PMI use proprietary, not standards-based, models [13].

A widely used standard format is STEP. Its development started in 1984 with the objective to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving [14].

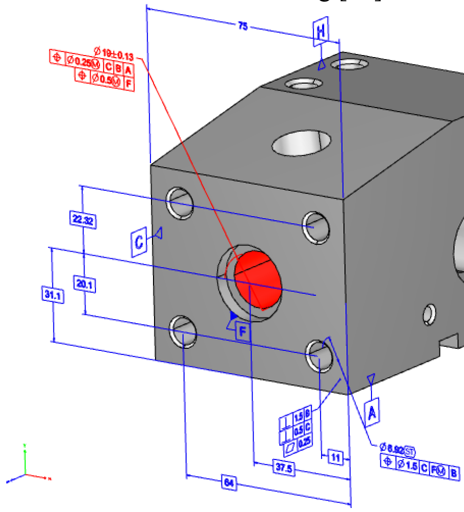

Figure 1: Example model-based definition

STEP includes a series of integrated data models known as application protocols (APs). There are dozens of STEP APs, which fall into the three main areas – design, manufacturing, and lifecycle support.

Today, both STEP AP203 and AP214 are still one of the most important parts of ISO 10303. Many CAD systems support STEP AP203 and AP214 for importing and exporting data. According to another survey [12] of SME manufacturers, STEP AP203 is the most commonly used format for CAD-to-CAD data interoperability. However, the STEP AP203 model contains only shape geometry, and not the PMI necessary for downstream processes.

In December 2014, the International Standards Organization (ISO) published the first edition of the application protocol STEP AP242, which combined and replaced several APs related to the presentation and representation of product-definition data. In addition, STEP AP242 contains extensions and significant updates for dimensional and geometric tolerances, kinematics, and tessellation. In other words, STEP AP242 offers standards-based models that include the representation of PMI that is computer interpretable [15]. This is a major breakthrough that supports manufacturing's need for model-based CAM and CMM processes.

While standards-based exchange provides significant benefit to industry, one challenge that must be addressed is verification and validation of translations, ensuring adequate product-data quality. The need for confidence in the conformance of 3D model data to quality standards is well understood [16]. Requirements for verification of model data, particularly PMI data, and validation of derivative variants of that data for collaboration purposes are now in place [17]. These concepts were taken into account in our study.

EXPERIMENTAL SETUP

The flow diagram shown in Figure 2 demonstrates the data-exchange process from CAD-to-CAM and CAD-to-CMM, using commercially available solutions. Rockwell Collins performed as the OEM. Rockwell Collins designed the test parts using Siemens NX™ CAD software.

Geater Machining and Manufacturing performed as the supplier. Geater used CNC Software's Mastercam® for numerical control programming for the manufacture (milling and turning) of the test parts. Geater used Mitutoyo MiCAT™ Planner automatic measurement program generation software to enable inspection of the test parts.

The data-exchange process required the use of CoreTechnologie 3D_Evolution© to convert data from the native NX™ CAD model into the standards-based STEP AP242 format. ITI PDElib® data exchange library was used to complete the import from STEP AP242 into Mastercam®. ITI eACIS utility library was used to complete the import from STEP AP242 into the ACIS® kernel used by MiCAT™ Planner.

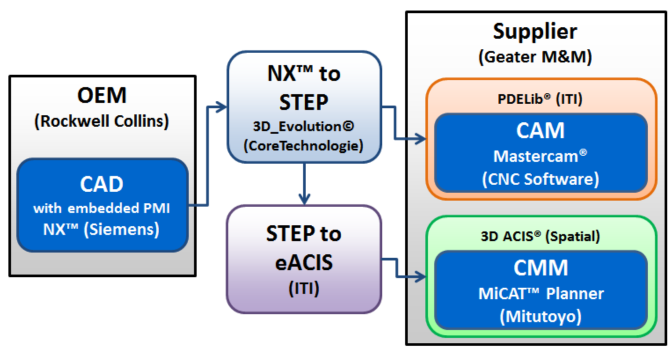

Figure 2: Data exchange process flow diagram

OEM and supplier components (see Figure 2) in the information-exchange process were analyzed to understand their constituent steps. The project team utilized two test cases – both a turned and a milled part. Figure 3 shows the test case models used in this project. Figure 3(a) is the turned test case and Figure 3(b) is the milled test case.

