NIST Advanced Manufacturing Series 100-22

Proceedings of the 9th Model-Based Enterprise Summit (MBE 2018)

Thomas Hedberg, Jr.
Mark Carlisle

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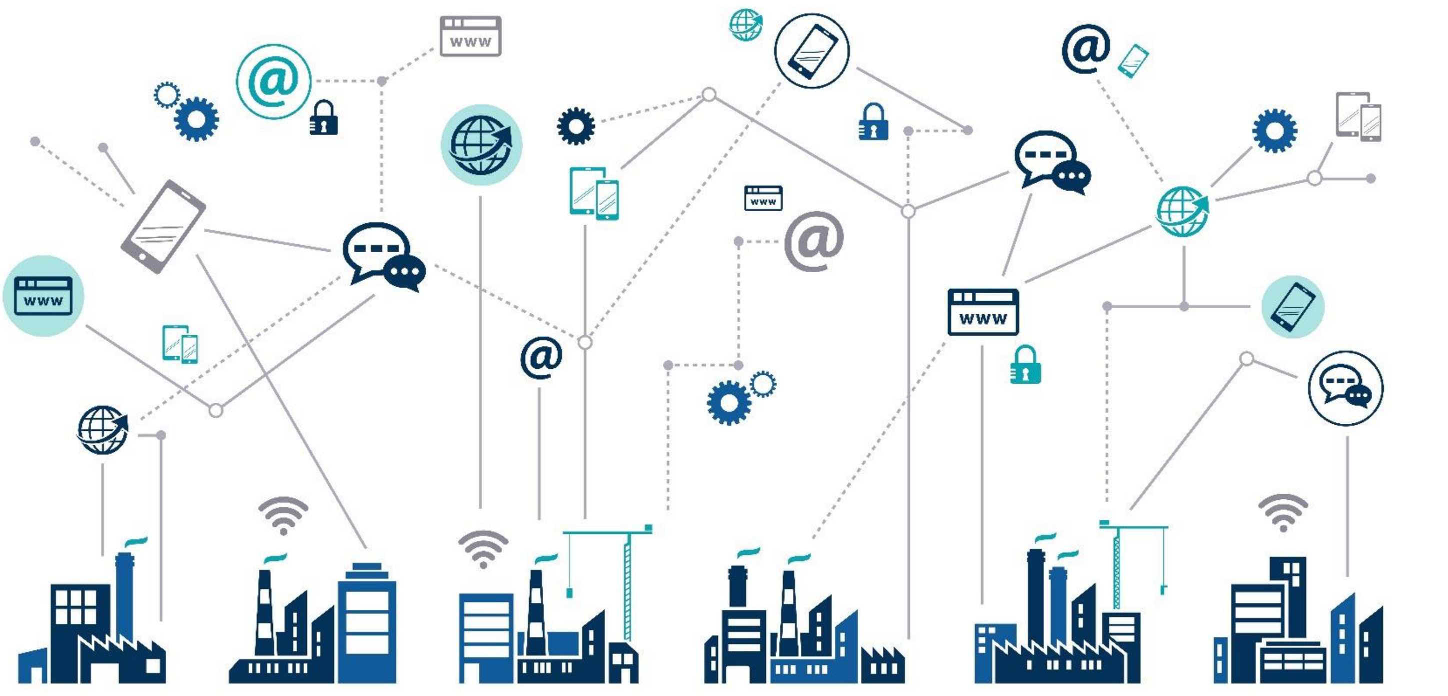

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Introduction

The ninth installment of the Model-Based Enterprise (MBE) Summit was hosted at the National Institute of Standards and Technology (NIST) on April 2-5, 2018. The MBE Summit 2018 witnessed another year-over-year registration growth. This speaks to the growing interest of MBE within the community and the importance of the Summit output.

The MBE Summit 2018 Program Committee undertook a significant effort to ensure a high-quality summit and signal to the community that the MBE Summit is the best place for gathering and sharing information dedicated to the digital transformation across the product lifecycle. The MBE Summit 2018 focused on empowering the industrial shift to MBE with recommended practices and how-to guidance. The MBE Summit 2018 theme was *Empowering the Digital Transformation with an Integrated Lifecycle*, with technical tracks spanning across Systems Engineering and Lifecycle Management, Design Recommended Practice and Model-Based Definition, Model-Based Manufacturing, and Model-Based Quality and Inspection. The MBE Summit had 70 submissions for presentation, of which the Program Committee accepted eight papers, 33 presentations, five posters, and two panels. This report is the proceedings of the MBE Summit 2018.

Program Committee

The Program Committee (PC) was responsible for the functional organization and technical content of MBE Summit 2018. It prepared the final list of conference topics and invited speakers, selected contributed papers, presentations and posters from amongst the submitted abstracts and refereed contributed papers. The PC consists of:

Thomas Hedberg, *Summit Chair* National Institute of Standards and Technology

Mark Carlisle, *Summit Coordinator* National Institute of Standards and Technology

Allison Barnard Feeney National Institute of Standards and Technology

Fred Constantino American Society of Mechanical Engineers

Daniel Finke The Pennsylvania State University

Kevin Fischer Rockwell Collins

Gregory Harris Auburn University

Anthony Holden U.S. Army

Paul Huang U.S. Navy, Office of Naval Research

Ben Kassel LMI, formerly of the U.S. Navy

Karla Quigley National Institute of Standards and Technology

Tony Still U.S. Army

Kym Wehrle Digital Manufacturing and Design Innovation Institute

Steve Weinman American Society of Mechanical Engineers

Phil Zimmerman Office of the Deputy Assistant Secretary of Defense for Systems Engineering

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Papers

Track 2: Design Recommended Practice and Model-based Definition

Presentation Executive Summaries

Track 1: Systems Engineering and Lifecycle Management

Track 2: Design Recommended Practice and Model-based Definition

Track 3: Model-based Manufacturing and Quality

Challenges of using Current Modeling Capabilities in Innovative Technology Development

David Gregory
Ursa Major Technologies
Berthoud, CO, USA

ABSTRACT

Innovations in CAD tools and processes will enable additive manufacturing to continue to mature as a revolutionary process. Ursa Major Technologies utilizes additive manufacturing extensively in its line of rocket propulsion products and uses conventional CAD tools and processes. However, some parts require non-conventional design information. Examples of additive part and process flows will be presented to highlight challenges and opportunities for future CAD innovation.

BIOGRAPHY

David Gregory is the Chief Technology Officer for Ursa Major Technologies, a Colorado-based manufacturer of turnkey propulsion solutions for a wide range of vehicles sized for servicing the micro- and nano-satellite launch community. He oversees technical and engineering processes for Ursa Major's Oxidizer Rich Staged Combustion engine family in a fast-paced R&D environment.

Mr. Gregory graduated with a Master of Science degree in Mechanical Engineering from Tennessee Technological University and went to work as a Research Engineer at the Naval Surface Warfare Center. He transition to the private sector through Pratt & Whitney Rocketdyne. Mr. Gregory later went to work for Blue Orgin, where he successfully led the propulsion design of the BE-3 engine that successfully launched and vertically landed the New Shepard space vehicle. After success at Blue Orgin, Mr. Gregory joined Ursa Major Technologies to pursue his engineering dream of developing and launching micro- and nano-satellite vehicles.

Model-Based Systems Engineering in the Real World

Thad Henry
National Aeronautics and Space Administration
Huntsville, AL, USA

Rick Steiner
Skygazer Consulting
San Diego, CA, USA

ABSTRACT

Use of Model-Based Systems Engineering (MBSE) has been growing across industry, extending beyond defense and aerospace to include various commercial enterprises such as automotive and healthcare. Tool vendors are quick to point out benefits of this model-based approach and practices, but are not always clear how MBSE benefits can be realized on a project. When deployed successfully, several key considerations should be addressed that maximize the value for a use-case, including:

- Digital artifacts that result from MBSE
- Identifying use-cases
- Interoperability and Data Exchange Standards
- Reading and using a SysML model artifact effectively

Our presentation will discuss the nature and purpose of the MBSE approach and how key information is used for successful MBSE deployment within real world projects.

BIOGRAPHY

Thad Henry has more than three decades of successfully organizing and managing varied technical projects within many of NASA's flagship programs such as the Space Shuttle Program, the International Space Station Program, the Tethered Satellite Program, the 2nd Generation Reusable Launch Vehicle Program, the Constellation Program, and the Exploration Systems Directorate. Mr. Henry currently serves as the NASA Agency Technical Lead for Configuration Management managing CM policy and best practices within NASA including several initiatives for model-based processes for using configuration management standards and advanced engineering concepts. Mr. Henry received an Engineering degree from Auburn University, an MBS in Systems Management from Florida Institute of Technology, and holds a Professional Engineering Certification. He is also an NDIA Certified Configuration and Data Manager. Mr. Henry serves on several external professional organizations in leadership roles such as SAE Configuration Management Committee, the NDIA Technical Information Division Council, the Association for Configuration and Data Management Board of Governors, and the PDES, Inc. Technical Advisory Council.

Rick Steiner is an independent Model Based Systems Engineering (MBSE) consultant and systems modeling coach, with clients in various Aerospace and Defense companies. He retired after a 30-year career at Raytheon as an Engineering Fellow and a Raytheon Certified Architect. He has focused on pragmatic application of systems engineering modeling techniques and has been an advocate, consultant, and instructor of model-based engineering. Rick has served as chief engineer, architect, and lead system modeler for several large-scale defense programs. He has been recognized by the International Council on Systems Engineering (INCOSE) as an Expert Systems Engineering Professional (ESEP), and has been honored as an INCOSE Fellow. Mr. Steiner continues to be a key contributor to the development and certification of the Systems Modeling Language (SysML). He is also co-author of “A Practical Guide to SysML”, currently in its 3rd edition.

The Evolution and Revolution of the Digital Thread

Dr. Don Kinard
Lockheed Martin
Fort Worth, TX, USA

ABSTRACT
The Aerospace industry has utilized the digital thread to improve the design, manufacturing, and sustainment product development processes and has enable increased factory automation. More recently we have provided digital information directly to mechanics on the shop floor, as well as validating the as-designed to the as-built configuration using noncontact metrology. The industry is now tying factory equipment to this digital thread to increase utilization and improve maintenance practices. On the future horizon the burgeoning connections between the major IT systems (ERP, PLM, MES, etc.) is seen as a foundational element of Industry 4.0 transformation – the industrial revolution of data.

BIOGRAPHY
Dr. Don Kinard is a Senior Fellow for Lockheed Martin Aeronautics Production Operations. Dr. Kinard established the F-35 Fighter Production System several years ago to manage production transition from the then one aircraft per month production rate to a 20 aircraft per month production rate; their current build rate is eight aircraft/month.

Dr. Kinard has been with LM for 33 years and prior to his current assignment he was Director of F-35 Production Engineering responsible for Joint Strike Fighter Tooling, Planning, Manufacturing Engineering, and Aircraft Systems Testing.

Before joining F-35 in 2004 Dr. Kinard held various positions in both Engineering and Manufacturing during his 18 years on the F-22 Program including Composite Risk Reduction Lead, Covers and Mate IPT Lead, Engineering Lead for F-22 Production Support, and Deputy Director of F-22 Production.

Don is also the lead for the LM Corporate Fellow's Manufacturing Team as well as the Corporate Future Enterprise and the Foundational Technology Thread Programs whose task it is to develop and share engineering, manufacturing, and sustainment technologies throughout all the LM business units. His technical interests include materials and structures, digital thread integration, industry 4.0, manufacturing technology, manufacturing system design, and production management.

Dr. Kinard earned a bachelor's degree in Chemistry from Trinity University in San Antonio, TX and a PhD in Physical (Polymer) Chemistry from Texas A&M University.

Internet of Things for Manufacturing

Dr. Thomas Kurfess
Georgia Institute of Technology
Atlanta, Georgia, USA

ABSTRACT
Sensors are ubiquitous in modern manufacturing operations, and they generate significant quantities of data. With the advent of low cost, readily available broad band communication and virtually infinite cloud storage, many of the old stigmatisms related to taking data from a plant are no longer of concern. However, the question remains as to what to do with the data. This lecture will discuss the use of large scale data sets from production operations and how they can be leveraged to better understand not only traditional operations, but untapped opportunities from data that are readily available today. Such opportunities provide an improved platform for classical analytic techniques as well as more modern, data intensive approaches to process and operations modeling. The talk will then focus on specific next-generation digital representations and their application to low cost, highly flexible implementations. Examples will be given for both manufacturing operations (additive and subtractive) and validation/verification, as well as how this capability is extensible to cloud computing operations, and next generation technology and business models such as Desktop as a Service (DAAS). The talk will conclude with a discussion of the technology, workforce and infrastructural directions and needs to fully enable the next generation digital twin, and where such a capability will drive the future of manufacturing.

BIOGRAPHY
Thomas R. Kurfess received his S.B., S.M. and Ph.D. degrees in mechanical engineering from M.I.T. in 1986, 1987 and 1989, respectively. He also received an S.M. degree from M.I.T. in electrical engineering and computer science in 1988. He is the HUSCO/Ramirez Distinguished Chair in Fluid Power and Motion Control and Professor of Mechanical Engineering at the Georgia Institute of Technology. During 2012-2013 he was on leave serving as the Assistant Director for Advanced Manufacturing at the Office of Science and Technology Policy in the Executive Office of the President of the United States of America. In this position he had responsibility for engaging the Federal sector and the greater scientific community to identify possible areas for policy actions related to manufacturing. He was responsible for coordinating Federal advanced manufacturing R&D, addressing issues related to technology commercialization, identifying gaps in current Federal R&D in advanced manufacturing, and developing strategies to address these gaps.

He has served as a special consultant of the United Nations to the Government of Malaysia in applied mechatronics and manufacturing, and as a participating guest at the Lawrence Livermore National Laboratory and at Sandia National Laboratories. He currently serves on the Board of Directors, the National Center for Defense Manufacturing and Machining, and the National Center for Manufacturing Sciences, and on the Board of Trustees for the MT Connect Institute. He is the President for the Society of Manufacturing Engineers. His research focuses on the design and development of advanced manufacturing systems targeting digital manufacturing, additive and subtractive processes, and large-scale production enterprises.

PMA-261 3D Data Exchange Project

Howard Owens
NAVAIR PMA-261
Patuxent River, MD, USA

Asa Trainer
International TechneGroup Inc (ITI)
Dayton, OH, USA

Ryan Mills
Anark Corporation
Boulder, CO, USA

Jonathan Scott
Razorleaf Government Solutions
Norfolk, VA, USA

Abstract
PMA-261 (CH-53K Heavy Lift Helicopter) is the first 3D Model Based platform at NAVAIR and the first PMA to instantiate a PLM system. A strategy on automatic upload of native CAD files into the PLM system, an automated verification/validation of native CAD files, and a format for non-CAD users to view the data is required. PMA-261 receives technical data from Sikorsky primarily in native CATIA V5 format and in neutral (TIF and PDF) format for lists and specifications. The priority is to have viewable data for non-CAD users to perform their jobs. As a non-CAD user, DLA needs to use PMA-261's technical data for provisioning, cataloging and sustainment. The project was initiated to increase the efficiency and automation of providing verified/validated technical data to all users in a consumable format, because manual conversion and validation of the volume of data appeared infeasible.

Anark Corporation, ITI TranscenData, and Razorleaf Government Solutions were engaged to prototype an automated system for creating and delivering consumable technical data, in an acceptable 3D PDF format. The team's work is ongoing, but the project has advanced sufficiently to allow presentation of the architecture and operation of the automated system along with the projected benefits. The automated system connects Dassault's ENOVIA PLM with Anark Core Server to automate the generation of 3D PDF documents and 3D PDF technical data packages (TDPs) for DLA, as well as ITI's DEXcenter and CADIQ products to generate STEP and verify/validate native CATIA V5, STEP, and 3D PDF file formats.

Executive Summary

Program Offices, such as the H-53 Heavy Lift Helicopters program office (PMA-261), transitioning to Model Based Enterprise (MBE) processes require a method of verifying/validating thousands of complex 3D models in a short time period. Also needed is the ability to generate production-quality model-based documents and Technical Data Packages (TDP) that provide non-computer-aided design (CAD), non-engineers, and other downstream consumers with the detailed engineering and manufacturing information required for effective model-based communication and collaboration.

The *3D Data Exchange Project* will configure and improve the Product Lifecycle Management (PLM) system production environment for technical data that is being delivered from Sikorsky's ENOVIA PLM system to the PMA-261 ENOVIA PLM system. This data can be pushed to or pulled from program partners, both external such as the original equipment manufacturer (OEM), U.S. Navy Naval Supply Systems Command (NAVSUP), Defense Logistics Agency (DLA), and internal, such as Fleet Readiness Center East. PMA-261 has contracted with ITI to provide the CADIQ software solution to accept, verify, validate and provide a certification report for technical data delivered to potential users. PMA-261 is on contract with Anark Corporation to provide Anark Core software for publishing 3D PDF as the standard for the U.S. Navy Naval Air Systems Command (NAVAIR), and proposes the same solution for the Navy, and Department of Defense.

The 8-month effort will analyze the as-is data and take the necessary steps to assure the project has useable data that meets the data requirements. Requirements will be developed in each of the components that make up the complete system. The team will mesh these requirements into the developing architecture and evaluate how each component system comes together to populate the architecture. The project team will then establish the architecture and develop the 3D Data Exchange System. This system will be pilot tested within the Sandbox environment and the project team will collect and analyze feedback. Upon completion of the project, PMA-261 will have a process in place that will reduce the amount of reverse engineering requirements for creation/verification/validation of data, reduce labor associated with corrections to the source CAD data, reduce the amount of rework due to incorrect technical data, and reduce the requirements for TDP Engineering Support Requests caused by programs using full model based definition in lieu of 2D drawings. This project is part of the Naval Shipbuilding Advanced Manufacturing which is a Navy ManTech Center of Excellence, chartered by the Office of Naval Research (ONR) to develop advanced manufacturing technologies and deploy them in U.S. shipyards and other industrial facilities.

Enabling Facility-Level Interoperability Between Robot Teams and Machine Cell Devices

Josh Langsfeld
Southwest Research Institute
San Antonio, TX, USA

Matt Robinson
Southwest Research Institute
San Antonio, TX, USA

Shaurabh Singh
The Association for Manufacturing Technology
McLean, VA, USA

William Sobel
Vimana
Berkeley, CA, USA

ABSTRACT
Manufacturing equipment is already designed to interoperate within a CNC machine, production cell, or a line. However, device interoperability at a factory-wide level or above still faces significant hurdles. The MTConnect standard and ROS bridge enable a new degree of orchestration with a multi-device interface model, which in turn will lower the cost of automation solutions especially for small and medium sized enterprises. The Cost Effective Coordinated and Cooperative Robotics Enabled by Open Technologies research project is being developed by SwRI, AMT, and System Insights. Funded by a NIST Measurement Science and Engineering (MSE) grant, the project investigates the use and bridging of open standards and technologies. It is exploring application of a flexible automation testbed that demonstrates lowering the cost of automating typical processes, such as in-process inspection, intelligent part management, and automated, just-in time servicing of machine and machine cell applications. Open source software permits free development over a very large workspace to solve complex problems at no cost to the end user. The output from this project is intended to be an enabler for industry-wide adoption of open source technologies by providing a use-case and testbed showcasing lower cost solutions for comprehensive factory floor integration for the small and medium sized manufacturer.

TOWARD THE STANDARDIZATION OF DIGITAL VERIFICATION TECHNOLOGYDEVELOPMENT OF GUIDELINES FOR CREATING 1DCAE MODELS OF MECHANO-ELECTRICAL PRODUCTS

Masatomo INUI
Ibaraki University
Hitachi, Ibaraki, JAPAN

Tomohisa FUJINUMA
Standardization Committee of New Digital Verification Technology, JEITA
Chiyoda-ku, Tokyo, JAPAN

ABSTRACT
Although 1DCAE is considered to be effective for supporting the conceptual/functional design of mechano-electrical products, 1DCAE is not popular in the mechano-electrical industry in comparison to the automobile and aircraft industries. To promote the use of 1DCAE, it is necessary to eliminate the obstacles associated with the use of 1DCAE, and to reduce the cost required to create models of mechano-electrical products. In the attempt to reduce the modeling cost, we have started to develop guidelines for creating proper 1DCAE models of mechano-electrical products. In this study, we briefly explain our guidelines and use part of them to develop a specific mechano-electrical component. We also explain our findings in the use of 1DCAE in the mechano-electrical industry.

Introduction

Small, precise, and high-performance electro-mechanical products, such as multifunctional copiers, printers, digital cameras, and automated teller machines, are manufacturing products in which Japan has traditionally excelled in. In the development of these products, higher functionality and lower prices are required, and technologies for supporting efficient product design are strongly expected. To realize such a design, it is important to actively use computer simulations in the conceptual and functional design processes to evaluate the feasibility of the function, and narrow down the appropriate design solutions at an early stage. Since limited geometric information is determined for the product at the early design stage, it is difficult to use existing 3D CAE technologies for simulations.

In the automobile and aircraft manufacturing fields, product functions are rapidly advanced, resulting in problems similar to those encountered in the mechano-electrical product design. In the design of automobiles/aircrafts, it is popular to use a problem-solving method known as model-based development (MBD). In MBD, various conditions related to the requirements and functions of products are defined by mathematical models. By evaluating the models, product functions can be verified at the very early design stages. Since simple analyses often begin before 3D information is determined, the application of MBD at the early conceptual/functional design stage is specifically known as 1DCAE. Tools such as Modelica [1] and MATLAB/Simulink [2] have already been extensively used in the automobile/aircraft industries. In these tools, mathematical formulas related to product functions are expressed as icons, and their interconnection in the computer display allows the definition of mathematical models for functional verification.

Although 1DCAE is considered to be effective for supporting the conceptual/functional design of mechano-electrical products, unlike the automobile and aircraft industries, it is not a popular design method for mechano-electrical products. Some reasons for its limited use include the facts that:

- The development cycle of mechano-electrical products is brief compared to automobiles and aircrafts, and the necessary cost for preparing the mathematical model for 1DCAE is relatively large.

- In the case of mechano-electrical products, the basic structure of the product changes rapidly. Therefore, reuse of prior models for new designs is difficult. The model has to be recreated for each new product.
- The scale of business of mechano-electrical product manufacturers is small compared to those in the automobile/aircraft industry, and it is difficult to train engineers specializing in 1DCAE.

To promote the use of 1DCAE in the mechano-electrical industry, it is necessary to eliminate the obstacles associated with the use of 1DCAE as much as possible, and to reduce the cost of model creation. In the effort to reduce the modeling cost, we are developing guidelines for creating proper 1DCAE models for mechano-electrical products. In this study, we explain our guidelines and use the formulated guidelines to develop a simple mechano-electrical component. We also explain our findings in the use of 1DCAE in the mechano-electrical industry.