The OEM process steps – 3D-CAD-model creation and 2D-PDF-drawing creation – represent the activities most likely affected by the inclusion of embedded PMI in the CAD model necessary for downstream manufacturing and inspection. In addition to these activities, CAD tool issue resolution, designer education, as well as CAD model resolution to address CMM issues were also required. The OEM metrics captured for this research focus primarily on these CAD-model creation process steps, but also provide some insight into CAD-model validation and verification processes.

The CAM-process steps represent the activity involved in CAM-model creation. The project focused on those data elements most useful to the supplier for CAM-related process.

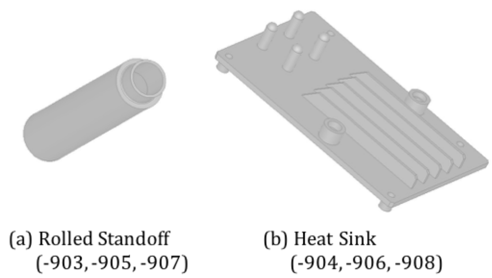

Figure 3. Test case models used in the project workflow

These elements demonstrate the difference between the current-state and the future-state process steps. They must provide enough detail to demonstrate the process areas significantly affected when ingesting models with embedded PMI for CAM programming. Finally, the elements need to align with the supplier process steps such that they can be easily recorded. The supplier completed the CAM-model-creation-process steps using the three technical data exchange scenarios and reported any observed data problems.

The project reviewed the manufacturing process steps identified in the NIST Testing the Digital Thread project [9]. The research compared these process steps to the manufacturing checklist steps used by the supplier. In the comparison, four general process step segments were identified.

Table 1: Process steps for manufacturing and inspection

Step	Manufacturing Process Steps	Inspection Project Steps
1	CAM Process Preparation	CMM Process Preparation
2	CAM Setup	CMM Setup
3	CAM Programming	CMM Programming
4	CAM Verification	CMM Verification
5		CMM Data Analysis

The CMM-process steps were identified in a similar way to the CAM process. Inspection steps previously defined in the NIST Testing the Digital Thread project [9] were compared to the steps in the supplier check-list for inspection. In the comparison, five general process step segments were identified. The final process steps are shown in Table 1.

As stated earlier, there are substantial benefits in switching from traditional 2D-drawing-based methods to 3D-model-based methods for transferring design information to manufacturing and inspection. However, product definitions are only useful to suppliers if the product-data quality is high. Verification of product-data quality in 2D drawings is done typically by visually inspecting the drawing for compliance with standards and best practices.

A standards-based workflow for design to manufacturing and inspection involves exchange of CAD-to-AP242-to-CAM-and-CMM models. Validation and verification of this translation process is critical, especially for regulated industries. An important part of quality assurance is traceability back to the design definition. To assure compliance at any point in the manufacturing or inspection process, it is essential to have validation and verification of the models throughout the data-exchange process.

When moving to a model-based paradigm, the verification process is more complex since the goal is for the model geometry and PMI to be consumed directly by downstream software systems. Verification in this context requires each and every PMI element be analyzed for syntactical and semantic accuracy, including proper association of the PMI to geometric references in the 3D geometry.

In addition to verifying that PMI content has been authored correctly, each time the data is transformed – from CAD to STEP and from STEP to CAM/CMM – the data must be validated to be sure no data corruption occurred during the transformation process. Since the information content in the 3D model is no longer in the form of a visually inspectable 2D drawing, software algorithms are required to perform the verification and validation processes on all but the simplest models.

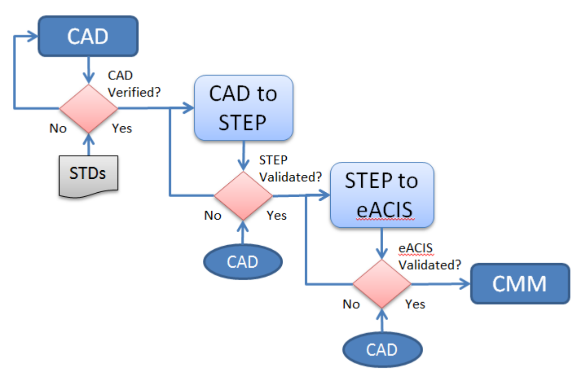

Figure 4: Verification and validation work-flow diagram

Real production models for two machined aerospace parts were used as the basis for testing the performance of the previously discussed processes and observing roadblocks that hampered process performance.

In the case of this experiment, the project team performed verification and validation following the work-flow outlined in Figure 4. The project team performed verification and validation using a combination of traditional visual inspection techniques and automated techniques. In general use on more complex models, automated techniques would have been required.

Table 2: CAD model creation metrics

CAD Metrics	***Rolled Standoff*** 			***Heat Sink*** 		
827-9999	**-903**	**-905**	**-907**	**-904**	**-906**	**-908**
2D PDF drawing	---	full dimension with 2D PMI annotation	key 2D PMI annotation only (PDD)	---	full dimension with 2D PMI annotation	key 2D PMI annotation only (PDD)
3D model	includes embedded PMI	not provided	with no embedded PMI	includes embedded PMI	not provided	with no embedded PMI
Number of PMI entities	23 (24*)	---	---	78 (90*)	---	---
CAD tool issue resolution and designer education	9.0 hours	0.5 hours	0.1 hours	4.9 hours	0.5 hours	0.1 hours
CAD model resolution to address downstream issues	2.3 hours + 4.5 hours to enhance process	---	---	3.0 hours + 1.3 hours to enhance process	original drawing missing dimension – rework required	---

* Original PMI entity count based on objects found in the NX Part navigator – eventually reduced count by issue resolution

RESULTS

Results from CAD Model Creation

Results and test case characteristics for the CAD model creation are shown in Table 2. For each test case, three data sets were generated. The future-state data sets (-903 and -904) included the 3D model (STEP AP242) with embedded PMI for the two test cases. The current state had two significant data sets to compare against the future state. The first current-state data set (-905 and -906) provided a full-annotated-2D drawing with dimensions and PMI. The part is represented fully and can be manufactured from the drawing. The second current-state data set (-907 and -908) contains the 3D-shape-geometry model (STEP AP203) and a 2D drawing with the PMI. The -907 and -908 data sets require both the model and the drawing together to manufacture the part.

Results from Mapping PMI between STEP and ACIS

The following PMI gaps were identified when mapping PMI between STEP AP242 and ACIS:

- Spherical dimension types (`RADIUS`, `DIAMETER`) are missing from ACIS
- Oriented and curved dimensions are missing from ACIS
- ACIS does not support angle selection (`SMALL`, `LARGE`, `EQUAL`) in an angular dimension
- Tolerance principal (`ENVELOPE`, `INDEPENDENCY`) is not supported by ACIS
- Dimension value with plus/minus bounds is not supported by ACIS
- Dimension value with qualifier (`MAXIMUM`, `MINIMUM`) is not supported by ACIS
- Limited support for dimension modifiers (`BASIC`, `REFERENCE`, `STATISTICAL`) by ACIS, many are missing (`CONTROLLED RADIUS`, `FREE STATE`, ANY CROSS SECTION, etc.)
- Movable datum target is not supported by ACIS
- Geometric tolerance type (`COAXIALITY`) is missing from ACIS
- Limited support for tolerance zone types (`DIAMETER`, `SPERICAL DIAMETER`, `PROJECTED`) by ACIS, some are missing (`NON-UNIFORM`, `RUNOUT`, `WITHIN A CIRCLE`, etc.)
- Limited to no support for tolerance modifiers (`FREE STATE`, `LMC`, `MMC`, `RFS`, `STATISTICAL`, `TANGENT PLANE`) by ACIS, many are missing (`ANY CROSS SECTION`, `COMMON ZONE`, etc.)
- Limited to no support for datum reference modifiers (`LMC`, `MMC`) by ACIS, many are missing (`FREE STATE`, `BASIC`, `TRANSLATION`, etc.)
- ACIS does not directly support POLYLINE presentation of PMI