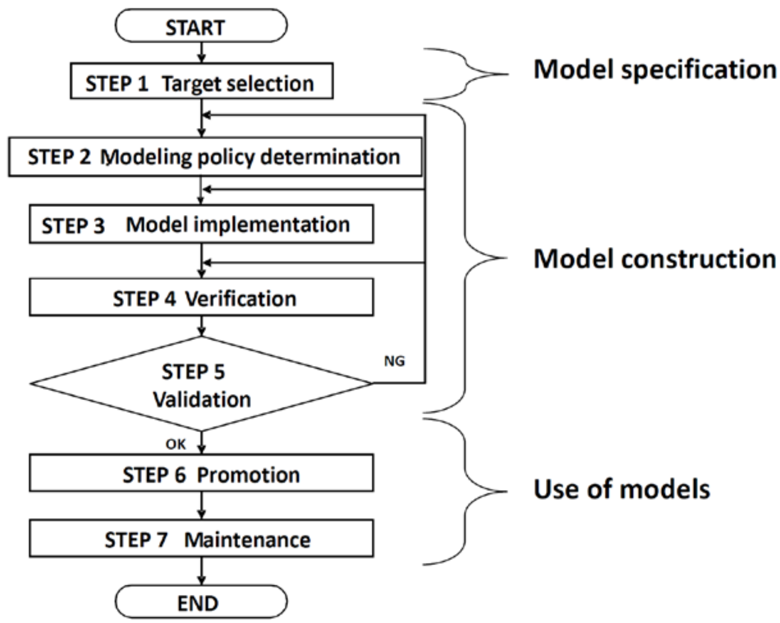

Fig. 1 Flowchart of modeling process set in our guidelines

Guidelines for creating 1DCAE models of mechano-electrical products

Figure 1 presents an overview of our 1DCAE modeling guidelines. In the guideline, a typical model development process is formulated in a flowchart. The flow can be subdivided in three stages, which include the model specification stage, model construction stage, and the subsequent use of the models. In this chapter, we explain some of the details of the steps.

Step 1 Target selection: In this step, the design target is determined and the function of the target product is clarified. It is desirable to carry out functional development and reduce function to physical models with proper input and output parameters. It is also desirable to establish communications with the designer in charge of the target product in advance to understand the necessary solution using the 1DCAE model.

Step 2 Modeling policy determination: In this step, the modeling level of components is determined based on the functional development result. The functional specifications, scope of modeling, design parameters, and their value ranges, potential disturbance, and modeling accuracy, are also determined. The modeling method depends on the functional specifications of the model. Consider a design of a gear train. When the purpose is the analysis of a conveying rotation, modeling of the simple gear ratio is enough. However, if the purpose is the analysis of the vibration of the gear train, modeling of the rigidity of the gear's teeth is necessary.

Step 3 Model implementation: In this step, a model is implemented according to the determined modeling policy. Modelica-based tools (OpenModelica or other commercial tools), or MATLAB/Simulink are usually used in the implementation. Selection of the proper tool is critical in this step. Many Modelica-based commercial 1DCAE systems are available in the market, such as

Dymola and SimulationX, for example. Each of these systems has its own characteristics. The selection of the most appropriate tool for the target problem is important.

Step 4 Verification: Constructed models are verified in this step. There are two types of verification, including the operation and accuracy verifications. In the operation verification, the following questions are evaluated:

- Does the constructed model move?
- Does it work properly with multiple design variables within their upper and lower limit values?

Additionally, we strive to confirm that the implemented model reveals stable motion with limited errors against a reference in the accuracy verification. When the combinations of design variables are tremendously high, it is necessary to devise an orthogonal table to track the design variable combinations in the verification.

Step 5 Validation: In this step, the entire model or a model of the subsystem are constructed by connecting component models. The model is subsequently compared and verified at the subsystem level with actual measurement values. We then check whether the results satisfy the accuracy requirements determined in Step 2. If they do not, Steps 2–4 are repeated to refine the model. The end-outcome is then compared with the actual machines, including past models or experimental benches, to confirm the accuracy of the model. Finally, PDCA cycles are executed to improve the model's accuracy.

Step 6 Promotion: Constructed models are sent to the design department. To encourage the designers to use them, various promotion works are necessary. These may include, for example, distribution of a usage manual, the formulation of a report explaining the theoretical background of the model, accuracy reports, and other documents. It is important that designers use the model with confidence.

Step 7 Maintenance: When the model is deployed in the design, new demands emerge, such as expansion of functions, addition of new design variables, and so on. To respond to the demands, realization of a model maintenance system with proper human resources is important. It is also necessary to establish rules for the control of the models and reuse them.

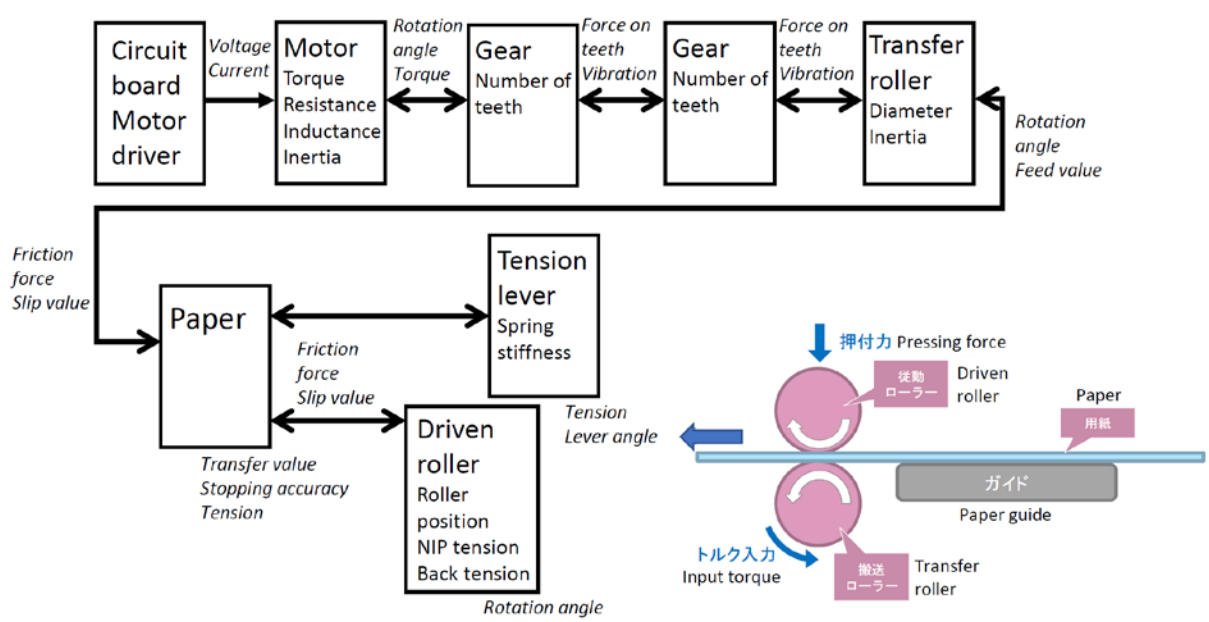

Fig. 2 Block diagram of a paper transfer mechanism

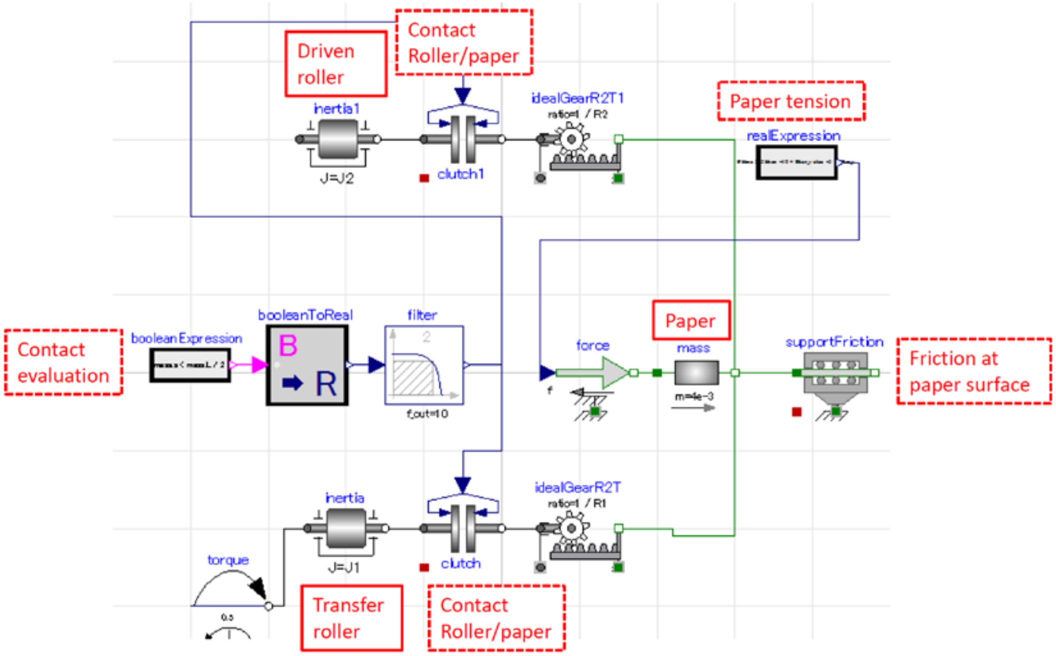

Fig. 3 Paper transfer model in Modelica

Evaluation results

To evaluate the applicability of the guidelines for constructing the 1DCAE model of the mechano-electrical product, we conducted some empirical studies on the modeling of typical components of the mechano-electrical product. In this study, we use OpenModelica [3] as a modeling tool. We adhere to the modeling process given in our guidelines as much as possible. In this paper, we explain the modeling result of a paper transfer mechanism. The paper transfer mechanism is complex but constitutes an important mechanism for the copier machine and the printer. Understanding the total behavior of the mechanism is necessary for developing the control software and the built-in system.

We decomposed a simple paper transfer mechanism to some components and clarified the physical relationships between the components. We then defined the functional model of the mechanism using a block diagram (see Fig. 2). The model is implemented in Modelica based on the diagram shown in Fig. 3. Fig. 4 shows the simulation results derived by the model. In this graph, the analyzed results of the friction force at the paper surface and paper tension are illustrated.

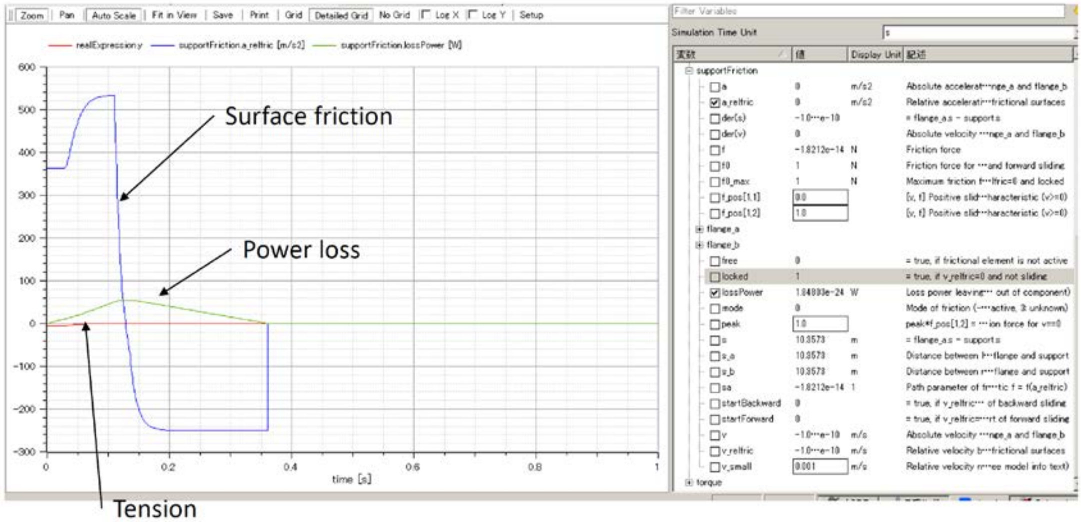

Fig. 4 Simulation results

It is difficult to quantitatively measure the effectiveness of the guidelines with this simple use case, but we believe that the guidelines are effective in creating models without mistakes. We plan to distribute the guidelines to member companies of the Standardization Committee of New Digital Verification Technology to thoroughly evaluate its applicability. In our empirical study, we also identified the following difficulties in using Modelica in the mechano-electrical industry.

- The standard Modelica library (SML) was inadequate to model complex physical phenomena. Some connections between parts in the belt/paper transfer mechanism were difficult to represent in Modelica.
- In the design of mechano-electrical products, it is necessary to represent switching mechanisms with sensors; however, these are not easily implemented in Modelica.
- There are some rules specific to the mechano-electrical industry, e.g., coordinate system. We think that the preparation of a Modelica library specializing in mechano-electrical products is necessary.
- In the mechano-electrical products, motion changes use sensor information and the timing chart. The modeling framework provided by Modelica is not suitable for representing such sensor- and timing chart-based motion.

We think that some enhancement of Modelica is indispensable to expand its use in the mechano-electrical industry.

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[3] Open Source Modelica Consortium, “OpenModelica User’s Guide, Release v1.13.0-dev-493-gddc51eb.”

Common Shared System Model for Evolvable Assembly Systems

David Sanderson
University of Nottingham
Nottingham, UK

Jack C. Chaplin
University Of Nottingham
Nottingham, UK

Svetan Ratchev
University Of Nottingham
Nottingham, UK

ABSTRACT
A vital aspect of distributed control in an adaptable production system is coherence between each system resource. The Evolvable Assembly Systems project addresses this challenge using a common shared system model. This paper provides an overview of the project and the shared system model approach as implemented in a real world demonstration cell.

Motivation

Assembly of final products in sectors such as automotive, aerospace, pharmaceutical and medical industries is a key production process in high labour cost areas such as the UK. In order to respond to current challenges, manufacturers need to transform capital-intensive assembly lines into smart systems that can self-heal, self-adapt, and reconfigure in response to external and internal changes [1]. This need is dictated by:

1. demand for rapid ramp-up and downscale of production systems;
2. lack of autonomous responsiveness to disruptive events and demand fluctuations in current assembly systems;
3. an economical and societal drive towards "manufacturing as a service".

Consequently, there is a need for new development approaches for assembly systems able to continuously evolve in response to changes in product requirements and demand. They must provide short set-up times, low cost of maintenance and reconfiguration, and easily integrate emerging new technologies.

Vision

There is a significant body of research in reconfigurable manufacturing systems [2], automatic and adaptive control [3], and manufacturing systems modelling and simulation [4]. The fractal factory concept [5] proposed an integrated approach to manufacturing systems that adapts to changes at different levels of the enterprise. Holonic Manufacturing Systems [6] use loosely coupled holons to represent resources such as robots, machines, orders, or even factories that cooperate to achieve their goals [7]. Building on techniques such as evolutionary computation and swarm intelligence, manufacturing systems capable of collectively optimising their performance in changing environments have been proposed [8, 9], as has the concept of co-evolution of products, processes, and production systems [10].

Achieving balance and harmony between products, processes, and systems in their continuous development and evolution is a key challenge for future successful cost-effective manufacture. Adaptation of a system can be triggered by different factors and driven by a variety of selective forces including breakdowns, changing product requirements, mutability of processes and equipment components, performance characteristics, and other indicators. Key knowledge gaps are in: finding the best model and architecture for product, process and system adaptation; finding the most appropriate levels of integration; understanding how and when configurations are updated; and understanding how disturbances in the system are managed and controlled [10]. There is also limited research and a lack of generic evolvable systems approaches that can be applied at different manufacturing system hierarchical levels.

Despite achievements to date, the above fundamental challenges remain and new theoretical foundations are urgently needed for next generation manufacturing systems. To achieve this, manufacturing systems require new levels of context-awareness, standardised "plug and produce" configuration methods, equipment module design and, crucially, new multi-stage/multi-scale algorithmic capabilities and interfaces capable of delivering this new behaviour.

Our research addresses these needs with the concept of "Evolvable Assembly" built upon the principles of autonomous distributed decision-making, ubiquitous context-aware equipment and systems, multi-agent control, learning, swarm intelligence and self-adaptation [11, 12]. This programme is complementary to recent theoretical developments in subject areas such as complex networks, machine learning, intelligent systems, distributed control, data processing and ubiquitous computing. This is also matched by the opportunity to shape future manufacturing systems by fusing current IT capabilities for sensing and control and infrastructure that could match and exceed the level of product and process complexity in modern manufacturing.

Challenges

As such, the research has adopted the methods of context-awareness, multi-agent intelligent control, and self-adaptation. Context-awareness provides each individual element with an understanding of the surrounding environment; multi-agent intelligence supports system self-organisation based on a community of autonomous and cooperative entities; and self-adaptation allows the development of goal-driven collective behaviour leading to purposeful system evolution. The programme is a departure from the previous philosophy of reconfigurable manufacturing – it creates a framework for autonomous, context-aware, and adaptable assembly and manufacturing systems that can co-evolve with products, processes, and the business and social environment. This transformational approach presents theoretical, technical and social challenges that demand new fundamental multidisciplinary research.

These challenges fall into three main areas:

1. **Infrastructure**: The morphology of future production systems in the project is based on intelligent resource objects. These are connected in a distributed architectural infrastructure inspired by flexible and reconfigurable manufacturing systems.
2. **Decision-making**: The evolution of the system structure and behaviour is based on context-awareness, learning, planning, and adaptation techniques. This enables decision-making across the entire spectrum from fully human-based, through hybrid, to fully-automated.
3. **Instantiation**: The core principles and methods developed by the project are instantiated at fixture, end effector, workstation, and assembly cell levels.

Crossing across these three areas is the requirement for a common "**shared system model**". This model is built across the infrastructure, enables distributed decision-making, and integrates across real-world instantiations.

Shared System Model

The “type problem” for the EAS approach is the “batch-size-of-one” problem – how to produce a given unique product on a given set of manufacturing resources. Our solution to this can also be leveraged to provide resilience, robustness, and general adaptability in the face of disruptions or changes in requirements [11, 12]. When considering the set of available manufacturing resources, they are characterised based on the *capabilities* they provide to the system. The products to be manufactured is defined by *recipes* that capture the product requirements. These capabilities and recipes are both modelled and the models are subject to a distributed adaptable analysis of manufacturability used to automatically plan a control approach that can produce the specified product on the specified set of resources.

The overall approach is shown in Figure 1. At the local level, each resource is controlled by an agent which maintains a local model of the system and environment, based on the BDI paradigm [13]. These agents interact via a common shared system model, maintained using a publish-subscribe approach [14], on which the distributed analysis and planning operates. This shared model can further be used as an integration point for other enterprise-level operations, and can be mined for large-scale data processes.

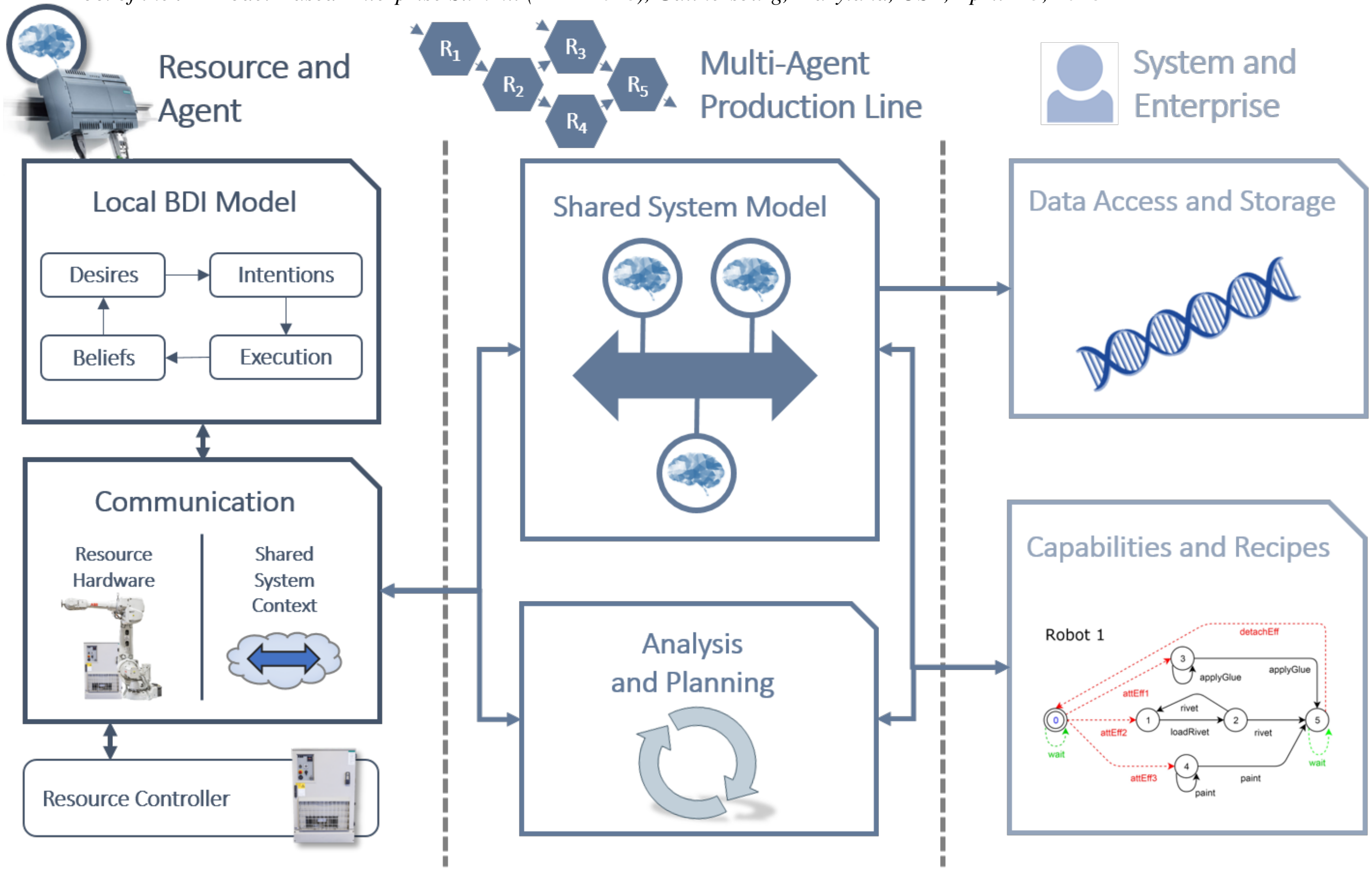

Figure 1: EAS Agent-oriented Layered Architectural Model

Implementation Example

This system has been implemented in a proof of concept demonstrator at the University of Nottingham shown in Figure 2. The demonstrator consists of two ABB IRB6700 robots, a shared central workspace, a tool rack accessible by one robot, and both a shared tool/part rack and a part loading conveyor belt accessible by the other robot. Each robot has access to a number of different end effectors on their respective rack and is equipped with an automatic tool changer.

The cell is designed to assemble aerospace components defined through a variety of recipe files. As such it is capable of the following processes, which map to the highest level of capabilities (sub-behaviours are defined hierarchically beneath these):

- Load and unload parts via conveyor
- Pick, place, and manipulate a variety of trailing edge ribs and non-structural skin panels from a common single-aisle aircraft
- Apply sealant
- Store parts in rack for curing
- Scan parts with a line scanner
- Apply temporary fasteners (semi-manual process)

Each resource in the system is controlled by an intelligent agent deployed on an embedded computer – in this case a Raspberry Pi 3 Model B, although other options such as the Siemens IOT2040, Intel Galileo, or National Instruments RIO are possible – that allows the distributed agent control layer to interact with the relevant PLC or hardware controller.