Table 3: Validation of model transformations using embedded PMI entity count

PMI Elements (by format)	NX		STEP		ACIS		Mastercam		MiCAT	
Model (827-9999)	**-903**	**-904**	**-903**	**-904**	**-903**	**-904**	**-903**	**-904**	**-903**	**-904**
Dimension	8	54	8	54	8	54	8	54	8	54
Tolerance	6	13	6	13	6	13	6	13	6	13
Datum Feature	2	3	2	3	2	3	2	3	2	3
Notes (not semantic data)	7	8	7	8	0	0	7	8	0	0
Total	23	78	23	78	16	70	23	78	13	68

Results from Embedded PMI Data Exchange

Development and demonstration of a process to exchange standards-based models with embedded PMI from design to downstream systems was successful within the scope of the limited test models used in this project. The validation results, as defined by PMI element counts, for the downstream models are provided in Table 3. The validation shows that all dimensions, tolerances, and datum features were properly transformed and exchanged.

As indicated in Table 3, general notes could not be mapped to ACIS and were not transferable to the MiCAT Planner. Although manual validation showed correct PMI counts (for PMI other than general notes), further detailed examination by automated validation of the downstream models using analysis software found anomalies in the transformed data.

Table 4 shows the results of automated validation of model transformations. In the -904 model, the automated validation tool showed that though all dimensions were transformed and, for the most part, semantically correct, a rule violation occurred when the dimension tolerance zone for one dimension was considered too large relative to its nominal value. The -903 model, like the -904 model, was flagged for an instance of this same rule violation. The -903 model was also flagged for failure to maintain the semantic definition of limit dimensions in four instances of that dimension type when transformed from STEP to ACIS.

Table 4: Validation of models using analysis software

Model File	DFS[2] Clean	DIM[3] Clean	FCF[4] Clean	Clean Percent
827-9999-903	2	3	6	69%
827-9999-904	3	53	13	99%

The counts shown in Table 4 refer to the number of entities that are clean (e.g., pass all syntax and semantic validity checks during analysis of STEP to ACIS transformations). The clean percent ignores note entity errors.

[2] DFS = Datum Feature Symbol
[3] DIM = Dimension
[4] FCF = Feature Control Frame

DISCUSSION AND CONCLUSION

The results of this testing provide evidence to support the hypothesis that STEP AP242 with embedded PMI can successfully exchange model-based data from design (CAD) to manufacturing (CAM) and inspection (CMM). The experimental findings of our study fall within the areas of tools, standards, and process, as detailed below.

Tools

This research provides evidence that there is benefit from the CMM-system ability to interpret embedded-PMI information versus using nominal-shape-geometry-model dimensions. It is anticipated that the same benefit could be gained by CAM software as well. While the basic ability to receive the embedded PMI was achieved, the CAM tools require further development to fully leverage the benefit of receiving that data.

In a number of instances, embedded PMI created by the designer does not align well to the needs of downstream-machine consumption. Since PMI-authoring capabilities of CAD systems evolved from origins where 2D visualization of PMI was the requirement, current CAD systems allow designers to create PMI content that is, at best, only partially useable for downstream consumption. Embedded-PMI rules could be implemented in CAD systems to better align model creation with the downstream-machine-interpretation expectations.