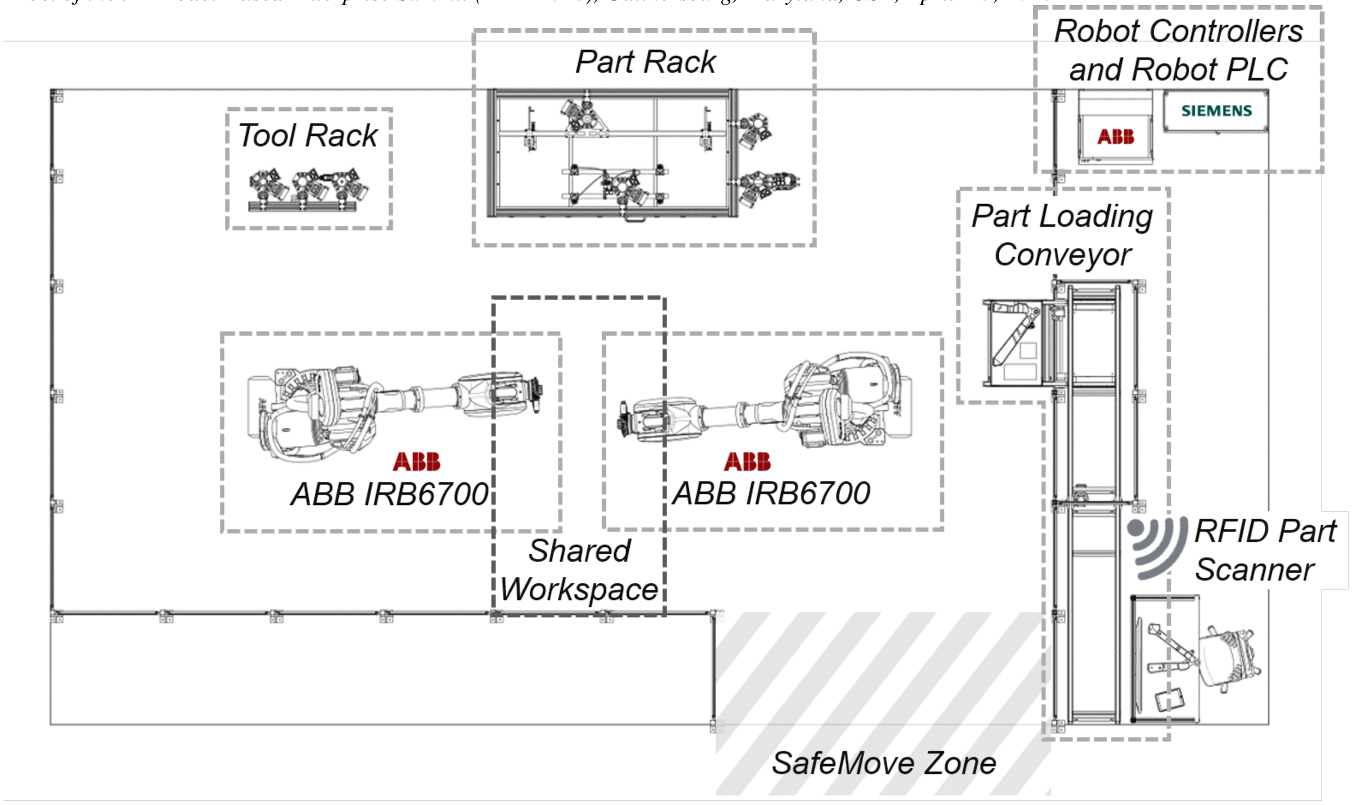

Figure 2: Assembly Cell Layout

Conclusions

Responses to current challenges in the manufacturing domain must address challenges in three main areas: infrastructure, decision-making, and instantiation. Solutions to these all rely on a common shared system model which is built across the infrastructure, enables distributed decision-making, and integrates across real-world instantiations. This paper has presented the overall approach to this shared system model used by the Evolvable Assembly Systems project in the context of a proof of concept demonstrator designed to assemble aerospace components.

Acknowledgements

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Integrating Data Visualization Software with Manufacturing Facility Databases: Reference Implementation and Lessons Learned

William Z. Bernstein
Systems Integration Division, NIST
Gaithersburg, MD, USA

Christopher M. Ricigliano
W.T. Woodson High School
Fairfax, VA, USA

ABSTRACT
The purpose of this study is to support the integration of smart manufacturing systems into the typical manufacturing environment. This paper enumerates challenges and limitations faced as an open source visualization software, namely Keshif, was paired with an SQL database from the NIST manufacturing shop located in the Fabrication Technology Division. The utility of interactive data exploration of traditional manufacturing shop floor data housed in SQL databases is demonstrated. In addition, a Keshif instance representing 6340 jobs in the NIST shops is showcased.

Keywords: Smart Manufacturing; Database Management; Job Tracking; Data Exploration; Data Visualization

INTRODUCTION
As manufacturing becomes increasingly complex, more sophisticated ways are needed to summarize the who, what, where, when, and why of manufacturing activities. Interactive visualization interfaces can help provide graphical summaries of activities such as manufacturing processes, jobs, materials, and human resources, allowing users to analyze large amounts of data, spanning multiple categories to make more informed decisions.

This paper demonstrates the use of an open source data visualization tool to facilitate deeper reasoning and understanding of shop floor data. Here, we use Keshif, a visualization tool for the exploration of tabular data [1]. Keshif allows users to select and compare various aspects of a data set, facilitating the identification of otherwise difficult-to-observe trends. The goal of this paper is twofold, (1) to integrate an open-source data exploration tool with a Structured Query Language (SQL)-based database of a small manufacturer and (2) to enumerate the capabilites and challenges of such a task. We hope to demonstrate the utility of interactive visualizaiton tools for understanding trends and informing decisions for manufacturing facilities and provide guidance to small shops that wish to implement similar technologies.

METHODS

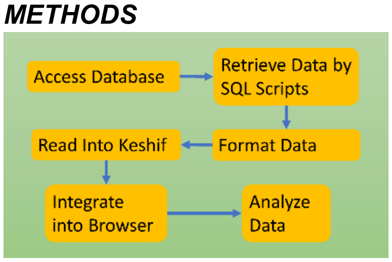

Figure 1: Project workflow

Figure 1 presents the workflow of the work presented. First, we access a SQL database of a contract manufacturer. Then, data is retrieved through targeted SQL scripts. We then format and clean the data to represent each manufacturing job as a row in a large table. The data is read into Keshif where we have designed a specific layout of a dashboard to suit exploration modes for trend finding and discovery. The dashboard is integrated into a browser and then users are able to explore possible trends of the data.

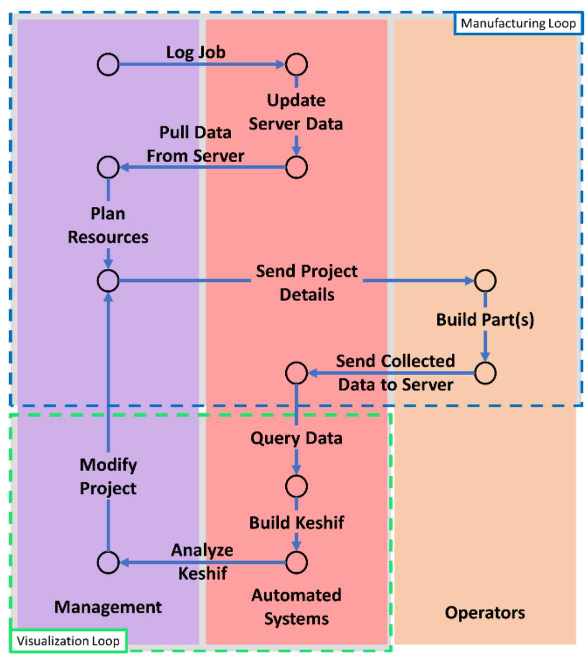

Figure 2: Swim lane depiction of user-system interaction in presented Keshif instance.

Figure 2 illustrates the interaction that our Keshif instance provides to different stakeholders. The purple column (left) specifies activities conducted by the shop floor managers. The right column in orange shows the interactions of the machine operators or workers that are focused on machining jobs. The middle column in red shows activities conducted by the computer system. These activities can be classified into broad "interaction loops" shown by dotted boxes in Figure 2. The blue dotted box signifies the "manufacturing loop" or traditional job shop management, e.g., logging jobs, planning resources, and building parts. The green dotted box is the "visualization loop", wherein the shop management can assess the efficiency of the shop's operations across various dimensions as depicted in the dashboard shown in Figure 3. The core idea here is that the "visualization loop" is kept separate from the primary activities of the shop's operations, allowing the shop to behave normally yet still providing additional capabilities for trend discovery through interactive dashboards.

We believe that more natural interaction with data as opposed to the traditional rigidness of SQL queries provides significant opportunities for small and medium enterprises (SMEs). Furthermore, we purposefully choose a visualization platform that is geared for non-experts to build fully integrated, interactive visualizations [1] so that this project can be viewed as a reference implementation that others can emulate.

CASE STUDY

The NIST Fabrication Technology Office (FTO) is a small-scale job shop, exemplary of a contract manufacturer. Here, the FTO is employed as a source of model data (6340 parts) for an interactive visualization. This dashboard can be used as a guideline for other shops to implement data exploration techniques.

In this case, we used SQL Server Management Studio[1] to perform queries on the Microsoft SQL Server set up by the NIST shops in the FTO. The FTO is also the primary subject of the NIST Smart Manufacturing Systems (SMS) Test Bed[2] [2]. In the SMS Test Bed, machines with varying capabilities already stream detailed information regarding their operation to an open server. Figure 3 provides a screenshot of a dashboard built using Keshif. This snapshot is representative of a user comparing job attributes between two facility managers, specified as "Manager A" in blue and "Manager B" in green. Though filtering interactions, the user can explore the differences and similarities in the distributions of specific job characteristics, such as production cost, labor costs, job time, and dates of delivery. In this example, we choose to show the following facility attributes:

- Production Code – signifies the manager responsible for job scheduling.
- Customer Code – signifies the customer associated with each job.
- Material Cost – cost associated with stock and raw material needed.
- Labor Cost – cost associated with the person-hours and labor rate.

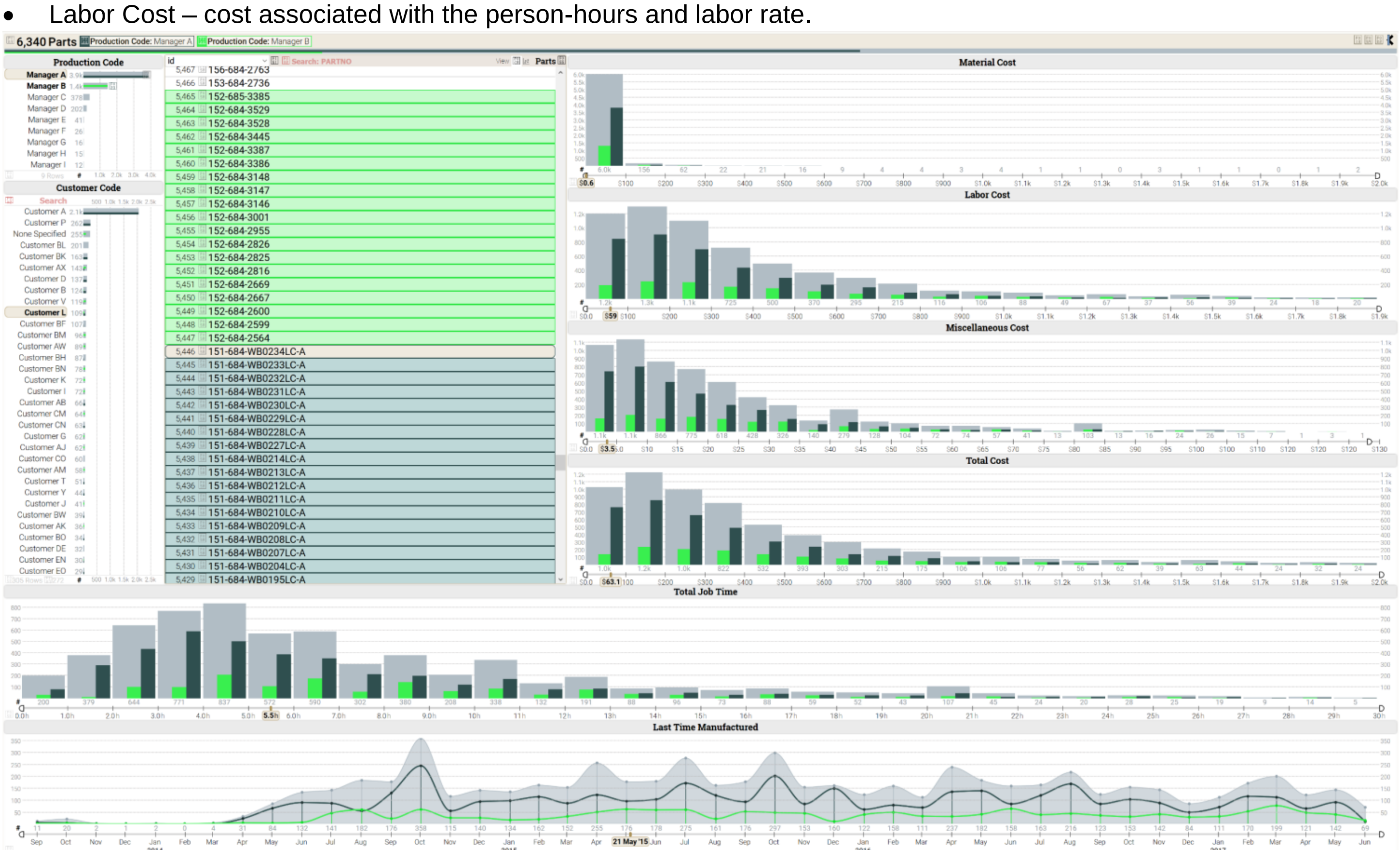

Figure 3: Instance of a Keshif dashboard interaction. Here, the user compares all jobs related to Manager A (blue) to Manager B (green). Different panels show different trends of the data.

[1] https://www.microsoft.com/en-US/sql-server/sql-server-2017
[2] https://www.nist.gov/laboratories/tools-instruments/smart-manufacturing-systems-sms-test-bed

- Miscellaneous Cost – all other costs.
- Total Cost – total cost of project.
- Total Job Time – total amount of time for job completion.
- Last Time Manufactured – the date when the job was completed.

In general, the summary provided by the Keshif dashboard is a useful "window" to the SQL database. Its highlighting feature allows for rapid review of processed data. For example, at the top left corner of Figure 3, the 'lock' feature is used to compare the amount of parts two employees have prepared across several categories. Looking closer at the data, it seems that there is a spike in job delivery around October of multiple years, see October 2016 and October 2017, at the bottom of Figure 3. It also seems that these dates are followed by less busy times in the following months. We can also see that the distributions of total job time and cost are similar comparing capabilities of "Manager A" to those of "Manager B". Implementing and evaluating key performance indicators (KPIs) would provide additional insight into the Keshif browser.

To justify such claims, targeted user studies are required. Eventually, we plan to develop automated queries, data cleaning, and dashboard updating. Implementing this example brought forward significant challenges with respect to linking such data exploration frameworks with small job shops like the NIST FTO. In the following section, we enumerate these challenges and limitations. The main goal of this exercise is to influence small and medium sized enterprises (SMEs) in their data handling and collection. If SMEs abide by best practices, they could significantly improve their readiness for introducing smart manufacturing technologies, e.g., visualization software. We see similar problems regarding maintenance reporting, where SMEs are not capable of consistently reporting information about maintenance activities [3].

CHALLENGES AND LIMITATIONS

In this section, we identify challenges confronted during this reference implementation. These challenges can be classified into two areas: (1) issues related to the open software and (2) issues related to the facility's practices.

Challenges related to the data exploration software

Keshif is designed to analyze complete data sets, and produce a graphical dashboard as an output. In the reference implementation, an incomplete set was used yet it was still possible to draw insight. Our dashboard, in its current form, cannot perform data analytics. As a result, to illustrate value to shop managers and foreman, it is necessary to provide additional backend capabilities. Though the learning curve is shallow, such interfaces requires some time to set up. This could also pose a challenge for SMEs. Setting up a more advanced data streams, e.g., from sensors, for deeper insight would also require the investment of time and money.

Challenges related to the facility's practices

Due to varying degrees of quality, the extracted data must be cleaned and consistently formatted. Slang, jargon, and unexplained abbreviations present in the database pose a significant challenge. For example, considering the 19,915 entries in the `JobMaterials` table, 2338 entries described shipping activates, but had over 20 different terms for describing the same activity, many of which were simple typos. Figure 4 presents a screenshot of a query to illustrate the variety of inconsistencies and incompleteness. This causes considerable issues in reading and aggregating information

```
1  select * from ShopSys.dbo.JobMaterials order by partno
```

Results | Messages

	OrderNo	JobNo	PartNo	Description	StepNo	MainPart	BinLoc1	QtyPosted1	BinLoc2	QtyPosted2	BinLoc3	QtyPosted3	BinLoc4	QtyPosted4	BinLoc5	QtyPosted5	PostedFromStock	Dat
1...	15-IS-974	15-IS-974-08	SHIPPING ORDER	Send parts to Omley - Lake	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	15-RSV-599	15-RSV-599-08	SHIPPING ORDER	Return Resin Tanks for Refill	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	15-RSV-599	15-RSV-599-08	SHIPPING ORDER	Send Circuit Boards to DynaPath for Repair	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	15-RSV-599	15-RSV-599-08	SHIPPING ORDER	Return Resin Tanks for Refill	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	15N6832016A	15N6832016A-20	SHIPPING ORDER	Ship material to Cabot Microelectronics - Addision, IL	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	1751	1751-01	SHIPPING ORDER	Send parts to Ronal Tool Company - Raines	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	17-IS-974	17-IS-974-08	SHIPPING ORDER	Return Board to VIC for Repair - Ronkonkoma, NY	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16N6864462A	16N6864462A-02	SHIPPING ORDER	Ship completed parts to Kris Bertness - Boulder, CO	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16N647W02...	16N647W024A...	SHIPPING ORDER	Ship completed parts to Tom Bruno - Boulder, CO	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16-IS-974	16-IS-974-10	SHIPPING ORDER	Sending parts to Gaithersburg from Boulder	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16-IS-974	16-IS-974-10	SHIPPING ORDER	Shipping HAAS VF8 from Boulder to Gaithersburg	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16-IS-974	16-IS-974-10	SHIPPING ORDER	Shipping misc equipment from Boulder to Gaithersburg (list in com...	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16-IS-974	16-IS-974-10	SHIPPING ORDER	Shipping Misc. items from Boulder to Gaithersburg Shop	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	16-IS-974	16-IS-974-08	SHIPPING ORDER	Shipping HAAS VF8 from Boulder to Gaithersburg	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	14N6845160A	14N6845160A-30	SHIPPING ORDER	Send payment to UNCC - McGlauflin	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	13N6859064A	13N6859064A-17	SHIPPING ORDER	Send material to Grover Gundrilling for Lake	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	NYSED-2017T	NYSED-2017T-...	SHIPPING ORDER	Ship Encasement Platform to Barbara Lilley @ NYSED - Albany, NY	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	NYSED-2017T	NYSED-2017T-...	SHIPPING ORDER	Ship Glass to M. Culver @ NYSED - Albany, NY	0	N	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	1268	1268-01	SHIPPING-1	shipping	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	2025	2025-01	SHIPPING2	shipping	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	2025	2025-01	SHIPPING2	Shipping	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	2378	2378-01	SHIPPING4	shipping charges	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	2367	2367-01	SHIPPING4	shipping charges	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	2088	2088-01	SHIPPINGMC	shippingmcmaster	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20
1...	15-IS-974	15-IS-974-09	SHOP	SHIP	0	N		1	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	N	20

Figure 4: Sample query conducted on the job database for the NIST Shops. Here, we see the breadth of incompleteness and the jargon, abbreviations, and "typos" abound in the database.

from the database. Since this data is mostly captured through human input as a String, inconsistencies across the data are very common. Using a machine to query across such inconsistence would hence not be effective. There are two possible solutions to address this challenge. We could use a "search and replace" program to correct common inconsistencies or develop a front-end tool that could correct data (or recommend changes to the data) before its stored. The first solution requires considerable computation time and effort and would make near real-time visualizations infeasible. The other approach would eliminate the need for a human or machine to format the data downstream, allowing for close-to-real-time visualizations.

RECOMMENDATIONS

This exercise can be considered as a microcosm of the challenges associated with merging emerging technologies with manufacturing systems. In this example, we see that even when systems are in place to properly store formatted data, best practices are often not followed. We see three primary opportunities, (1) developing front-end tools that deal with ambiguous natural user input to the database, (2) formalizing key performance indicators (KPIs) and metrics along with the data, and (3) improving data wrangling and querying without affecting the job shop database. If a front-end natural language-based tool were developed, there would be no need to change the behavior of workers responsible for inputting data. If KPIs were formally defined by those ultimately responsible for decision-making, visualization dashboards, as shown in Figure 3, could be generated automatically to specifically show the right data at the right time to the right person. This vision would promote the further use of advanced interactive visualizations with non-experts and promote more domain-driven automated visualization. Note that recommender systems specifically geared for automating the design of visualizations is an open research challenge [4, 5]. Manufacturing remains a relevant domain for such research. Understanding domain expertise in manufacturing to automatically generate visualizations to meet those domain-driven needs will advance the domains of both information visualization and digital manufacturing.

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DISCLAIMER

No approval or endorsement of any commercial product by NIST is intended or implied. Certain commercial equipment, instruments or materials are identified in this report to facilitate better understanding. Such identification does not imply recommendations or endorsement by NIST nor does it imply the materials or equipment identified are necessarily the best available for the purpose.

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Digitally Enabling the Supply Chain

Gregory A. Harris, Ph.D., P.E.
Auburn University
Auburn, AL, USA

Chris Peters
The Lucrum Group
Annapolis, MD, USA

Roy Whittenburg
MBD360, LLC
Huntsville, AL, USA

Rendell Hughes
ITI
Cincinnati, OH, USA

Kevin Fischer
Rockwell Collins
Cedar Rapids, IA, USA

Daniel Hartman
Rolls Royce
Indianapolis, IN, USA

Kong Ma
Rolls Royce
Indianapolis, IN, USA

Jeff Shubrooks
Raytheon
Andover, MD, USA

Thomas Hedberg, Jr.
NIST
Gaithersburg, MD, USA

ABSTRACT
This paper describes a project that will deliver a set of playbooks designed to accelerate the depth and breadth of adoption for digital supply chain practices and technologies. The resulting benefits of reduced cost and time along with greater innovation better position the U.S. industrial base to compete in the global market. The team will utilize existing tools and technologies developed in previous commercial and government funded research to create a roadmap and set of playbooks for Original Equipment Manufacturers (OEMs) and Small/Medium Manufacturers (SMMs) to guide the implementation of secure digitally-enabled supply chain practices and technologies.

Introduction

In the 1920s Henry Ford stated that the longer a product is in the act of manufacture, and the more we move it around, the greater is its ultimate cost. That is still true today. Anything that hinders the flow of product through a manufacturing system can be considered friction in the system. Friction slows product flow and increases costs. Information flow is just as important and can be just as costly when that flow is impeded. If the right information is not in the right place at the right time in the right format to allow for the best decision to be made, the cost of the product will increase due to friction in the system. Reduction in lead time has long been a goal of manufacturers and great strides have been made by the application of continuous process improvement and innovation. Interoperability between systems in the product realization process is a significant source of friction and increased costs. Information flow in the supply chain is an additional level of complexity placed upon the product realization system. Shifting to Model-Based Enterprises (MBE) has the potential to dramatically reduce friction and cost. However, adoption of MBE has been slow.

There has been a sustained effort in industry to become model centric, but there is still significant manual intervention in the supply chain to adapt to a Model-Based Enterprise (MBE) environment [1]. Companies have provided anecdotal evidence of the benefits of MBE and connecting nodes within the digital thread [2]. Some areas in which there has been evidence of improvement include the elimination or reduction in the need to re-create downstream models, reduction in cycle time and costs, reduction the introduction of downstream errors, and production of parts that meet customer requirements and expectations [1].

With knowledge of the benefits available with a MBE, industry has embraced MBE on an ad-hoc basis. This approach has generated islands of excellence amid a sea of unclaimed opportunity. But there are significant issues with achieving implementation of the digital thread. Interoperability is a bane against the effort to the exchange of data between supply chain partners. Efforts have been made to navigate through this interoperability by developing standards such as STEP AP242, STEP AP203, STEP AP214, JT, and QIF that may affect how data is created, transferred and consumed within the supply chain, but these efforts have not been completely realized by software and service providers in the MBE community.

This project is focused on providing a playbook and roadmap of the processes and tools that can be used to enable a digital supply chain for OEMs and SMMs. The playbook and roadmap will recommend tools and processes that have been proven to address many of industry's pain points. This project is the first known effort to define a systematic and comprehensive approach to affordably implementing a MBE. The output of this project should inform industry standards such as ASME's forming MBE Standard Committee[1].

The Project Plan

Supply chains for both new parts and legacy parts will be addressed. Industry team partners provide insight and access to supply chain partners and opportunities to demonstrate project generated solutions for the implementation of Digital Thread/TDP/MBE at both OEMs and SMMs. By leveraging existing work this project will be building upon, and maturing, proven technology solutions, enhancing and multiplying the benefits already identified, and achieving benefits that come only from the multiplicative effect of building on a solid foundation. Reducing the manual intervention into the development, use and exchange of models and production information, positive impacts upon performance are going to be shown through the elimination of time required for human input and the potential for errors leading to rework. Demonstrations will be used to show how these and other solutions can be woven together to significantly improve communications and collaboration throughout a manufacturing supply chain for efficient real-time feedback loops. The digitalization of the supply chain will benefit the industry partners by improving communications and minimizing scrap and rework. Additional opportunities for process improvement through MBE and a digitally enabled supply chain are in the automation of model updates and workflow. One economic analysis estimates the total annual impact of enabling a digital supply chain at near $60 billion [3]. Automation in supply chain processes removes friction from the information system; thus reducing the overall lead time and reducing cost. The issues of Intellectual Property and contractual development and execution, cybersecurity details, and regulatory requirements of specific industry sectors will also be addressed.

Legacy parts or systems are a multi-faceted issue and must be addressed in a manner that not only makes financial sense, but also allows for the most efficient use of resources within the supply chain. The approach this project team will take looks at tradeoffs that can be applied on a case-by-case basis and a path forward selected to satisfy the requirements of the system or organizations involved. The tradeoff approach will look at three potential courses of action; 1) Use data as-is (everyone in supply chain recreates their own version based upon need), 2) All data is recreated in model-based form (typically not all data will be available and if more than one configuration of the component is required, each will have to be modeled), and 3) Use a combination of technology and manual data recreation to build a data set that becomes reusable in the supply chain. By reviewing each legacy part or system in this way the best decision can be made on how far to take the modeling of a part or system based upon the needs of the customer and the supply chain partners. A goal of this project team is to develop a framework for understanding this dynamic between MBE and legacy systems to provide a guide for organizations to use in making the legacy system determination.

Greenfield parts and systems that start with a digitally capable supply chain and a MBE focus will benefit throughout the product life cycle. The cost-value proposition with greenfield projects is based upon the idea that questions why it would be considered profitable to introduce inefficiency and friction into the development and realization of a new system. Thus, MBE and digital supply chain capability should be pursued from the outset of these systems; where the information for the system is easily accessible and visible to the OEM and supply chain to aid in reuse and minimization of manual intervention. The MBD will be communicated to the supplier similar to how drawings and 3D geometry is today, but the MBD will contain all required information embedded in the MBD itself and not in separate files that can be lost, misplaced or corrupted. With the information embedded in the MBD, digital thread maps can be used to find opportunities for data reuse and the processes required to use the data. The project team will define the process for industry to tailor these digital-thread maps for their unique processes. Due to the digital nature of the project, the team will define sample "misuse" cases in which information confidentiality, availability and integrity are commonly compromised. To gather the required stakeholder needs, the team will build upon the NIST-funded Minimum Information Model study [5, 6, 7].

Roadmap and Playbooks: The following is a short description of the products to be developed:

Define and establish the business objectives and drivers for OEMs and SMMs

Enlist all relevant information/data/model/approval process types, define near and long-term business and system goals, establish gaps and requirements, and identify tools and standards. A review of the information provided in previous works mentioned earlier in this proposal, process and value stream mapping exercises, focus groups, activity models, system models, etc. will be used. The team will develop a pervasive and generic

[1] https://www.asme.org/about-asme/standards/standards-certification-update/ongoing-development-modelbased-enterprise

purchasing process and the associated digital data flow architecture (applicable for legacy and NPI drawing based to advanced MBD based products), develop a prototype system, provide system validation and demonstration, and aggregate lessons learned. The team will develop and prioritize digital thread maps based on availability of capability.

Define the roadmap and playbook format structure.

A format and structure for the roadmap and playbook for both OEMs and SMMs will be developed that is conducive to implementation. The roadmaps will include the current state of digital supply chain capabilities including the standards and tools currently available. Companies that have been pioneers in the digitalization of supply chain operations such as Exostar and Covisint along with companies just starting the initiative to become digitally capable will be studied to identify the current state of technology and implementation. The industry members on the project team will provide access to some of their supply chain partners to provide insight into current state and digital capability. The team will conduct brief validation efforts with participating manufacturers to confirm processes and tools used today. The team has several connections to the standards communities and will reach out to those bodies to achieve an even greater level of validation.

Next the team will identify the desired state for digital supply chain capability and MBE for industry in general. This will include global access, export considerations, and acceptable protection for data and information. The effort will culminate in an Operational View 1 (OV–1) of the digitally enabled supply chain to provide a visual instrument for communicating the vision of the future of supply chain operations. The OV-1 helps to visualize the constraints on the system, the performance requirements to be attained, the user and maintainer roles, and how the system should interface with other systems [4].

The difference between the current state and the desired vision for the digitally capable supply chain provides the input for the identification of gaps in technology and capabilities that must be developed to attain the future state. In this section, the team will include any impediments uncovered from previous work or in the validation research. Additionally, the team will identify the high-value gaps in technology and difficulties arising from complexity, security and costs that are preventing the realization of a digitally enabled supply chain. In this part of the project, the team will provide suggested solutions for handling legacy product data and new product data. The team will examine commercially available technologies (multiple products that cover large percentage of supply chain) today and work well (when tested with representative sample of production data produce accurate results) today, but are not used due to cost, usability, awareness, etc., or not used well. The effort will include a look forward to technologies and tools that will be available in 3-5 years. Use cases to be developed for the roadmap and playbook include Manufacturing - Demonstration, Prototype, LRIP and Production, tooling, manufacturing programs (CAM and CAI, etc.), planning, work instructions, inspection, etc., Engineering (analysis, design, test), Procurement (bids, purchase, inspection), and Support operations

The playbook will highlight the business case and motivating factors for adopting the MBE and digitally enabled supply chain mode of operations. The playbook will provide a sequence of steps based on product strategy time line which will allow opportunities for technology insertion. A phased approach will be suggested so that deliverables can offer near-term benefits, while also helping laying down stepping stones to achieve the broad transformation of current practice into a comprehensive secure digital-thread-based enterprise framework. In addition, the playbooks will provide guides and assists to flow down the digital capabilities to their supply chains and detail the capability to flow data up to upper tiers and OEMs/Customers.

Roadmap and Playbook specifics.

The playbook will address workforce education and learning curve expectations across the enterprise. The roadmaps and playbooks must address the contracting and purchasing processes and how to bring both organizational units into the digitally capable supply chain environment. The team will provide insight into the supply chain organization process. Supply chain strategies should be a function of characteristics of the products, thus each may be unique. The days of a “one size fits all” supply chain strategy are gone and the digitally capable supply chain will allow each organization to assemble a unique set of expertise and capabilities to compete in the global marketplace [8].

The team will review the current state of model-based technology solutions and standards such as STEP AP242, STEP AP203, STEP AP214, JT, and QIF that may affect how data is created, transferred and consumed by entities within the supply chain and show these technologies as they appear in the digital thread maps. The team will also consider workflow standards in addition to data standards (e.g. MoSSEC). The playbooks will highlight where data/documentation can be presented in workflows, visible to both parties, and stored.

Many initiatives have focused on improving the content of TDPs, including native or neutral models with product manufacturing information (PMI), visualization formats, and validation practices. The CSI initiative focused on automating the preparation and delivery of TDPs and providing tools to cost-effectively shift industry from 3D models & 2D drawings to a comprehensive 3D TDP for supply chain interactions. The results of the full adoption of CSI technologies by the three companies involved in the development of CSI, which was likely given that each entity utilized ITI software prior to the CSI program, was a staggering $9M in non-recurring cost savings and $22M in annual cost savings. Given that this program was a $1.5M government investment, this is at least a 50 to 1 return-on-investment (ROI).

Another foundational technology project the team will build from is the work at the NIST Manufacturing Lab. The NIST Manufacturing Lab replicates the configuration of a contract-manufacturing shop. The Manufacturing Lab contains several fabrication machine tools (e.g., CNC milling, CNC turning) and inspection equipment (e.g., CMM, digital micrometers). The equipment was outfitted for data collection at minimal costs. Data is collected from the Manufacturing Lab using the MTConnect standard helping quantify benefits by quickly turning data into information thus reducing lead time.

Easy and secure exchange of data throughout the supply chain increases the opportunity for lower tier suppliers to participate in design collaboration and manufacturability. Collaboration tools and capabilities are needed, but the suppliers need help in how to acquire, install and utilize them. Another significant challenge is in the integration of the existing tools and capabilities to be used as the foundation for the playbook. Each of these tools and capabilities focus on an activity in the digital thread. The integration of these into a complete strategy defined in a roadmap, with a playbook, to enable a transition to a digitally enabled organization is not a trivial matter.

A challenge to the digitalization of the supply chain and the implementation of MBE is overcoming the general lack of technology knowledge and the lack of a compelling business case in the manufacturing industry as related to digital supply chain capabilities and model usage. This is most true in the SMM environment where the resources necessary to implement an initiative such as MBE and digital capability simply don't exist. Because SMMs lack the resources to evaluate their needs and determine a strategy for obtaining these capabilities, education and assistance will be needed to encourage and motivate SMMS to take the steps to create these capabilities in their organizations. The training and education deliverables of this project will be an extremely important component for success in overcoming this challenge. The development of future project calls is a significant deliverable from this project.

Transition

The team has put together a Transition Plan for the playbooks and roadmaps. The industry and academic team members plan to sponsor workshops for OEMs and SMMs at locations around the US. Project outcomes will be presented to the Defense Industry at the Defense Manufacturers Conference and to the MBE and digital supply chain community at the NIST MBE Summit. Industry members plan to use the deliverable to initiate digitalization capability creation with their supply chain partners. ITI will hold several webinars to industry, academia and government participants through this venue. All the capabilities developed will be made available on the Digital Manufacturing Commons and published to industry through websites such as NIST, DoD ManTech, and the Southern Alliance for Advanced Vehicle Manufacturing. In addition, industry reports will be published in the NIST Advanced Manufacturing Series publication. Training and education materials will be developed and made available to academic institutions. The NIST Manufacturing Extension Partnership will be able to take the training materials to work directly with SMMs to implement these capabilities and enhance the SMM's ability to participate as a value-added supply chain partner.

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An Integrated Process for the Manufacture of On-Demand Small UAS

Nathan Beals
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD, USA

Eric Spero
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD, USA

John Gerdes
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD, USA

Abstract

A digital catalog of small unmanned aircraft systems able to be rapidly manufactured on-demand was developed by the U.S. Army Research Laboratory in support of the United States Marine Corps' vision for providing Warfighters in small units with mission-tailored, vertical take-off and landing small unmanned aircraft systems near the point of need. The digital catalog was populated by designer-provided vehicle technical data packages which included all information necessary for a Marine to manufacture, assemble, setup, and fly the small unmanned aircraft systems available in the catalog. A crucial part of the technical data packages were parametric computer-aided design models which were used to scale vehicle designs up and down in size based on user-provided mission descriptions, providing a range of trustworthy performance and mission capabilities. The parametric models also allowed for the selected vehicles to be rapidly manufactured using additive manufacturing technology, ensuring that the vehicle was delivered to the user within 24 hours of its original selection from the catalog.

Introduction

Small unmanned aircraft systems (sUAS) are becoming ubiquitous, driven by a combination of accessibility, size, maneuverability, and general knowledge of capabilities. Users are discovering that they are able to improve system capability by inserting more advanced components in pace with manufacturer component refreshes. These on-the-fly improvements result in nominal increases in vehicle performance, but they circumvent deep understanding of the tradeoffs across size, weight, endurance, and payload. The tactical 3D printing (Tac3D) effort is focused on leveraging the benefits of additive manufacturing to rapidly provide Warfighters at the squad level with mission-ready sUAS. One of the project deliverables is a digital catalog and decision-making tool which enables a user to efficiently select an sUAS capable of performing a specific mission. A vehicle selected using the catalog is then 3D-printed using STL files derived from a parametric computer-aided design (CAD) model and the fully assembled, ready-to-fly, vehicle is delivered to the original user within 24 hours. The Tac3D tool utilizes a technical data package (TDP) for each vehicle which contains parametric models and all required manufacturing specifications, making it possible for a user with minimal training in additive manufacturing to select and build a vehicle.

The Tac3D Digital Catalog

The Tac3D tool's user-facing front end is a digital catalog containing the technical data packages of several sUAS. Upon launch of the catalog application the sUAS options are visually displayed to the user using an image of the vehicle as well as some basic performance information such as maximum endurance, maximum payload, and build time [Fig. 1]. Users can filter and sort vehicle options by comparing vehicle performance specifications to their mental model of mission requirements in order to select the best sUAS. The flight performance of the vehicles in the catalog is estimated beforehand using physics-based models combined with empirical data. This approach is a departure from the current best practice where flight performance is derived from empirical data only, so that any change to the system requires new flight tests or experiments. Even after filters are applied it may be the case that multiple feasible vehicle alternatives remain and the user needs more information in order to down-select to one alternative. In this case more detailed performance information is available for each vehicle including payload-range-endurance tradespace analysis. Once a single vehicle is identified the role of the digital catalog is complete and the TDP is uploaded to an external storage device for further use.

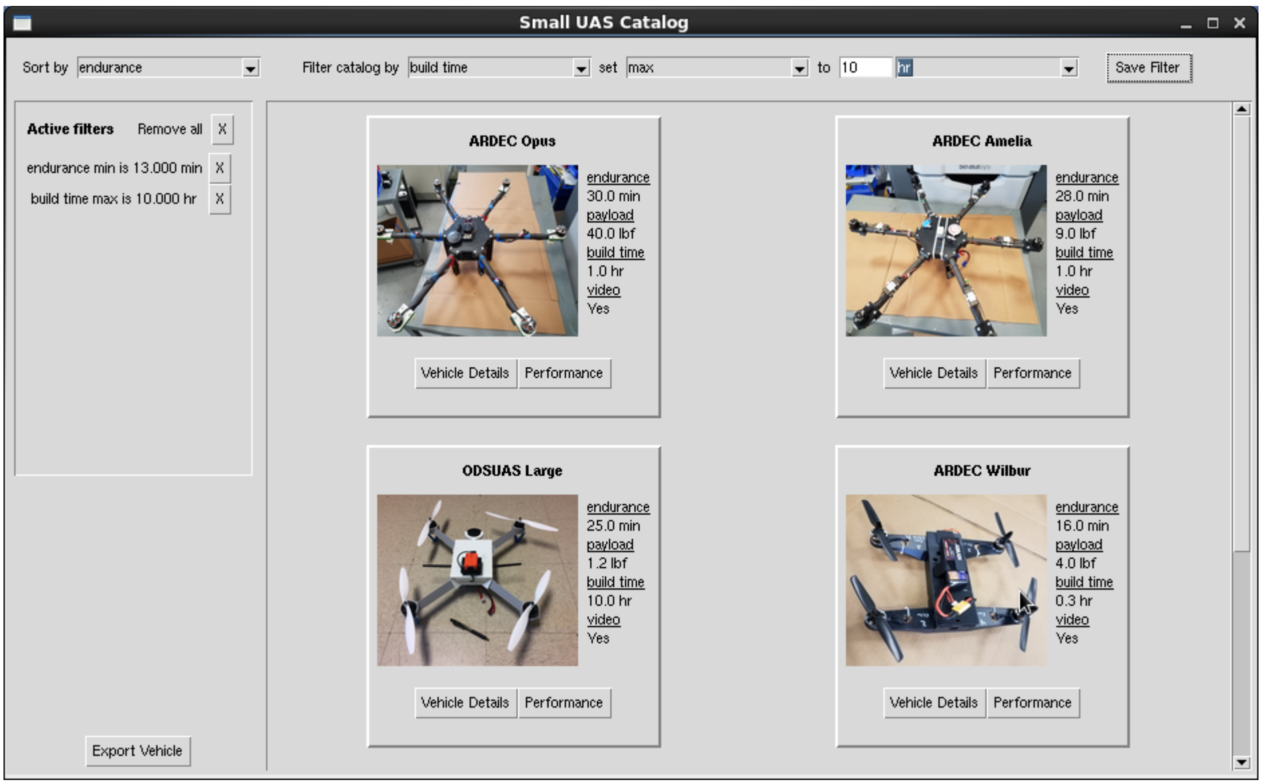

Figure 1. The Tac3D digital catalog graphical user interface.

The Tac3D Process

<u>*The Parametric Model*</u>

In the sUAS design space, a wide range of performance goals can be achieved by simply scaling the size of a baseline model up or down depending on a user's mission requirements. The Tac3D parametric model makes the entire sUAS feasible design space accessible to the user. For example, the primary ARL design for the Tac3D project is a quadrotor architecture, the rotors of which can be made larger or smaller while the airframe is scaled accordingly. Larger rotors are generally more efficient than smaller rotors and therefore a scaled-up vehicle would have nominally better performance metrics, such as endurance and range, than a smaller version of the same quadrotor. On the other hand, a user may desire a vehicle that is easier to carry or that can fly into small spaces, placing greater importance on size and weight. In this case the user may want a smaller scale version of the vehicle at the expense of some other performance metrics. In order to enable this kind of vehicle scaling, parametric CAD models were developed for the vehicle architectures included in the Tac3D tool.

The parametric CAD model is an equation-driven representation that scales the dimensions of a generalized baseline vehicle design by accepting a text file of formatted variables and values. By specifying the design in this manner it is possible to accept input from a broad range of software packages, retain fine-grained control over the sizing of the design, and avoid software lock-in resulting from highly customized software wrappers. Certain important features of the design are enforced as constraints that ensure assembly compatibility across parts, appropriate interfaces to chosen interfacing parts like motor bolt patterns, and properly sized sockets for press-in parts. Because the parametric design is refreshed each time the equations are updated, it is possible to offload the computational burden of 3D geometric representation and manufacturing part file generation to the CAD software, while keeping the digital catalog focused on the vehicle performance tradeoffs.

The Technical Data Package

Vehicles exist within the Tac3D digital catalog in the form of a technical data package (TDP). The TDP is a directory containing all of the information about a vehicle including the parametric model, photographs of the vehicle to be shown to the user in the catalog, performance specifications, a parts list, and documentation regarding the assembly of the vehicle and setup of vehicle components such as the flight controller. Upon launch of the digital catalog the program searches a specific directory for TDPs and creates a vehicle entry in the catalog for each TDP found this way. After a vehicle is chosen by the user using the catalog, the corresponding TDP is uploaded to an external storage device and taken to a 3D-printer where the STL files contained within are used to manufacture all non-commercial-off-the-shelf components such a quadrotor’s hub, arms, and landing gear. Currently, discrete vehicle sizes created using the parametric model of a single vehicle architecture each have their own TDP within the catalog. For example, there may be a large and a small version of the same quadrotor in the Tac3D catalog, each with their own TDP. Ideally, the STL files in a TDP required to 3D-print the vehicle would be regenerated automatically using a programmed connection between the Tac3D application and a parametric CAD program. This capability has been implemented in the past by ARL and Georgia Tech [Refs. 1-3] and may be integrated into Tac3D in the future. A bi-directional link between the technical data package and the parametric component models enables researchers to have complete control over the system design, and provides insight into which user needs are driving system choices.

The downside to using a totally integrated, black-box style, TDP format is that the structure and content of the TDP must be nearly identical for all vehicles hosted in the catalog. Specifically, certain performance data and vehicle details must be included by designers so that all relevant information is available to catalog users when a vehicle selection is made. In some cases vehicle performance must be determined via time-consuming flight or bench testing when validated analytical models are not available. This TDP structure and content uniformity across many vehicle designers is difficult to achieve and someone must always screen new TDPs to ensure the quality of their contents.

Despite the aforementioned drawback, the TDP is a crucial aspect of both the Tac3D catalog and the Tac3D process. The significant time and effort that vehicle designers put into the TDPs takes the burden off of digital catalog users and vehicle assemblers, making the on-demand vehicle process available to almost any Soldier or Marine with minimal training regardless of primary military occupation.

Use of Additive Manufacturing

The USMC and the Army have shown interest in using additive manufacturing in the field to rapidly manufacture mission-tailored sUAS at a fraction of the cost and time of other highly engineered vehicles designed to perform a large variety of missions. A 3D-printed vehicle, for example, can be manufactured, flown, and discarded. Inexpensive vehicles can be used to fly one-way missions and do not have to be recovered in potentially dangerous recovery operations. For these reasons the Tac3D project placed a heavy emphasis on 3D-printed vehicles and incorporated all models and information required to 3D-print a vehicle into the vehicle's TDP.

One of the downsides of using 3D-printing to manufacture sUAS is that thermoplastics commonly used in 3D-printing are poor materials for aerospace applications. They are generally heavier, not as stiff, and have rougher surface finishes than alternative materials such as composites. The goal of Tac3D, however, is to position future users to be able to leverage large improvements in additive manufacturing. Improved 3D-printable materials may be available and new processes may allow a larger percentage of the total vehicle parts to be manufactured on-demand. Ideally, every part of the sUAS will be 3D-printed on-demand including electronics, wiring, fuselage, and even motors. As the number of 3D-printable parts increases, the quantity of different parts that must be procured and the burden on vehicle assemblers both decrease.

Investment in, and leverage of, additive manufacturing technology has high upside for on-demand applications compared to traditional manufacturing methods and is the key technology enabler in the Tac3D process. Future ARL research will focus on extending the application of rapid additive manufacturing to vehicle architectures more complicated than a quadrotor, such as fixed wing, tail-sitter, and bio-inspired designs.

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Realization of the 5-Axis Machine Tool Digital Twin Using Direct Servo Control from CAM

Roby Lynn[1]
George W. Woodruff
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA, USA

Mukul Sati
School of Interactive Computing
Georgia Institute of Technology
Atlanta, GA, USA

Tommy Tucker
Tucker Innovations, Inc.
Charlotte, NC, USA

Jarek Rossignac
School of Interactive Computing
Georgia Institute of Technology
Atlanta, GA, USA

Christopher Saldana
George W. Woodruff
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA, USA

Thomas Kurfess
George W. Woodruff
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA, USA

ABSTRACT

This paper describes an architecture for control and monitoring of a 5-axis computer numerical control (CNC) machine tool directly from a computer-aided manufacturing (CAM) system without reliance on the text-based G-Code toolpath definition format that is currently standard in industrial practice. Instead of defining a toolpath as a set of geometric primitives as is done with G-Code, this architecture utilizes a high-speed bidirectional data pathway between the CAM system and the CNC machine to transfer dense time samples of axis position information between the CAM system and the servo controllers of the machine tool's motion control system in near-realtime. Time samples of axis position are created using a time-optimal trajectory planning algorithm instead of a proprietary trajectory planning strategy that is common in industrial CNC systems. The developed architecture is machine agnostic, and can be used both for enhanced control of machine tool motion and powerful visualization and analysis tasks. An implementation of the system using an open-source machine tool controller known as Machinekit is presented, and a Digital Twin of the machine tool is constructed in the CAM system and shown to be capable of visualizing the as-executed toolpath during machine operation.