CAD-model structures are also not optimized for downstream consumption. The ability to capture groupings of design features to represent geometric sets that correspond to equivalent manufacturing features is needed for downstream use and no method exists currently to achieve this functionality.

Standards

The project team recommends that the STEP community (standards development and implementer forum) should address certain gaps. During the course of the project, it was observed that there is incomplete PMI coverage and documentation of recommended practices for the standards.

Two examples illustrate the need for more coverage. There is the industry practice to use an unless-otherwise-specified tolerance callout as a general note. Although a workaround was achieved, a recommended practice is needed for this often-used callout to properly account for the required geometry associations.

The other example is surface-finish PMI, which is also not yet implemented by the STEP community. A development activity to support this construct is necessary. This also necessitates a recommended-practice document and the introduction of a test case into future test rounds of the STEP CAx Implementer Forum [18]. Formal extension of the ACIS format is also necessary for complete transformation of PMI data content.

Alternatively, the new Quality Information Framework[19] (QIF) format appears to show potential as a better standard for supporting inspection. In this project, QIF was also mapped against STEP and ACIS. QIF appears to be more complete than ACIS for PMI transfer. QIF also shows promise for allowing metrology results to be shared back to design. As a result, QIF may become the standard of choice for metrology, but additional research is necessary once downstream tools begin supporting QIF more widely as an import mechanism.

Processes

It was clear that designer education is not aligned with requirements for downstream-PMI consumption, especially for machine-interpretable expectations. Industry needs recommended practices for proper association of PMI to geometry elements.

There would also be value in a post-process to repair PMI geometry associations so they are complete and consistent. CAD systems should be augmented to provide design rules for creation of embedded PMI with downstream-machine consumption in mind or, at a minimum, recommended-practice documents need to be developed to guide designers as they annotate 3D models with PMI data.

Verification tools are needed to ensure that recommended practices are followed prior to the release of models for downstream consumption. Also, automated validation tools are required to insure information content is not lost or misinterpreted during transformation to formats needed for downstream consumption.

The latest version of AS9102 [20], the aerospace standard for reporting First Article Inspection (FAI) results, suggests potential exists to improve FAI reporting, particularly through automation. There is also potential for developing a visual presentation that integrates metrology results with MBD. Lastly, there is potential to provide metrology-results feedback to upstream users for analysis and prediction to better consider design decisions and manufacturing technologies for future products.

Summary

In summary, motivation exists for industry to continue its drive for the MBE vision through model-based data interoperability for design to manufacturing and quality inspection. A number of conclusions have been drawn from the research presented here. An attempt has been made to organize them broadly into categories of tools, standards, and processes.

Fundamentally, the project successfully demonstrated standards-based CAD-to-CAM and CAD-to-CMM data interoperability when using STEP AP242 with embedded PMI. In doing so, there were many issues uncovered — some the project team was able to address within the scope of the current research activity and others require further effort to overcome.

Some significant gaps were identified as well. These gaps will need to be addressed through changes in the tools, standards, and processes used currently to share information from design to manufacturing and inspection across the supply chain.

While this project was based upon a small-sample-size demonstration, the authors believe the results are potentially scalable for increased model complexity and PMI-element counts. Additionally, the project team tested the most popular modelling kernels used by CAM and CMM tools. The results suggest that the CAD/CAM/CMM workflow is scalable to all tools that use the ACIS or Parasolid geometric-modeling kernels. However, it is recommended that additional testing of the process be completed over a broader sample size.

Future research should seek opportunities to increase the number and variety of participants in the testing activity. This would result in a broader range of example data to work from and provide the opportunity to better assess the impact of variation in both design and processes.

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- 70NANB14H256, International TechneGroup Incorporated, “Validation for Downstream Computer Aided Manufacturing and Coordinate Metrology Processes”

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