KEYWORDS: Computer-aided manufacturing, computer numerical control, cyber-physical systems, Digital Twin, G-code, time optimal trajectory planning, servo control

1 INTRODUCTION

The current state of data communication for CNC machine tools relies on a more than 50 year old format known as G-Code, which is a text-based programming language used to convey movement primitives between a toolpath planning system and the controller of a CNC machine. G-Code allows unidirectional data transfer between the CAM system and the CNC, but in-process monitoring of the machine must be accomplished using separate protocols, such as MTConnect or Object Linking and Embedding for Process Control Unified Architecture (OPC UA) [1]. Familiarity with numerous control and communication standards is required for technicians and manufacturing engineers to be proficient at implementation of a CNC machining process.

The creation of G-Code from a CAM system necessitates translation of geometric entities into the text-based format that consists of lines, arcs, splines, and other motion primitives, each of which is completely defined by endpoints and other parameters. It is the responsibility of the CNC system to realize motion of the cutting tool from information contained in the G-Code commands, and machine tool vendors often use proprietary trajectory planning algorithms to accomplish this task [2], [3]. As a result, some amount of information is lost in translation from the CAM system to the CNC: although the CAM system may be capable of computing desired velocity, acceleration, jerk, and higher positional derivatives along a toolpath, this information cannot be conveyed to the machine tool using G-Code [4], [5]. Additionally, monitoring of actual machine tool motion is hampered by a vendor's implementation of a chosen communication protocol (e.g., MTConnect),

[1]Corresponding Author E-mail: roby.lynn@gatech.edu

which may be insufficient for engineers and supervisory staff to evaluate an as-executed toolpath [6], [7]. This paper describes the development and implementation of a tightly-coupled CAM-CNC architecture that enables more complete control and monitoring of a machining process from within a CAM system. The implementation presented in this paper uses the SculptPrint voxel-based CAM system in conjunction with the PocketNC, which is a desktop-sized machine tool powered by the open-source Machinekit platform.

2 SYSTEM ARCHITECTURE

2.1 SculptPrint: Voxel-Based Computer-Aided Manufacturing

This research uses a CAM software package known as SculptPrint, which leverages the high-performance computing capability of modern graphics processing units (GPUs) to perform automated toolpath generation and analysis for multi-axis machine tools [8]. Part geometry in SculptPrint is represented using voxels, which are the three-dimensional analog to two-dimensional image pixels. The use of voxel models enables creation of high-density toolpaths that can be used to machine intricate and organic shapes that would be difficult to create with traditional CAM [9].

2.2 Machinekit: An Open-Source Machine Tool Controller

The overwhelming prevalence of proprietary machine tool control platforms has motivated the development of a Linux-based open-source alternative CNC known as Machinekit, a fully-featured software machine controller that is capable of controlling both simple and complex multi-axis machine tools [10]. Machinekit enjoys a thriving development community that is committed to creating a usable and fully-featured machine control environment [11]. This research relies on an embedded computer known as the Beaglebone Black (BBB), which runs Machinekit in conjunction with the Xenomai realtime (RT) Linux framework to provide reliable and deterministic control of a physical machine tool. The actual machine tool used for this work is the PocketNC, which is a 5-axis desktop-sized machine that is targeted at the maker community.

2.3 Time Parameterization of Toolpaths

An interactive design session in SculptPrint allows the user to describe toolpaths as the result of voxelized constructive solid geometry (CSG) operations [12]. The output of the session is a sequence of very finely spaced affine frames that represent sample orientations of the cutting tool. Additionally, SculptPrint also provides, for each sample orientation, the corresponding sample positions that the joint motors should track. This is done with the aid of a machine specific inverse kinematic model.

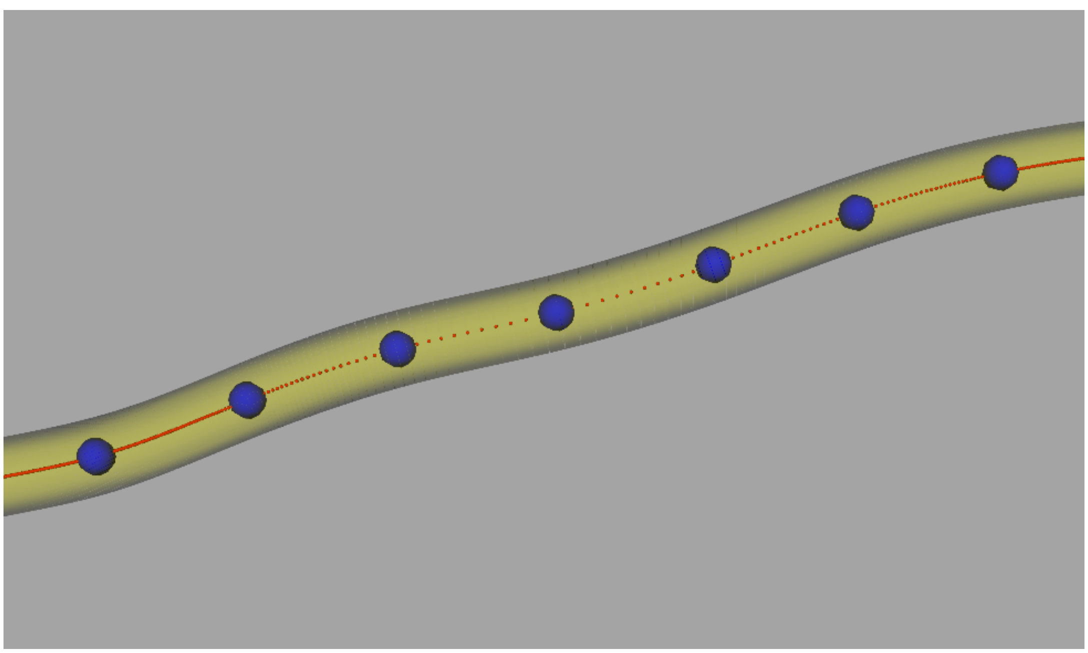


Figure 1: Position Samples and Resulting Time Parameterization

Typical motion planning algorithms work by blending G-code primitives. It would be possible to use Machinekit's motion blending algorithm by interpreting two consecutive joint samples as defining the directed edge that has the two samples as end points. Given the dense position sampling provided by SculptPrint, the direct control architecture instead directly fits and optimizes a spline that interpolates axis position samples using techniques presented in [13]. After the joint samples are broken into retraction-free sequences, the approach described by Pham is applied as follows: a cubic spline is fit to the joint samples with an a-priori prescription of individual joint velocities at the beginning and end of each sequence; then, the time paramaterization of the spline is optimized while being constrained to obey both path geometry and the manufacturer-specified velocity and acceleration bounds of the motors for each joint. The resulting motion can be sampled to obtain the position of each joint at the servo update rate. An example path parameterization is shown in Figure 1. The yellow tube is the optimized spline, the blue points are the position constraints obtained from the CAM system, and the red points are the actual servo samples in the part reference frame. Larger spacing between adjacent points indicates faster traversal of the cutting tool along the path. The very dense sampling ensures that the joint motions affect a motion of the cutting tool that adheres to the user's design intent.

2.4 Direct Servo Control Scheme

Communication of command and feedback information between the CAM system and the RT CNC system is accomplished according to Figure 2. The non-RT CAM system resides on a standalone workstation PC, and serves as both the toolpath planner and the operator interface for the machine tool. The user interacts with SculptPrint to perform process planning and

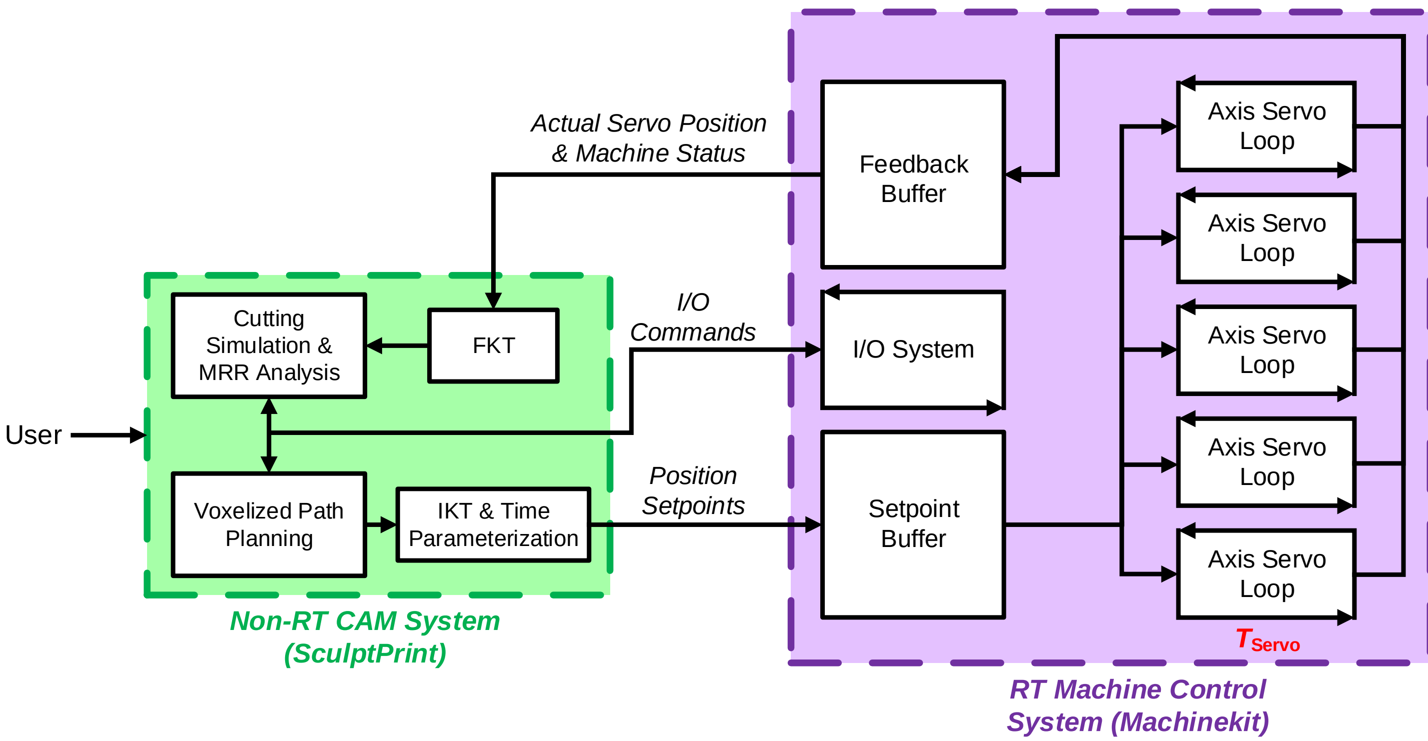


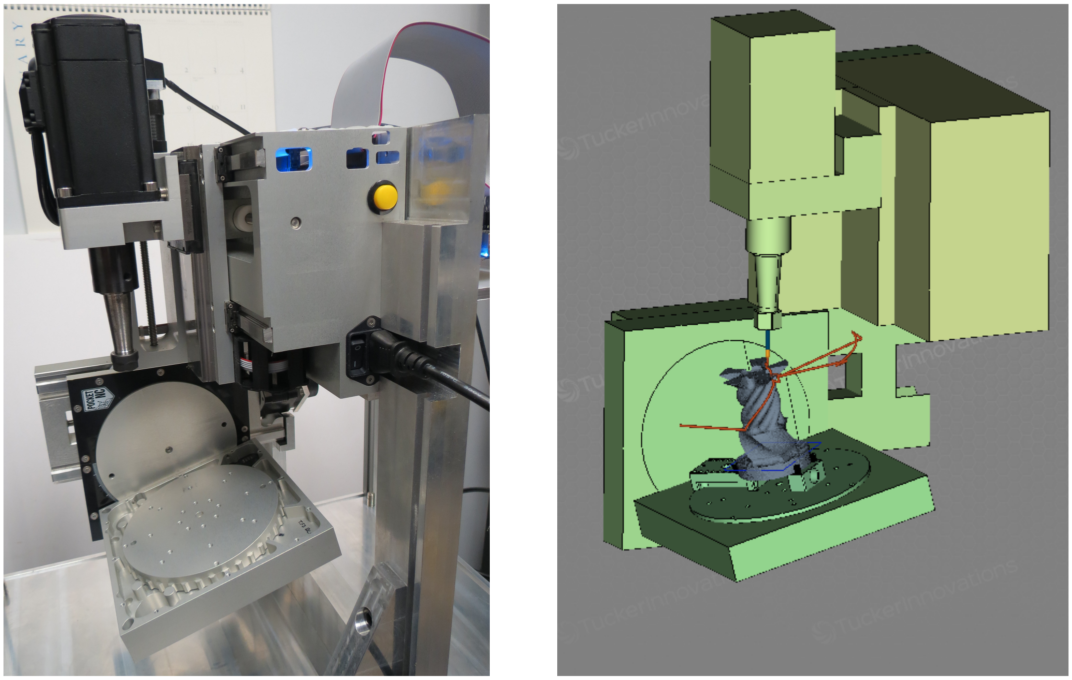
Figure 2: Direct Control System for a 5-Axis Machine Tool

analysis, and the resulting toolpaths consist of pose samples in the part coordinate frame which the tool should track. These poses are then converted to axis positions using the Inverse Kinematic Transformation (IKT) derived from the geometry of the machine. The resulting axis position commands are transformed to time-based position samples using the method presented in Section 2.3 to create axis position setpoints that can be written to each axis servo controller at T_{Servo}, the update rate of the servo system. Upon execution of each setpoint, the servo loops record the actual axis positions, also at T_{Servo}, which are passed back to the CAM system and converted to poses that are visualized in the part coordinate frame using the Forward Kinematic Transformation (FKT) for the machine tool. This architecture thus consists of a machine-agnostic control and monitoring environment that can be used to execute and monitor toolpaths for any machine tool configuration in near-realtime.

Communication of RT data between the RT machine controller and the non-RT CAM system is accomplished using setpoint and feedback buffers whose fill level can float to absorb non-deterministic latencies introduced by the connection of the RT and non-RT subsystems. The CNC system consumes one position setpoint per axis from the setpoint buffer every T_{Servo} and supplies one position sample per axis to the feedback buffer every T_{Servo}. The CAM system must maintain the proper fill level of the setpoint buffer to ensure that it is not exhausted during machine operation (which would cause a cessation of movement) and must also consume position samples from the feedback buffer quickly enough so that the buffer does not overflow. In this research, communication was performed using an Ethernet connection between the BBB and the network interface of the CAM workstation.

3 THE 5-AXIS MACHINE TOOL DIGITAL TWIN

The direct control system architecture in Figure 2 was implemented using the SculptPrint CAM system, a collection of Python applications, and changes to core Machinekit code. The Python scripts performed both time parameterization of SculptPrint toolpaths and high-speed bidirectional machine communication. A CAM workstation with an NVIDIA Quadro M5000 GPU was used to run both SculptPrint and the supporting Python scripts, and communicated with the PocketNC with a direct (i.e., switchless) Ethernet connection. The PocketNC used to validate this system is shown in Figure 3(a). One Python



(a) *5-Axis Desktop-Sized CNC Machine* (b) *Interactive Representation in CAM*

Figure 3: Machine Tool Digital Twin

script was responsible for wrapping the time parameterization algorithms provided by [13]. The generation servo position samples were sent by a separate multithreaded Python script over a transmission control protocol (TCP) connection to the machine; the script also received machine position feedback from a user datagram protocol (UDP) socket listener on the CAM PC. The feedback samples were relayed to SculptPrint and used to move the axes of the interactive machine model and to generate the orange tool tip trace as the machine was running, as shown in Figure 3(b). To limit computational load and bandwidth consumption, the update rate of the Digital Twin in the CAM system was controllable by the user.

4 CONCLUSIONS

This paper described a CNC control architecture and its realization to create a tightly-coupled CAM-CNC system that enables enhanced control and monitoring of a 5-axis machine tool directly from a CAM system. This work lays the foundation for a new machine tool control strategy in which the traditional generation and transfer of G-Code to a CNC is no longer required; instead, machinists and manufacturing engineers need only manipulate a CAM system to create, execute, and analyze toolpaths in an interactive fashion. Future work will investigate both automated process plan generation and enhanced trajectory planning strategies that are realizable by controlling point spacing between axis position samples.

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Issues in Implementing a Model Based Enterprise

Gregory A. Harris, Ph.D., P.E.
Auburn University
Auburn, AL, USA

Daniel Abernathy
Auburn University
Auburn, AL, USA

Roy Whittenburg
MBD360, LLC.
Huntsville, AL, USA

Anthony Holden
U.S. Army, AMRDEC
Huntsville, AL, USA

Anthony Still
U.S. Army, AMRDEC
Huntsville, AL, USA

ABSTRACT

System complexity is constantly increasing while the lead time to develop and move products from design to the customer is decreasing. Early consideration of manufacturability, during the development of the science and technology and the design and acquisition phases, is essential to dealing with this complexity. Organizations have recognized the need to integrate physics-based characteristics into models that enable the simultaneous consideration of the physical configuration, computational elements, and predictable system behaviors to promote products and processes that are designed and built correctly. The purpose of this research is three fold. 1) Develop a comprehensive listing of the most critical issues facing organizations as they engage in digital manufacturing and the model-based enterprise for the creation, use, and sustainment of products and systems. 2) Develop system needs and requirements based upon the issues identified and the desires of the stakeholders to engage in model-based enterprise. 3) Develop a strategy for organizations to utilize in developing their capabilities in model-based enterprise. This paper is concerned with the first purpose, the comprehensive list of issues.

1. Introduction

From the Antebellum Era through Mass Production and into current day, most engineering and manufacturing activities rely on 2 Dimensional (2D) drawings in hardcopy or digital format to convey engineering data and to drive manufacturing processes. With the maturation of manufacturing data format standards and capable engineering software, it is possible to now perform engineering functions using models. A Model-Based Enterprise (MBE) environment employs models rather than hardcopy documents and drawings as the authoritative source for all engineering activities. In a MBE environment the model is the central artifact used to drive all actions throughout the product lifecycle. With this approach data is created, consumed and modified by users throughout the lifecycle and supply chain without having to recreate previously learned models or information [1].

Models are representations, or idealizations, of the structure, behavior, operation, or other characteristics of a real-world system and are used to communicate design information, simulate real world behavior, specify a process or task, and/or express the definition of the product in terms of its form, fit and function. Models can be computational or descriptive with computational models capable of computer interpretation and have a machine-readable format and syntax, and descriptive models being human interpretable for human consumption. In the MBE environment it is imperative that descriptive models are integrated with computational models. Computer Aided Design (CAD) models are a good illustration in that early CAD models were meant for human viewing but now annotated CAD models can be directly understood by engineering software applications [1].

Although industry has worked to become model centric there is still significant manual intervention to adapt to a 3-D model and associated product manufacturing information MBE environment [2]. Several companies have provided anecdotal evidence of the benefits of MBE and connecting the major points within the digital thread [3]. With knowledge of the benefits available through MBE, industry has attempted to embrace MBE on an ad-hoc basis. The ad-hoc approach has generated islands of excellence amid a sea of unclaimed opportunity.

2. Issues

The most complicated and difficult components of developing a strategy for engaging in a MBE for an organization is understanding the issues and needs. The inefficiencies created by the inability to communicate accurate and timely technical data continues to be one of the most significant sources of waste and project overruns [4].

A historical literature review was performed to provide a baseline of issues encountered in implementing MBE. The first approach to finding a list of common issues was to review a library of past articles, presentations, white papers, and reports to collect issues or pain points from the documents that were hindering the adoption and integration of digital capabilities, such as MBE, through the lifecycle of products and systems. The list of issues naturally distributed into five categories, shown in Table 1. Component issues were aggregated into the five topical categories in an initial list and sent to a known group of subject matter experts (SMEs) for review. After this initial review of the categorized issues some SMEs provided additional materials to add to the issue review and the reference list. In an effort to derive the true issues from those that may actually be on the fringe, the team compared the list of topics and the component issues with the Advanced Manufacturing Enterprise (AME) Subpanel taxonomy which allowed additional insight into issue credibility.

Once the categorized list of issues was developed additional sources of issues were evaluated to either corroborate or modify the initial list. The main categories of issues found in the research, (1) Interoperability, (2) Data Reuse, Communication, and Archiving, (3) Advanced Manufacturing Vulnerabilities, (4) Analysis, and (5) Infrastructure, all affect the overall production costs and time of systems acquisition and sustainment.

Table 1 - Issue Categories

A	**Interoperability**
A1	High cost of transitioning from 2D to 3D models (man hours and $)
A2	Manual intervention of interoperability issues (increasing errors which increases time and cost)
A3	Interoperability with supplier increases difficulty and time
A4	Disconnected engineering change process, and process is manual
A5	Data management issues with file sizing and archiving
A6	CAD type A to STEP to CAD type B issues
A7	Hard to get full customer TDP (Never get an EBOM and manually create MBOMs)
A8	CMM programing uses IGES (should accept other formats)
B	**Data Reuse, Communication, and Archiving**
B1	Organization lacks standard approach to receive digital data that maintains data structure for reuse.
B2	TDP in different PLMs are not interoperable
B3	Point solutions to data management are usually not broadly applicable. Relies on custom tools to facilitate NC programming
B4	TDP and CAD files are often too large to transmit which leads to unorganized data in PLM
B5	Software developers are slow to support an open standard
B6	Inability to transmit TDPs delay design change notices, and changes are made manually
B7	Tracking material batches to finished product is difficult
B8	Customer model quality is poor
B9	Waiver history is hard to see, (use army EPDM or PLM/DM software implementation to build library)
B10	Relies on old custom databases (replace tooling database with PLM/DM)
B11	Poor communications with procurement

B12	Quality reporting is all manual
B13	Lack of visibility into other areas data
C	**Advanced Manufacturing Vulnerabilities**
C1	Operational Technologies are not designed to the same level of security as Information Technology.
C2	Devices designed for convenience and not security. Made to be easily attached to machine and digitally operated, but not defend itself from a cyber-attack.
C3	Skill gap of capable manufactures is growing as fewer enter the tradesmen skills.
C4	Physical inspection is costly and ineffective
C5	Lack of flexibility to meet variable demand and surge production
C6	Organization lacks capability to digitally monitor machine tool & work piece monitoring
C7	Forensic Manufacturing
C8	Machine and Facility Scheduling
C9	Estimating is almost totally experience based and no knowledge tools
C10	Overall lack of training
C11	Weld planning is all manual, time consuming and wasteful of materials
C12	Labor retention is an issue.
D	**Analysis**
D1	Drawing and model verification is manual peer only
D2	Little to no analysis for manufacturing simulation or engineering product performance simulation
D3	Lack of good visualization tools
D4	Lack of in-process modeling
D5	Need better verification of master model
D6	Need for graphic assembly planning
E	**Infrastructure**
E1	Lack of IT tool management and support

(The following is a description of some of the main issue findings. Due to length restrictions the authors are unable to provide the descriptions of the full list of issues.)

The lack of interoperable systems is a major issue. Different systems used by manufacturing and design companies do not communicate. Imagine you were trying to buy something at a store and the person selling the product did not speak a language you know. You might be able to make a transaction but it would not be easy and probably not correct. This is the issue with the lack of interoperability while trying to share information throughout the supply chain in that it adds unnecessary time and costs to products making the U.S. less competitive.

Interoperability is the idea that once data is created it is able to be used through all other applicable processes. This eliminates the need to regenerate the same model repeatedly in order to support different processes in each step of the lifecycle. Often parts are created in 3D modeling systems then translated into the 2D drawings. The cost is high to translate the 2D drawings back to a 3D model due to the additional man hours for an engineer, analysist, or machinist to remodel parts (A1).

Additional costs come from increased human interaction with the data which can result in errors and omissions while recreating the model. These errors are difficult to identify but cause defects in manufacturing which increases the time and cost of delivery or use of the system (A2).

When a model is actually available, the lack of interoperability issue occurs when the supplier and lead organization need to exchange information. This can be due to the differences in software the supplier uses and that of the other organization. It can also be due to a limiting bottleneck from the supplier on the processes used to receive models or it may be that the models obtained from the supplier do not contain all the information the lead organization requires. All these issues increase the time for a system to be completed and increase the costs of manufacturing and sustainment (A3).

Another issue that leads to higher costs is the disconnect between an engineering change and the distribution and execution of that change notice which can lead to parts being manufactured that are no longer to specification. The engineering change process is typically manual with email, a non-standard data source, often serving as the primary means of communication and record keeping (A4).

A significant issue in the product lifecycle is the inability to take the model from one software package into another. In most cases, the model created in one CAD system is not able to be directly and completely transferred into another CAD system. Currently the main method for this process is to translate the model into a neutral format, such as a STEP file, and then upload the neutral file into the new CAD system. Most CAD translators are poor and model data is lost in the process, requiring an inspection of the model in the new format compared to 2D drawings, which is usually attempted manually. Another issue is that the ability to translate full assemblies is error prone and typically requires for the assembly to be rebuilt a single part file at a time. This becomes difficult as systems gain complexity and number of parts. All of these translations and rework increase the man hours required for the process and increase the chances of error being introduced into the system (A6). An additional issue that comes from rebuilding the model from the neutral format is that the Product Manufacturing Information (PMI) associated with the model is not always contained in the neutral format. This leads to Engineering and Manufacturing Bills of Materials having to be manually compiled and introduces a source of error (A7).

Although organizations typically have standards on how they are to receive data, each customer/supplier combination has unique file interactions. These interactions can differ on file format, data quantity and quality, and communication frequency (B1). This can also be seen with how once Technical Data Package (TDP) information is entered in a PLM system, they are unable to communicate between different PLM types (B2).

When data is communicated from the supplier it is often in a different format than that used by the receiving organization. Point solutions are sometimes created to help automate the process, but the solutions are not broadly applicable. The process of automation relies on custom tools to facilitate NC programming that have varying degrees of automation and are time intensive to create and change (B3). Another limitation encountered in the supply chain is that some of the CAD model assembly files are so large it makes distribution and storage prohibitive (B4).

Interpretation errors occur with neutral format file exchanges because the developers of the software are slow or even resistant to supporting the latest open standards. The developers each have custom features in their software and would not want to see their market share decrease by reducing the switching cost between software. With the current lack of use of open standard files, most models are stored in the native file format, requiring the company to stay with that software (B5).

When models are acquired from suppliers, there are often stipulations, requirements, bottlenecks, and model quality issues due to concerns over intellectual property protection, which can result in the purchase and delivery of incomplete data sets. These partial data sets may meet the contractual requirement but are often the result of an overabundance of protectionism on the part of the supplier, and fail to support additional efficiencies in the engineering and production enterprise that would otherwise be easily achievable (B8). Another reason that data is not used across the whole life cycle of a project is that data is not accessible. Each area of production operates similar to a silo and if the existing model is not on the requested list, it will be recreated from drawings (B13).

The CNCs and other machines used in manufacturing are becoming more connected as technology increases. This allows for more data collection and control over the machines. Operational technologies are not built to the same standard of security as information technology. The computer hardware and software controlling a CNC mill is often much less robust with regards to both processing power and cybersecurity than an average desktop (C1).

Older machines are being brought into the digital age with low cost technologies that can be integrated onto or into the machine and provide inputs and outputs to the network. While this does allow for the machines capabilities to be increased while avoiding a large capital expenditure, it increases the vulnerability of the system as many of those devices are made to be simple to install and operate, with little or no concern for IT security (C2).

The skills gap is widening in the United States as older generations leave the workforce and the workers left to replace them do not have the same expertise. Manufacturing systems are increasing in capability, but this increase is being offset by the loss of skills possessed by more experienced workers. This "brain drain" is another gap that is difficult to overcome because it is only attained from experience (C3).

3. Summary

There are still many issues to overcome before the full benefits of a MBE environment can be realized. Fortunately there seems to be a convergence of the issues that can be addressed by the MBE community to help achieve the completion of the digital thread in commercial and government systems.

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Requirements for a Digital Twin Manufactuirng Framework

Dr. Martin Hardwick,
Convener ISO TC184/SC4 WG15 Digital Manufacturing
President STEP Tools, Inc.
Professor of Computer Science, RPI
Troy NY 12180, USA

In the context of manufacturing, digital twins are evolving models of the physical items used in production. Twins reduce costs and increase quality by making manufacturing processes easier to operate and validate. Accuracy is essential so that digital twins can be used to optimize production. Timeliness is necessary if the issues to be corrected are to be addressed before they harm products or processes.

Timeliness is being made possible by faster computers and faster networks. The faster computers are making real time manufacturing simulation possible. The faster networks are delivering data from sensors at speeds exceeding 100Hz.

Accuracy requires models of all aspects of the production processes including the design tolerances, the manufacturing machines, the production plans, and the consumable resources. Digital twin manufacturing gets this information from the digital thread (see Figure 1). Three data standards are used in the thread: STEP, MTConnect and QIF. They have overlapping definitions but meet different requirements.

1. STEP is a technology for product modeling. The data normalization used in STEP enables long-term archiving for complex products [1].
2. MTConnect is a technology for process monitoring. The simple formats used in MTConnect make it fast for real time streaming [2].
3. QIF is a technology for documenting product quality. The rich associations in QIF ensure that it is good at explaining the reasons for a quality issue [3].

Figure 1 Digital Twin Machining

The digital thread makes manufacturing more efficient by enabling feedback loops. As shown in Figure 2, the first level loop delivers models to CAD systems for tolerance validation. The second level loop delivers processes to CAM systems for optimization. The third level loop delivers adjustments to CNC systems so that they can be adaptive.

The first level loop can use an enterprise protocol such as OPC/UA to notify other systems when new models are available. The second level loop can use a data protocol such as STEP-NC to share process models. The third level loop can use a language such as JavaScript to enable real time corrections.

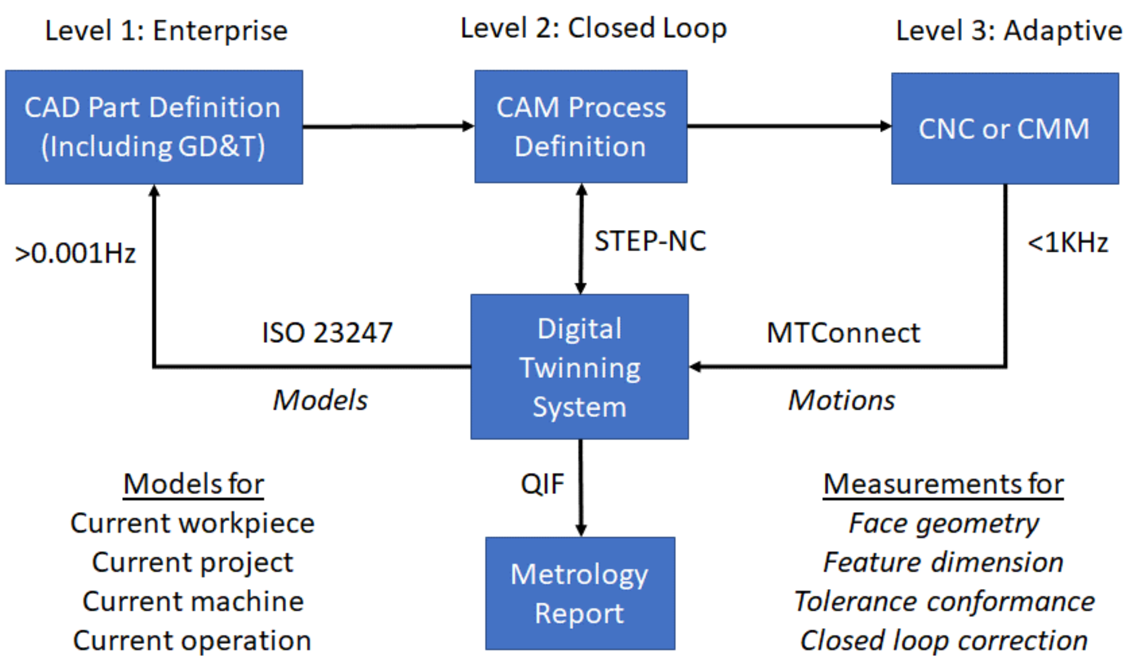

Figure 2 The Digital Thread

The new ISO 23247 standard defines how the framework operates. Universal identifiers are used to link the models. A UUID is defined by a unique string of numbers that can be generated by web sites, and seeded by algorithms. Newer standards such as STEP and QIF include information for these identifiers, and older standards such as APT frequently have a field that can be used to store them. Figure 3 shows the benefits of linking. As shown in the code below, a QIF evaluation of a touch probe measurement on a STEP model is enabled using MTConnect. In this example, the SHDR format of MTConnect links a measurement to a face and a tolerance. Six records are shown. After six have been measured, the metrology system evaluates the tolerances and generates QIF results. These results are then read by the digital twinning system with red, yellow and green to display failure, partial success and full success (see Figure 3).

017-02-20T15:32:24.223-05:00|measure|feature:"9ffd7cbf-25bd-4be9-ab37-90b7ee855c69" order:1 count:6 id:"FACE27454" characteristic:"3DLocation" x:-11.000000 y:-33.333333 z:9.500000

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The digital twinning system makes processes more efficient by giving applications the ability to make more accurate estimates of manufacturing properties. Problems such as potential collisions can be detected and avoided. Issues such as tolerance conformance can be monitored and corrected. Opportunities to make processes more efficient can be identified and executed. For example, if the schedule changes, then it may be possible to reduce tool wear by adopting gentler feeds and speeds, or it may be possible to use a better machine so new tool paths are followed. In either case the digital twin has a model that can be used to generate the new data.

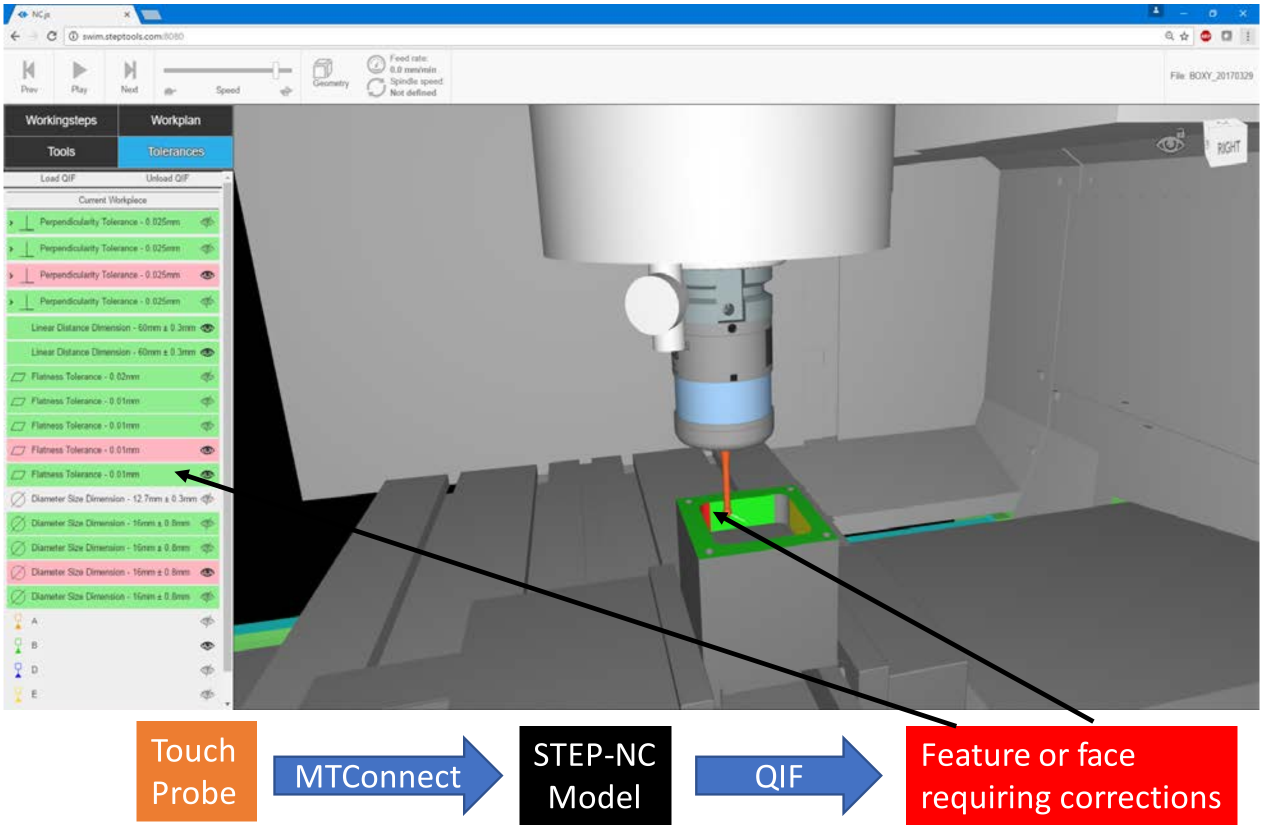

Figure 3 Twinning system showing QIF results on a STEP model

Depending on the circumstances, tolerances can be evaluated in a CAD system, and processes can be optimized in a CAM system. The first two levels of the framework make this possible by delivering models to those systems. The third level of the framework is more aggressive because it assumes that the models are to be corrected in real time. This requires the ability to make measurements and adjustments while a process is executing.

NC.js is a system for dynamically modifying machining data: https://steptools.github.io/NC.js/. It is a JavaScript environment that evaluate digital thread models. The environment includes functionality for generating just in time Gcodes. The language is still being tested but it has the potential to change CNC programming from paper tape and assembler codes, to data streaming and callback promises.

NC.js is made possible by the digital thread because it supplies models. An ongoing roadmap for its deployment is shown in Figure 4. In the first phase, machining has been made "transparent" by delivering visual models to smart phones and other devices (see Fig.1). In the second phase, machining has been made "measurable" by connecting results to metrology systems (see Fig.3). In the third phase. machining is being made "optimizable" by using CAM systems to define better solutions. In the fourth phase, the machining is to be made "adaptable" by using intelligent apps to automate optimizations. In the fifth phase, the framework is to be made "connectable" so that servers can supervise machines across the supply chain.

The Machine Tool Builders are being challenged to connect their systems to the digital thread using the framework. IMTS 2018 will feature several machine tool builders sharing data for an aerospace part. On each day the part will be machined in three or more stages. One will do the stock preparation, the next will do the roughing and the final participant will complete the finishing. The order will be chosen at random and the audience will be able to follow the part as it moves between the vendors. At their option the vendors will be encouraged to make on machine measurements and report the results. And they will be assisted if they wish to make process optimizations to show the flexibilities offered by machining from models.

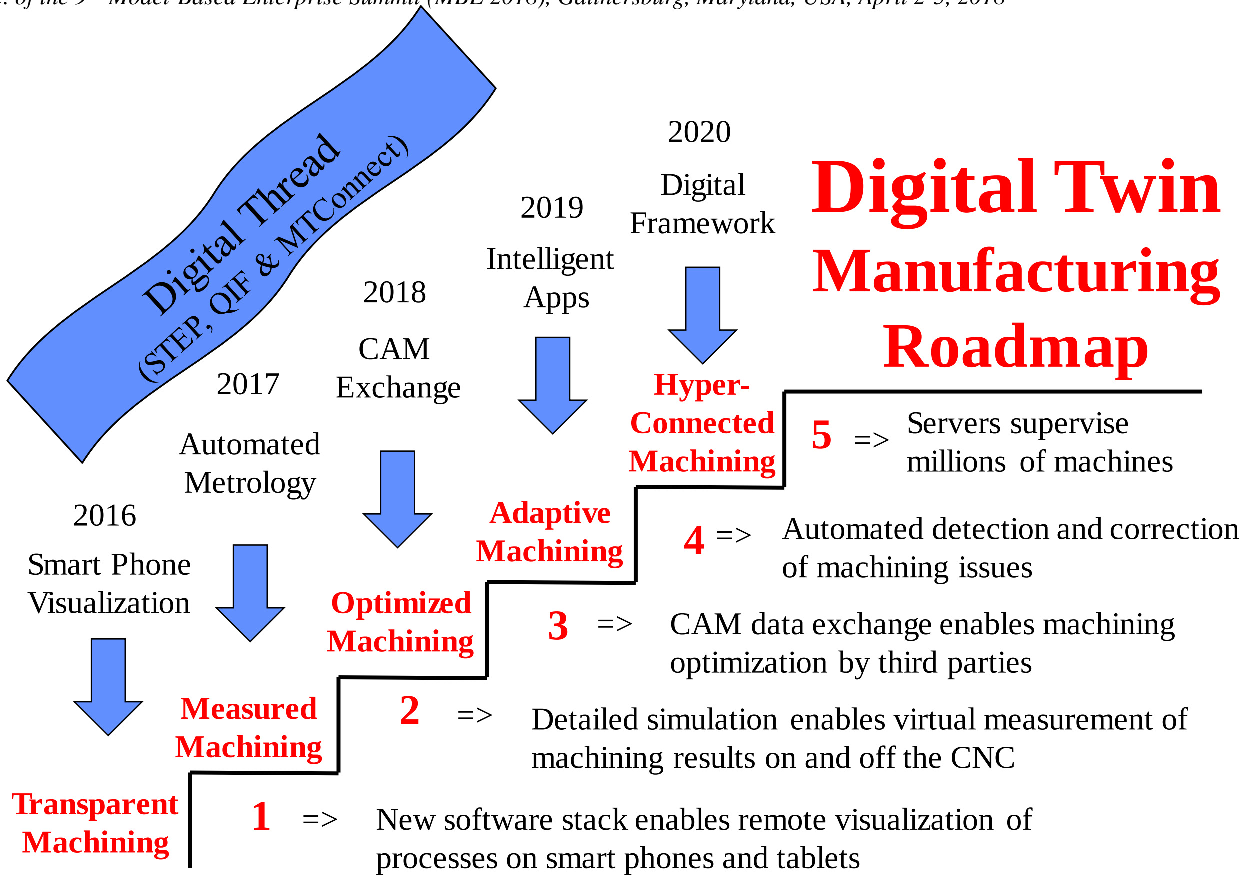

Figure 4 Framework deployment roadmap

ISO 23247 is a new standard. Its completion is projected for January 2021. This coincides with the last stage of the Roadmap when enterprises should be able to connect their systems to thousands of machine tools. There are many potential road blocks. QIF and MTConnect are not yet ISO standards. STEP-NC is being evaluated by the machine tool vendors but is not yet available as a standard option. The framework standard has just been started and no drafts are publicly available.

However, the available resources on the average CNC are increasing rapidly. Real time simulation is within reach for complex processes. With the right standards manufacturing control can return digital data to the digital enterprise. This will yield many new efficiencies.

STEP-NC is used in production today. Up to 5,000 unique parts are machined daily at one large aerospace enterprise. If you flew here on a large new airplane, there is a 50% chance that some of the pieces were made using STEP-NC.

The next step (pun intended) is to formalize the linkage between the three digital thread standards by enumerating the types of entities and objects that can be linked by the UUID's. This should be followed by a definition of Level 1 for an application such as robot tending so that CNC machines can share models with robots and vice versa.

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[2] "Improving Machine Tool Interoperability using Standarized Interface Protocols: MTConnect", Athulan Vijaraghavan, Will Sobel, Armando Fox, David Dornfield, Paul Warndorf, Proceeding of 2008 Symposium on Flexible Automation 2008, http://escholarship.org/uc/item/4zs976kx

[3] "QIF 2.0: A New Digital Interoperability Standard for Manufacturing Quality Data", Curtis Brown, Dimensional Metrology Standards Consortium, 2014, http://www.nist.gov/el/msid/upload/17_cBrown.pdf

Incorporating Standardized Factory Device Data into the Model Based Enterprise

Russell K. Waddell
The Association For Manufacturing Technology
McLean, VA, USA

Shaurabh K. Singh
The Association For Manufacturing Technology
McLean, VA, USA

ABSTRACT

The Model Based Enterprise depends on a complex ecosystem of standards intermixed with proprietary software and tools. An interoperability-first approach to information standards will allow scale and address a missing interaction layer in the current MBE technology stack. An example of an open but incomplete stack already exists in discrete manufacturing built on ISO13399 and MTConnect, and although end-to-end standards have a poor track record of adoption there remains a considerable risk that proprietary approaches remain or become obstacles to MBE development and adoption.

1. Introduction

An interoperability-first approach to information standards and data modeling is necessary for the Model Based Enterprise to scale up and be adopted in the marketplace. Both engineering and manufacturing functions are currently supported by a host of robust and growing standards, but there is a gap between the upstream and downstream functions. Some interaction models have already been created, and even commercialized, but have not fully filled the gaps. Where standards step in to fill the missing connective layers, the Model Based Enterprise will remain severely limited if proprietary, end-to-end approaches win out over harmonization, modularity, and interoperability among standards themselves.

2. Background

Enterprise level manufacturing systems rely on inputs from other systems, equipment, and actors. Many of these inputs are associated with a 3-dimensional product model, the basis for and namesake of Model Based Enterprise and Model Based Definitions. Where the value of model based definitions has been described, it is frequently expressed from the perspective of a product lifecycle management (PLM), engineering, or design function, leaving manufacturing functions to be characterized as downstream.[1][2][3][4][5] The manufacturing industry has a long history of using highly proprietary, vertically integrated systems, but open,

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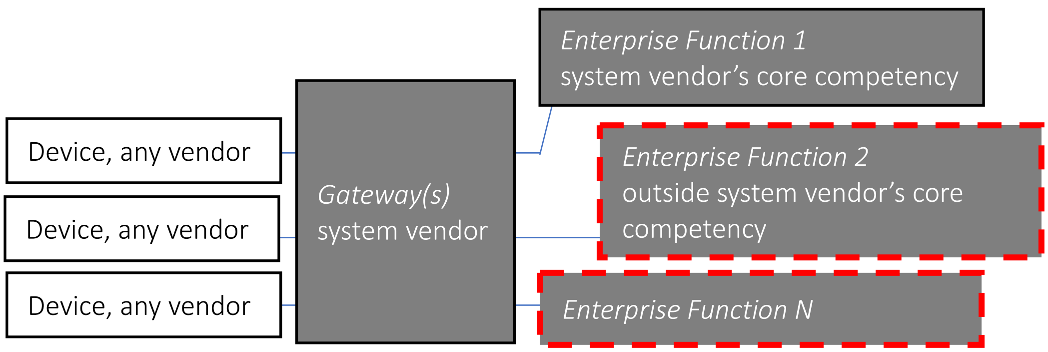
[5] Virgilio Quintana, Louis Rivest, Robert Pellerin, Frédérick Venne, Fawzi Kheddouci, Will Model-based Definition replace engineering drawings throughout the product lifecycle? A global perspective from aerospace industry, Computers in Industry, Volume 61, Issue 5, 2010, Pages 497-508, ISSN 0166-3615, https://doi.org/10.1016/j.compind.2010.01.005.

standards-based architectures have emerged as an alternative. This has paved the way for implementation of software and digital tools for production on a vast scale, which in turn makes the full realization of Model Based Enterprise more plausible now than ever before.

Standards reduce the cost of interoperability and minimize wasted, duplicate effort on translation between and across systems. Information and communication within the PLM, engineering, and design functions of the manufacturing enterprise are well-served by international standards such as ISA-88 and ISA-95 and by organizations such as Manufacturing Enterprise Solutions Association (MESA). Device manufacturers and developers in manufacturing functions have embraced open data access, and standardized device data models for manufacturing functions are in active development via standards such as PackML for continuous manufacturing and MTConnect and ISO13399 (cutting tools) for discrete manufacturing. These standardized device data models have yet to be fully integrated with enterprise level systems.

1. Proprietary, End-to-End Interactions

Although model based approaches are gaining favor and robust standards have established footholds in the marketplace in both upstream (PLM, engineering, and design) and downstream functions (manufacturing), the interaction layer between upstream and downstream functions is poorly defined. Vertically integrated, proprietary technology stacks are available and offer something approaching end-to-end solutions. In many cases, these vertically integrated options are prohibitively expensive. They may also offer lower



functionality than dedicated but narrow class leading alternatives.

Figure 1: Proprietary stack from a single vendor or system integrator offers a high degree of control and consistency, but may exclude best-in-class functions provided by non-interoperable supplier.

2. Cutting Tools: An Incomplete Stack for Discrete Manufacturing

An open, standards-based technology stack built on layered device data models already exists for cutting tools for CNC machines. ISO13399 models cutting tool geometries, which are harmonized with MTConnect CNC machine data models in Part 4.1 of the MTConnect Standard and carried with MTConnect XML documents. These layered models are included in tool libraries to be consumed by CAM packages. Proprietary tool libraries curated and maintained by a series of ad-hoc partnerships between toolmakers and CAM companies have now been supplemented by the Machining Cloud open tool library, which collects tool geometries from toolmakers and makes that data available for anyone.

Via this open standards stack, model based cutting tool definitions are available and in current use. However, gaps persist in incorporating other device models to the stack and between CAM and non-CAM enterprise functions.

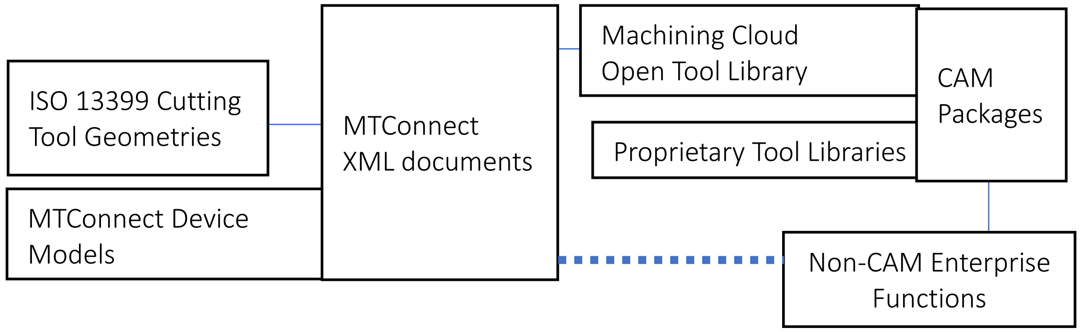


Figure 2: Model based cutting tool definitions are made available via an open, standards-based stack upstream through the CAM function. CAM packages are well integrated to other enterprise functions, but MTConnect device models so far are not.

3. Scalability and Monolithic Standards

Monolithic approaches to manufacturing standards have attempted to create universal, end-to-end, and all-encompassing definitions. The resulting standards have failed to achieve critical mass in terms of adoption, and ultimately suffer the same obstacles to scale as highly integrated proprietary ecosystems. Where tight control is required, de facto standards imposed by market-moving manufacturers are often able to achieve success without outside standards development. Even these standards tend to be narrow and specific in scope, albeit far-reaching in their impact on the industry via large, compliant supplier networks.

Calls from the manufacturing industry for convergence around one single standard persist, but fly in the face of decades of experience in IT, software, networking, semiconductor manufacturing, and other industry verticals. While manufacturing may eventually see a dominant, near ubiquitous standard or set of standards, it is still early days and the industry is more likely to see continued standards proliferation rather than convergence and consolidation.

Closed architectures pose a significant threat to wide adoption of model based approaches. While vertically integrated single vendor solutions are the most obvious example, closed standard development or “boil the ocean” efforts intended to create a single dominant standard are equally challenging to widespread adoption of model based approaches.

4. Conclusion

Open, pluggable, and modular system architectures underpin the modern IT and telecom industries. As new information and communications technologies dramatically transform manufacturing, standards developers in the space should embrace a similar framework for the manufacturing standards ecosystem to enable and drive further adoption of the Model Based Enterprise. The foundations for harmonized standards development have already been laid and some small examples exist today, but even where open, non-proprietary standards exist there remains considerable potential for false starts or total failure of MBE should proprietary approaches persist or return to prominence.

Empowering the Digital Transformation via Digitalization within the Integrated Lifecycle

Gerald Deren
Siemens PLM

Today's reality is that challenges facing global and high-growth innovation manufacturing enterprises are not trivial. For example, dealing with and overcoming "Disruption" in the forms of:

- Growing products or processes complexity.
- Ever changing rapid innovation cycles
- Detailed traceability requirements
- Regulatory requirements
- Complex genealogy
- Massive documentation requirements

Success or failure in dealing with these could be the pivotal point determining success and growth versus lack of competiveness and possible expiration.

"To survive disruption and thrive in the digital era, incumbents need to become digital enterprises, rethinking every element of their business." Digitalization across the entire end2end production lifecycle represents an approach towards solution enablement that helps win in this environment.

Digitalization a fundamentally a new approach that affects Trends in Product Development by

- Changing the way systems come to life
- Changing the way *systems* are realized
- Changing the way *systems* evolve

The key to successful adoption is the way companies start their journey in their systems engineering / digitalization practice. The focus of this topic is to discuss a digital enterprise-based approach to MBE and discussion on gains and challenges certain customers have seen. Lifecycle

Digitalization is NOT a single answer and does not define a correct way for all to adopt it, but it does make visible the need for companies to enable a discipline with respect to communication, collaboration, and measurement throughout the entire product development lifecycle.

The Model-based Enterprise Transition Initiative (MBET-I): An NNSA Stockpile Services Solution to the challenges of Model-based Enterprise (MBE) implementation in the National Security Enterprise (NSE)

Ryan Kuhns
DOE/NNSA
Washington, D.C.,
USA

ABSTRACT

The Nuclear Security Enterprise (NSE) is the network of national labs and plants that carry out the work of stewarding the nation's nuclear weapon stockpile on behalf of the Department of Energy's (DOE) National Nuclear Security Administration's (NNSA) Defense Programs, which manages the nuclear stockpile. Currently within the NSE, 2-D drawings are the official product definition format used to provide design definition from NSE Design Agencies (DAs) to Production Agencies (PAs). At the same time, 3-D models and the data associated with them are utilized extensively in design and production processes at the respective NSE sites. Expanding the use and transfer of models across the NSE, and the positive business outcomes from such use, requires DOE/NNSA policy and processes conducive to a Model-based Enterprise (MBE).

The Stockpile Services division of DOE/NNSA's Defense Programs is jumpstarting a Model-based Enterprise Transition Initiative (MBET-I) to help address the process-based and organizational hurdles to MBE in the NSE. MBET-I will establish MBE friendly policies within NNSA and DOE (where necessary) and will work to formalize and expand model-based practices among the NSE DAs and PAs. Driven by the success and excitement surrounding the Model Authorized Product Realization (MAP-R) study between Sandia National Lab (SNL) and the Kansas City National Security Campus (KCNSC), MBET-I will support additional pilots and studies attempting to map MBE's potential and related gaps across the NSE. MBET-I funded pilots are also expected to inform investment and policy. MBET-I will also engage key management at the NSE sites and partner with the grassroots Model-based Integrated Tools (MBIT) community, which is the premier gathering of the NSE's product definition and realization technology subject matter experts (SMEs).

The activities above will combine to form a non-permanent project with the goal of having 3-D models available for use as official product definition for the production and qualification of the NSE's product. Following implementation of MBE friendly policy from DOE/NNSA, the NSE will have the opportunity use model-based practices to help support and improve both current business and technical practices and help expand on and permit advanced manufacturing techniques that require model-based design definition and model enabled production and qualification activities.

The NSE and NNSA may face a “tipping point” with regards to MBE. The enterprise has absorbed the lessons of previous attempts at integrating model-based design definition technology in NSE processes and implemented technological solutions to those problems. At the same time, current business practices and DOE/NNSA policy disincentivize the use of model-based product definition and a concerted NSE wide effort to implement a MBE in as far as is possible. This presentation will describe how Stockpile Services has programmatized its effort to give MBE the “pull” it needs to realize its potential in the NSE.

Connecting the MBE: Integrating 3D Technical Data throughout the System Lifecycle

Bruce Kaplan, Ben Kassel, Thomas Parks
LMI

Dick Tiano, Scott Truitt
ATI

The model-based community is now actively addressing how best to deploy the Model-Based Enterprise (MBE). System engineers and designers creating digital models are vigorously considering and confronting model use throughout the system life cycle. Accordingly, they need to ensure the models can serve the needs of a myriad of processes such as provisioning, cataloging, sustaining engineering, depot work instruction development, parts procurement (sustainment), technical manual development, and a host of other logistics processes. The majority of these processes occur during the operations and sustainment phase of the system, a period that spans 80% to 95% of the system's life cycle and accounts for 65% to 80% of total system costs. So, to effectively deploy the MBE for DoD weapon systems, it is imperative that it meet data information requirements for the various life cycle processes. Clearly, not thinking ahead and failing to build models for an integrated lifecycle can cripple a program for decades, driving up costs and driving down readiness. Integrated MBE done right is an enabler of smart sustainment.

As a future recipient and consumer of MBE products, DLA has been researching 3D technical data for the past 4-5 years to ensure it understands the implications and constraints associated with using such data to carry out its operational responsibilities for cataloging and sustainment. DLA has conducted numerous studies to explicitly identify the specific data and data format requirements necessary in 3D technical data to successfully catalog and competitively procure weapon system parts to facilitate life cycle sustainment. As part of these studies, DLA has tested its findings by conducting actual procurements of Class IX weapon system parts working diligently with a variety of Engineering Service Activities (ESAs), three DLA supply centers, and various commercial suppliers/manufacturers. Additionally, DLA worked closely with the Navy's CH53K (King Stallion helicopter) Project Management Office (PMO) and the Naval Supply Systems Command (NAVSUP) to review the condition of CH53K 3D technical data and assess its ability to meet information and format requirements to support the provisioning, cataloging, and sustainment processes. The findings, conclusions, and lessons learned from the procurement studies and the CH53K technical data assessment is critical information for the model-based community as it works to deploy the MBE and effectively integrate it across the weapon system life cycle.

This presentation will address the specific information gathered during DLA's 3D technical data studies and assessments. The presentation also will briefly describe DLA's current 3D technical data outreach project targeted to the Military Service ESAs, PMOs, and other activities that own and manage technical data and regularly supply that data to DLA.

Tradespace Exploration of MBSE and MBE Integrated Workflows

Dr. Joseph Simmons, PhD
Phoenix Integration
Washington, DC, USA

Dr. Scott Ragon, PhD
Phoenix Integration
Novi, MI, USA

Anthony Davenport, MBA, BSME
Phoenix Integration
Baltimore, MD, USA

ABSTRACT/Executive Summary

Concepts associated with Model Based Engineering have been progressing for the past 20 years. In recent years, a subset of MBE, Model Based System Engineering (MBSE), has evolved to help system engineers move away from document driven systems engineering towards a model based approach for capturing system structure, behavior, requirements, and parametrics. With this model based approach, there is a need for systems engineers to integrate their system engineering models with more sophisticated MBE tools for requirement verification and system optimization. The overall objective is to minimize program risk, minimize program cost, and maximize system performance while meeting or exceeding program objectives.

Implied in the above is the need for a method to integrate existing domain expert models (physics, financial, etc.,) into a system of system model that can reliably verify and validate the real-world physical system before parts are manufactured and assembled. And do this as early as possible in the product life cycle so that mistakes don’t scale as a program moves from affordability (purchase) through the sustainability (field) phases.

This presentation will show how bi-directional integration of MBE with MBSE can provide domain expert simulation models to systems engineers, so that system engineers at the earliest stages of concept and design can perform graphical tradespace analysis that includes design sensitivity, design optimization, and risk/reliability analysis through probabilistic analysis. The presentation will show how these methods are used to make decisions during the acquisition process (conceptual design) and transition into manufacturing (production). The presentation will conclude with a description about how this is being accomplished across organizations (internal and supply chain) that are spread across wide geographical distances while securing Intellectual Property and data integrity and model portability.

Enabling MBE across the Life Cycle through 3Di TDPs

Marc Lind mlind@aras.com
Aras Corporation
Andover, MA USA

ABSTRACT

The need for a Model-based Enterprise (MBE) approach across the life cycle has never been more critical as defense technologies become increasingly complex. New warfighter capabilities combine sophisticated hardware designs with more and more electronics, software and firmware. The move to 3Di technical data packages (TDPs) is important to gain efficiencies and enable new digital thread processes for manufacturing and support.

Consistent creation, ingestion, verification, change control and distribution of MBE data requires a better TDP delivery process and quality verification, as well as, greater visibility into status and performance data to support PO, SE, LCLS, CM/DM, QA, and PM through the life cycle.

See a real-world example of a 3Di TDP initiative that realizes an MBE approach without forcing IT system 'rip & replace'. Learn how to take a targeted and measured path to MBE modernization in an Agile way.

Maturing MBE Deployment via a Collaborative Model Authorized Product - Realization (MAP-R) Project

Adrian S. Miura
Sandia National Laboratories*
Albuquerque, NM, USA

Curtis W. Brown
Kansas City National Security Campus**
Kansas City, MO, USA

This presentation reviews the objectives, use-cases, insights, and results from a joint project between Sandia National Laboratories (SNL), a design agency, and the Kansas City National Security Campus (KCNSC), a production agency, for advancing the U.S. Department of Energy's National Security Enterprise's (NSE) readiness towards transitioning into a Model-Based Enterprise (MBE).

SNL and KCNSC have a unique relationship in which the lifecycle of products span multiple locations and companies. SNL's primary mission is to ensure the U.S. nuclear arsenal is safe, secure, and reliable, and can fully support our nation's deterrence policy. KCNSC is a manufacturing and technology facility where it fabricates non-nuclear components for our nation's nuclear stockpile. Whereas KCNSC receives designs from multiple national labs (e.g., Lawrence Livermore National Laboratories and Los Alamos National Laboratories), the working relationship with SNL covers common mission spaces and collaboration between the design and product agencies are vital for an impactful MBE implementation.

This SNL/KCNSC joint presentation initiates with a brief overview of the NSE and the relationship between SNL and KCNSC. It covers the collaboration between both agencies in preparation for transitioning to a MBE via the engineering release of an authorized part defining model. We plan to share what we have learned by reviewing some MBE deployment results from a joint collaborative project entitled, Model Authorized Product - Realization (MAP-R). The MAP-R project builds upon the past while leveraging current advances in technology, processes/standards, and the motivation of our current workforce to use a product-centric, model-based definition. Furthermore, the MAP-R project leverages findings from a NIST study, "Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection". The MAP-R project was designed to evaluate our ability to design, manufacture, inspect, and sell a part using an authorized part-centric, model-based approach as compared to our current document-centric, drawing-based practice. A critical project accomplishment involved the product realization and acceptance of NSE's first weapons-like product, authorized via a part defining model-based definition data set. That is a design agency, engineer released a certified part defining model with associated baseline to a production agency which authorized their use of the digital product definition data set for all production activities. Additional project objectives includes quantifying key MBE business benefits throughout the enterprise's development lifecycle, identifying existing challenges, and capturing the differences between the 70+ year tradition of drawing-based practices with the processes required to implement a model-based enterprise for product design, manufacturing, inspection, procurement, and acceptance. All of the project's thirteen use-cases have been exercised for both product definition approaches and the project status is on track to be completed this year. The final phase of this project involves reviewing and documenting our findings.

** Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc. for the Department of Energy's National Nuclear Security Administration under contract number DE-NA0003525.*

*** The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839*

Linking Technical Requirements beyond PLM vault

Rupert Hopkins
XSB Inc.
Setauket, NY, USA

Tatyana Vidrevich
XSB Inc.
Setauket, NY, USA

ABSTRACT

Technical requirements (e.g. drawing notes, tech data, work instructions, and specifications) are primarily published as blocks of text or as pdf documents. This format obscures the complex web of concepts about parts, materials and processes that must be understood to ensure industry acceptable quality, which requires close coordination across the enterprise and its supply chain. The problem is further complicated because these concepts are often drawn from a network of documents generated by different entities residing on both sides of the enterprise firewall. This network of concepts can be modeled using modern linked data and semantic technologies. In this paper, we describe how SWISS – The Semantic Web for Interoperable Specs and Standards – can be used to model the web of relationships among concepts in non-geometric technical data.

PLM/CAD systems employ a sophisticated approach to creating and managing digital models describing part geometry. However, non-geometric information is still primarily communicated through rudimentary free text documents that are created both within the enterprise and by outside entities. The inability to model and easily link to relevant concepts in drawing notes and Standards complicates configuration management and results in a lack of consistent interpretation of requirements throughout the product life-cycle. The inability of a supplier to effectively evaluate the impact of concept revision and cancellation over time increases the need for manual clarification from buyer. This prolongs product lead time and may result in costly rework.

The Defense Logistics Agency Defense Logistics Information Research Program (DLIR) has sponsored the creation of SWISS digital models for frequently used commercial and military Standards. Plugins have been developed that make these models interoperable with enterprise content that is stored within a PLM system. The result is smart, connected technical data that is aware of what it references and the current states of these references, such as whether they have been cancelled, superseded, or revised.

In this presentation we will explore how engineers can understand these relationships and their states from within their PLM system and determine, precisely, what changes are relevant to their product. We will show how digital models of Standards enable visibility into the impact of changes in Standards to derivative requirements and work instructions, and will reduce the rework associated with inadvertent reference to obsolete requirements.

A Matrixed Approach to Model Based Product Implementation

Philip Jennings
Newport News Shipbuilding
Newport News, VA USA

OVERVIEW

Transitioning large complex organizations through technology and cultural changes is a multi-faceted process. How best to manage "Disruptive Technology" and lead change drives organizational evolution and alignment. Leadership readiness with a long term focus, integrated with an end-user bottoms-up approach is critical to ensure the ultimate effectiveness of process and tool adoption.

BACKGROUND/OBJECTIVE

This presentation presents a large organization's, Newport News Shipbuilding's (NNS), implementation experiences transitioning from drawing-based products to digital products for Submarines & Aircraft Carrier. We detail the Experience/History of NNS's transition to SIEMENS PLM TeamCenter & NX-3D applications, Organizational & Culture evolution, Leadership & Technology Readiness, and Training necessary to maximize business processes. This supports NNS's objective to move all of our Navy ship programs into Model-Based Enterprise (MBE) ecosystems.

SUMMARY

NNS's experience implementing SIEMENS PLM applications and evolving to model based processes has required organizational agility and has been evolutionary. Critical aspects of the transition are related to implementing a "Matrixed Approach Organizational Theory" which provides "Structure for Complexity" and allows for industrializing large scale innovation practices. The Technology Adoption Theory, Design Thinking, Appropriate Scalability, and Train & Train more, coupled with proper organizational structure form the basis for successful production process transitioning.

MoSSEC (Modeling & Simulation information in a collaborative System Engineering Context) ISO Standards Effort

Gregory Pollari
Rockwell Collins
Cedar Rapids IA USA

Adrian Murton
Airbus
Filton, Bristol UK

Nigel Shaw
Eurostep, Ltd.
St. Asaph, Denbighshire UK

Judith Crockford
Airbus
Filton, Bristol UK

EXECUTIVE SUMMARY

Large, geographically-distributed and organizationally-diverse enterprises that adopt model-based approaches must still figure out how to answer the same types of decision-making questions that any company would ask: “What is the impact of this requirement change?” or “Which supplier has the skill to perform this task?” or “Who made this assumption and what evidence supports the decision?” This is the “who, what, why, when, where, and how,” or Kipling Method, and model-based processes must support it. The system-of-system definition can be distributed across multiple organizations, platforms, and locations. How does one facilitate a joined-up, “big picture” view? The MoSSEC (Modeling & Simulation information in a collaborative System Engineering Context) data standards effort addresses this need.

MoSSEC compliant tools can monitor and track this lifecycle model metadata and facilitate data exchange up and down the supply chain and across the extended enterprise. MoSSEC is an ISO Approved new Work Item (ISO/AWI 22071, AP243) under ISO 10303. A Committee Draft is planned for the first quarter of calendar year 2018. The effort is supported by industrial partners Airbus, BAE Systems, Boeing, Rockwell Collins and solution providers Eurostep, Dassault Systemes, MSC Software, Siemens, and Modelon. MoSSEC scope addresses:

- Security & Trust
- Actors & Organizations
- Value Generation
- Models Management
- Study Management
- Requirements & Quality
- Methodology
- Architecture & Interfaces
- Optimization

The standard is built on the STEP modular architecture (mapped to AP239) and REST/OSLC services. MoSSEC was developed and demonstrated on the European CRESCENDO and TOICA projects..

Proc. of the 9th Model-Based Enterprise Summit (MBE 2018), Gaithersburg, Maryland, USA, April 2-5, 2018

Critical MBE Themes that Enable a Collaborative Government-Industry Digital Engineering Process throughout the DOD Acquisitions Lifecycle

Dr. Zhigang (Peter) Pan
Northrop Grumman Corporation
Falls Church, VA, USA

The future threat landscape is evolving to become more agile and dangerous as our adversaries are able to field new capabilities at an increased pace and complexity. New and emerging technologies in areas such as AI Swarm Logic, Multifunction Digital Electronics, Cyber, and Advanced Anti-Access Area Denial Systems, all contribute to a battle space environment that evolves at an increased agility and lethality. There is a very high likeliness that if left unchanged, the Department of Defense's (DoD) traditional document centric processes will be unable to efficiently field solutions that can keep pace to counter these ever changing future threats. There is currently a critical need to transform the process in which the US government acquires, develops, fields and sustains future weapon systems such that they can keep up with the ever changing and increasingly complex threat landscape. Model Based Systems Engineering (MBSE) offers a promising way to achieve such a transformation within the DoD Acquisitions and Development lifecycle process.

MBSE, used in this context, will transition away from the traditional document centric process of maturing a weapon system from initial conception through sustainment into a much more dynamic, efficient, and flexible Digital Engineering (DE) process through use of models. Model based artifacts will enable increased traceability and allow errors, inconsistencies and broken links in the system to be detected more rapidly and earlier in the development lifecycle. This in turn will drive down the cost needed for "re-work". It has been empirically proven that the amount of time and money needed to correct flaws in the system exponentially increases the later they are discovered in the lifecycle. The ultimate vision is to realize a single digital representation of the defense system, where each subsystem component is accurately represented via analytical and descriptive models, and can easily be traced to the initial set of mission and requirement definitions. In 2017, the Aerospace Industry Association (AIA) MBSE working group collaborated with key government stakeholders from the Office of the Deputy Assistant Secretary of Defense (OSD) to discuss strategic focus areas that would need to be addressed in order to transition from document centric to model centric. In this presentation, we will highlight some of the key issues and themes that the AIA MBSE team has identified that will help both industry and government take the next steps in realizing this vision. We will cover the following main themes outlined in the whitepaper:

- **Facilitate** ownership of technical baseline through an MBSE collaborative CONOPs
- **Collaborate** to understand & manage IP and data boundaries
- **Expose** insertion opportunities for MBSE throughout the acquisition lifecycle
- **Shift** the government and industry culture to the new model centric paradigm

Using Linked Data to Expand Your MBD with OSLC

Brian Schouten
Director of Technical Presales, PROSTEP INC
Birmingham, MI

ABSTRACT
Abstract (if manuscript)

3D Models are primary source of MBD implementations which lay the foundation for future manufacturing automations. However, your Model Based definition doesn't tell the whole story. Strategizing a plan for requirements and analysis of the design is a monumental and essential task to prove production ready processes. Further, non-CAD data impacts are inevitable and can lead to disaster without the proper planning and tools guided to the shift to Model Based Systems Engineering.

Leveraging linked data enables the traceability you need across your enterprise without replicating data. Imaging being able to access the traceability you need. Presentation will focus on the utilization of the OSLC standard for Model Based Systems Engineering to enable full enterprise intelligence.

3 Take Aways:
1. Why you need Integration
2. How OSLC future proofs your Integration
3. Solution for harmonizing systems between different departments and organizations

System Lifecycle Handler for Enabling a Digital Thread for Smart Manufacturing

Dr. Manas Bajaj
Chief Systems Officer, Intercax

Dr. Dirk Zwemer
CEO, Intercax

ABSTRACT

The NIST "Digital Thread for Smart Manufacturing" project is developing methods and open standards that support validating, certifying, and connecting engineering models across the lifecycle of a product to enable continuous analysis, seamless design-manufacturing transition, high-quality manufacturing, and knowledge reuse.

In this presentation, we will share our vision and progress on the "System Lifecycle Handler" software platform being developed by Intercax to enable a digital thread for smart manufacturing. The System Lifecycle Handler will provide services to: (1) create a digital thread by connecting artifacts in engineering modeling tools and enterprise repositories, such as PLM[1], ALM[2], SCM[3], and databases; (2) lookup and query versioned models and model-elements participating in the digital thread, such as SysML[4], CAD[5], CAE[6], STEP[7], QIF[8], and MTConnect[9] models; (3) compare and propagate changes in the connected models on a continuous basis; and (4) visualize the complete state of the digital thread model federation in support of model-based analysis and decision making.

The System Lifecycle Handler leverages the Syndeia Cloud[10] platform, specifically RESTful web-services ready-to-integrate with other service providers in the digital thread.

A key capability in the digital thread is a global identifier system, similar to the Distributed Object Identifier (DOI) system used for documents today, that can be used to uniquely address and locate artifacts (models, hardware, and other resources) participating in the digital thread. The System Lifecycle Handler system will provide services to enable the global identifier system.

[1] *PLM = Product Lifecycle Management*
[2] *ALM = Application Lifecycle Management*
[3] *SCM = Software Configuration Management*
[4] *SysML = Systems Modeling Language*
[5] *CAD = Computer-aided Design*
[6] *CAE = Computer-aided Engineering (referring to physics-based simulation models)*
[7] *STEP = ISO 10303 family of standards*
[8] *QIF = http://qifstandards.org/*
[9] *MTConnect = http://www.mtconnect.org/*
[10] *Syndeia® = www.intercax.com/syndeia*

Proc. of the 9th Model-Based Enterprise Summit (MBE 2018), Gaithersburg, Maryland, USA, April 2-5, 2018

DMDII 15-11-08: Capturing Product Behavioral and Contextual Characteristics through a Model-Based Feature Information Network (MFIN)

Nathan Hartman
Purdue University
West Lafayette, IN, USA

Daniel Campbell
Capvidia
Sugar Land, TX, USA

Charlie Tokowitz
DMDII
Chicago, IL, USA

Michael D. Sangid
Purdue University
West Lafayette, IN, USA

Mark Nielsen
TechAzul
Hermosa Beach, CA, USA

Saikiran Gopalakrishnan
Purdue University
West Lafayette, IN, USA

Computer Aided Design (CAD) software used to design mechanical parts continues to evolve, and Product Lifecycle Management (PLM) processes continue to advance, but the transfer of data between mechanical designers, manufacturing, and product sustainment has changed very little in the last 15 years. The current state-of-the-art in Model-Based Definition (MBD) is design product geometry centric, typically containing Geometric Dimensioning & Tolerancing (GD&T), annotations, Bill of Material (BOM) and limited processing information stored as Product and Manufacturing Information (PMI). Build data today is comprised of a combination of electronic and paper documents spread across many disconnected files and multiple formats, (i.e. PDF, HPGL, JPEG, STEP, IGES, ASCII, QIF, MatML, etc.). This assortment of delivery formats is unintelligently linked, making data transfer — and more importantly design intent — difficult to communicate and interpret. As a result, today's manufacturers must review, translate & interpret and/or re-enter the design data, causing their manufacturing processes to be labor intensive and prone to error. In addition to the re-creation of the design data, significant amounts of sustainment data captured during the product lifecycle remains disengaged from both design and manufacturing. This full range of lifecycle data can include material properties; design methods; analysis; manufacturing; measurement; inspection; certification test; field service; operations; maintenance; repair and overhaul data. This data is lacking meaningful connectivity to the digital thread, and access to this data is cumbersome at best. The reasons include both the complexity of the data models within which the data must be stored, and the absolute volume of new data, which is fast approaching Petabytes per year.

The DMDII 15-11-08 project is addressing this problem by demonstrating the use of semantic PMI and the capture of materials characteristics at a part feature level and linking those behavioral characteristics to the features in a CAD model via MFIN links. Through the use of semantic PMI and MFINs, enhanced part and feature definitions will be linked to design intent, production information, and sustainment product data to automate inputs into analysis tools, generate planning documents, generate high level measurement plans, and to form a feedback loop to the design decision process.

The diverse project team includes Lockheed Martin, Purdue University, Capvidia, Materials Data Management Inc., MSC Software, PTC, Rolls-Royce, and Siemens PLM. By involving end users, software vendors, and leaders in academic research, this project will bring the leaders in MBE research together with leading software companies to address real-world workflows provided by end users. The objective is to provide real-world MBE software tools and workflows to advance the digital thread for manufacturing.

This presentation will review the current progress and findings of this important and ambitious project.

Bill of Features

Ryan Gelotte
Action Engineering

Jennifer Herron
Action Engineering

In a world where digital engineering and manufacturing is quickly gaining momentum, there is an increasing focus on the “Engineering Bill Of Materials (EBOM)”. Many EBOM efforts leverage some PLM “Part-Centric” design capabilities to create and manage “Parts”. In many cases the EBOM’s are initially derived from a CAD structure but regardless of how the associations are made, there are associations created between the PLM logical “Part” and the CAD model. The CAD model includes the part’s: geometry, annotations, attributes, and presentations states. A key data item to leverage in Model-Based Defintion (MBD) is the characteristics critical to ensure the quality of a produced part (end item). It is possible to leverage much of the embedded model data at the enterprise using a Product Lifecy-cle Management (PLM) framework and the software tools associated with that framework (e.g., Enovia, Windchill, Teamcenter). These type of software systems build a logical ar-chitecture of data, creating logical relationships that free an enterprise to leverage data in non-traditional ways. Data analytics and Knowledge-Based Engineering strategies can also be leveraged.

The System Engineering Vee - Is It Still Relevant in the Digital Age?

Daniel Seal
The Boeing Company
St. Louis, MO, USA

Don Farr
The Boeing Company
Huntsville, AL, USA

Jason Hatakeyama
The Boeing Company
El Segundo, CA, USA

Scott Haase
The Boeing Company
Mukilteo, WA, USA

ABSTRACT

Since its introduction in the early 1990s, the Systems Engineering (SE) “V” symbol has been adopted industry-wide as a clear, relatively intuitive, and instructive framework for understanding the system development process. In general, the SE “V” symbol depicts a roughly sequential development process that starts with concept exploration and requirements development proceeding through design and implementation, progressive integration, verification and validation, and ending with fielding of the system to the customer or user. While it has been modified countless times across industry to communicate or emphasize various needs; some aspects are common:

- Left hand side of the “V”: depicts a progressive ‘top-down’ approach starting with high level conceptualization and ending with a detailed design ready for implementation.
- Bottom of the “V”: depicts implementation of the design.
- Right hand side of the “V”: depicts incremental ‘bottoms-up’ integration, verification and validation ending with fielding of the product system.

What this symbol fails to clearly depict is that later activities on the “V” often provide learnings that feedback into previous activities or even feed forward to change planned later activities. The need to depict this ‘missing’ integrative activity is heightened by the development of increasingly capable modeling and simulation tools that enable early high-fidelity analysis, verification and validation of system behavior. Attempts to address this perceived issue have resulted in updated versions of the “V” containing horizontal “feedback lines” to “close the “V”. Other attempts have included the development of spiral development or agile process models. However, inclusion of these models into the “V” symbol generally result is a graphic that is both more complex and less intuitive to understand.

A further shortcoming of the “V” symbol is that many people incorrectly interpret it as only being applicable to development of a “Product”, when in reality it should also be simultaneously applied to the “Production System” and “Services and Support” systems associated with the product across the lifecycle.

To address these shortcomings, and to better reflect the increased complexity of a Model Based Enterprise (MBE) ecosystem, Boeing proposes a new depiction that acknowledges the all-ways feedback enabled by MBE. Key tenets of this new depiction are:

- Represent MBE as a multi-dimensional, iterative process that evolves the system from requirements, through models, to the physical and virtual implementations.

- Reflect the integrated nature of each element in the life cycle, linked with inherent feedback to related elements.
- Show the lifecycle relationships that span the business in terms of Product, Production, and Service & Support.
- Communicate how the process is different by using MBE approaches.
- Easy to understand.
- Flexible and tailorable for a wide variety of industry applications.

In summary, Boeing feels that the traditional “V” symbol is a linear representation of SE that lacks the expressive detail required for the adoption of an MBE ecosystem that is multi-dimensional, integrated and iterative across multiple product domains. To better represent the complex interactions of an MBE ecosystem, Boeing has identified potential options for a new “MBE Symbol” and is soliciting industry feedback.

Inter-Domain Model-Based Workflows at Baker Hughes GE Using SOLIDWORKS.

Hadi Jafari
Baker Hughes, a GE company
14990 Yorktown Plaza Drive, Houston, TX 77040,
USA

Oboe Wu
DS SOLIDWORKS
175 Wyman Street, Waltham, MA 02451,
USA

Track
Design Recommended Practice and Model-based Definition (MBD).

ABSTRACT
The NIST study, "Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection", proved the solid values of the digital thread. It articulated both qualitative and quantitative benefits of Model-Based workflows. Sharing a similar vision, Baker Hughes, a GE company has been partnering with DS SOLIDWORKS to apply the Model-Based workflows to the actual production across multiple domains, such as Modeling, Definition, Inspection, Procurement and the Supply Chain.
The project scope at Baker Hughes GE is to create digital MBD data and derived 3D PDF documents for internal manufacturing and suppliers to build physical components. It is part of the Baker Hughes GE Model Based Enterprise (MBE) and Digital Thread roadmap. Native MBD data is used for both human and machine consumption during production. The primary goal of using SOLIDWORKS is to directly consume digital 3D models and the annotations for Model Based Machining (MBM) and Model Based Inspection (MBI). 3D PDF is used for human consumption. Informative and intuitive 3D annotations can reduce miscommunications significantly. Multiple files can be attached to one 3D PDF to build a Technical Data Package (TDP) to consolidate technical communications. Furthermore, multiple configurations and configuration-specific properties are published into one 3D PDF. The single compact PDF document can reduce the number of separate files to manage from hundreds down to one.
Following the 3D PDF deployed in production at Baker Hughes GE, the next step is to expand to machine consumption. The semantically defined 3D annotations can be acted upon by Computer Aided Manufacturing (CAM) software to automate the Numeric Control (NC) code generation by using Feature Based Machining (FBM) and Tolerance Based Machining (TBM). The 3D size tolerances and surface finishes automatically drive the selections of machining strategies, tools and setups, which can reduce the CAM programing time from hours to minutes and avoid human oversights. Another key need at Baker Hughes GE is to extract key characteristics from the 3D annotations and create a Bill Of Characteristics (BOC) for Critical To Quality (CTQ) and First Article Inspection (FAI). Using SOLIDWORKS Inspection, a quality inspector can balloon the 3D annotations manually or automatically, and then output the BOC into an Excel or a 3D PDF document for inspection reports.
Once the machine-consumable Model-Based data is created, Baker Hughes GE needs the intelligence be preserved in a neutral STP format because not every supplier can read native CAD formats. Therefore the machine-consumable annotations can be exported into the STP242 format to support the extended enterprise collaborations.
Attendees will learn the pragmatic applications and proven successes of the Model-Based workflows at Baker Hughes GE. Upcoming progressions toward more complete and automated Model-Based workflows can inspire attendees to strategize their own specific implementations.

Ensure solid GD&T practices with Model-Based Definition

Oboe Wu
DS SOLIDWORKS
175 Wyman Street, Waltham, MA 02451,
USA

Track
Design Recommended Practice and Model-based Definition (MBD).

ABSTRACT
Geometric Dimensioning and Tolerancing (GD&T) is an engineering language widely used in both 2D drawings and Model-based Definition (MBD). ASME Y14.5-2009 and ISO 1101-2017 are the latest and most popular GD&T standards that specify the required and recommended practices. In MBD implementations, it has become increasingly important to discern the GD&T differences between 2D drawings and MBD. For example, manufacturers, suppliers and service providers may need to convert existing 2D drawings into MBD datasets. However, the GD&T standards were designed and written mostly according to 2D drawing conventions. The 2D-oriented requirements and recommendations are not completely accurate or appropriate in the 3D model space. On the other hand, the model-based approach brings encouraging and significant advantages to ensure solid GD&T practices. Therefore, it is highly recommended that MBD implementations recognize and leverage the model-based differences and advantages, three of which will be shared in this presentation.

1. Define features rather than geometries directly and unambiguously.

In the 3D model space, features are more tangible and intelligent than on 2D drawings. It is recommended to define features such as faces, widths or hole patterns, rather than geometries such as edges, middle planes or circles, because features deliver product functions. Additionally, in the actual production, features are what get machined or inspected.

2. Ensure compliances with GD&T intelligences in MBD software.

Based on the intelligent 3D features, MBD software applications with built-in GD&T rules can help detect and correct violations in small details which are prone to be overlooked by designers and inspectors. Therefore, costly or time-consuming manufacturing issues due to GD&T errors can be alleviated.

3. Facilitate GD&T interpretations with automatic visual aids.

GD&T definitions can be hard to interpret, especially for a global network of suppliers at different skill levels. To ease the communications, MBD software applications can provide instant and intuitive visual aids which are not feasible or available on 2D drawings yet.

Attendees will learn the important and practical GD&T differences between 2D drawings and MBD. Specific GD&T requirements will be discussed and relevant 3D applications will be illustrated. Attendees will be able to make better use of the model-based approach to communicate engineering requirements with solid GD&T practices.

Robust Strategy for Using Authoritative Source Standard Part data for MBD/MBE Assemblies

Author #1
Timothy N. Thomas
CADENAS PARTsolutions
255 Deep Valley Drive
Rolling Hills Estates, CA, 90732 USA

Author #2
Jennifer Herron
Action Engineering
12081 W Alameda Pkwy, #455
Lakewood, CO 80228 USA

ABSTRACT

In today's design environment, designers are integrating data that has, over the years, become untraceable to its source information. This continued proliferation of rogue data will bring and Enterprise to its knees. The Department of Defense (DOD) requires traceable source authority data when delivering a TDP, and this also applies to standard parts.

In this presentation, you will learn a strategy to mitigate risks in an Enterprise created by the lack of standard part traceability and certification. By exploring the handoff of information between component creator (component manufacturer) and component consumer or integrator (OEMs), we will describe the minimum information needed through that transfer.

Manufacturers (creators) who are producing physical components and assemblies often have unique challenges as compared to challenges the consumers (OEM's) of those same components face. While creators are most concerned with fidelity, accuracy and how well the part will integrate into the consumer's engineering systems, consumers may be most concerned with cost-reduction, CAD format interoperability and product revision history. The area where these common interests intersect, from a Supply Chain perspective, is where Model Based Definition (MBD) as part of a larger Model Based Enterprise (MBE) comes to fruition. Learn the minimum amount of information in the model needed to leverage standard parts within MBD assemblies.

Extending and Evaluating the Model-based Product Definition

Nathan W. Hartman, Ed.D.
Purdue University
West Lafayette, IN, USA

Jesse Zahner
Purdue University
West Lafayette, IN, USA

Thomas Hedberg
NIST
Gaithersburg, MD, USA

Allison Barnard Feeney
NIST
Gaithersburg, MD, USA

EXECUTIVE SUMMARY

Industrial practice is in a state of transition, away from the use of drawings towards the use of annotated 3D CAD models as a means of communication. Working as a representation of an object or a system, a model-based product definition (MBD) is used to communicate information inside of a model-based enterprise (MBE). Such an enterprise will find itself in a transitional state as well, moving away from paper-based information sharing towards the use of model-based, digital product data. Being able to leverage the communicative power and the depth off information provided by the MBD requires an understanding of the information needs of the various authors and consumers of product information across the enterprise. However, critical information stored in the digital product definition is often lost in translation or not explicitly defined in a way that users in the communications processes can consume it effectively.

Historically, technical drawings contained much more information than just the geometric and dimensional information for an object. They contained information about materials, steps for the assembly process, revision or version history, production process information, and many other bits of information that were implicitly defined based on the context in which the drawing was used. In current industrial practice, much of that same information is not captured in a digital model, even though a model is often considered a replacement for drawings. Just as the practice for creating technical drawings was loosely governed by a company's adherence (or not) to published standards, so is the case with the creation of model-based definitions. Yet, manufacturing companies often express that they have a goal to use the communicative power and accuracy of an MBD across the enterprise, especially the supply chain, but there is a lack of understanding and agreement for what data is to be included in an MBD. Thus, the development and enforcement of standards is difficult, and the ability to document a return on investment for switching to a model-based definition approach is tenuous.

This research investigation sought to identify the minimum information model (MIM) – those information elements necessary within an MBD to effectively employ that model as a replacement for a technical drawing in each workflow. Over the course of this investigation, another phenomenon emerged – the common information model (CIM), which represents those information items that are necessary for the workflows targeted in this study. As expounded upon later in this report, the impacts of contextual domain knowledge on the implementation of the common information model is what formed the minimum information model discovered in this project.

ECN Cost Improvements

Annalise Suzuki
Elysium Inc.

Rich Eckenrode
Elysium Inc.

While developing methods and processes to support MBE/MBD TDP definition, derivative files of CAD product definitions were identified as necessary components of downstream (from Design) activities for visualization. Archivable formats were also identified as required elements of TDPs. The process of Validation/Verification (V&V) of the derivative files compared to the source files was determined to be a needed component of being able to trust these derivative files. The initial use of V&V in TDPs that might be requested was to determine the integrity of derivative files.

An extended use for the V&V results turned out to support a vital activity in the product design lifecycle. This vital activity is the change incorporation process. Change processes are necessary when the product as designed is deemed to be less than optimal and the cost of not changing outweighs the cost of the change itself.

We will attempt to illustrate what the Change Incorporation Process is and how the results V&V routines can help to reduce the “Cost of Change”.

Estimates for Engineering changes sometimes run into the $30,000.00 range and sometimes can consume four to six weeks of time span. The length of time depends on where the Design Authority resides. For some products used by the DoD this means communication with the engineering command who is responsible for the product. The dollar amount will be the touch time for all persons who will have some task to accomplish. This is without accounting for various efficiencies or inefficiencies throughout the process.

During the times when the 2D drawing was (is) the design authority the practice of “Hanging Paper was used to hold off on incorporating changes until a sufficient quantity of low level changes accumulated prior to executing an Engineering Change. The “Hanging Paper” needed to be incorporated into the production plan as the transition to production took place.

This means that the design authority for a product was “The Drawing plus whatever changes were hanging on that drawing”. This causes the need for specific documentation to be created to support the manufacturing process.

Official changes to Technical Data are typically documented using Engineering Change Orders (ECO, ECN or EC) only after the initial release of the design. Most of the effort prior to initial release is contained within the design development process. Changes like design trade studies happen and there is some design baseline activity that happens there. These changes are documented but not for production differences.

The cost savings we see are in the documentation of the ECO of the change. While this cost is small in the overall process, these small steps in improvement help in their own way. This process improvement will allow us to semi automate the ECO documentation by reusing the differences report from V&V activities.

Reasons for change are:

- Safety
  - End user safety
  - Manufacturing production process safety issue
- Design mistakes where
  - Requirements were incorrectly identified or changed,
  - Material specifications were incorrect or unavailable for manufacturing
  - Design error was not identified until "Production Run" testing.
- Transition to Production (TTP) mistakes
  - Manufacturing Bill of Material (MBOM) Definition
    - Errors on Drawings and Models specifically for Manufacturing purposes is included here
  - Material not available
  - Work Instruction (WI) error
  - Tool Design Error

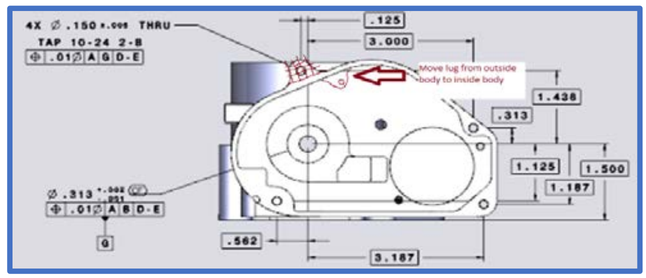
All changes boil down to three basic types; Add, Modify and Delete. You can apply the definition of any change that is required down to this level. Within any Change Proposal there may be many of these activities, but these three comprise the root level of change in all change proposals.

Engineering change processes begin when an Engineering Change Request (CR, ECR) is submitted for consideration. Usually anyone can initiate this CR. The CR will be forwarded to someone in engineering or manufacturing engineering to determine the validity of the request. If there is good cause to propose a change to the Engineering Change Board (ECB), someone will determine the scope of the required changes and document the proposed changes in an Engineering Change Proposal (ECP). This ECP will be presented to the ECB for approval or not.

Change Scoping Process

- Change Request submitted, routed to the person who determines the scope of the engineering change.
- Engineer determines:
  - If a change is justified.
  - Extent (scope) of the change that would be required
  - Where is the item subject to change used at (How many different next higher assemblies)?
  - If existing stock is on hand the engineer assigns disposition of that material (Use as is, Modify, Scrap)
  - If existing stock is useable, determine cut in date/line number of the change
  - If stock needs modification, plan its modifications and cut in date/line number of when change is incorporated
  - If stock needs to be scrapped, plan for new material and cut in date/line number of change
  - If change is manufacturing process issue, changes to process need to be in place ASAP
  - If change is due to end user safety issue, changes need to be incorporated ASAP and Field replacement/update need to be defined and incorporated ASAP

- Plans all actions required to TTP
- Prepares ECP for ECB review
- **Submits the ECP and TTP plan to the ECB**
- If Approved…
- Leads the TTP plan through normal production
- Modifies MBOM and request MRP run to cut in the change into the production planning system
- Works with Configuration Management to insure **TDP** is updated properly **(TDP updated by Design Engineering/Manufacturing Engineering)**
- Develops the approved ECN
- Sends work orders to Tool Design and CNC programming to review their tools and tapes to incorporate the changes required
- Works with QC department to insure changes are incorporated into their QA Plan
- Works with procurement/buyers to flow the change to suppliers
- Works with various shops to insure change cut in is per plan

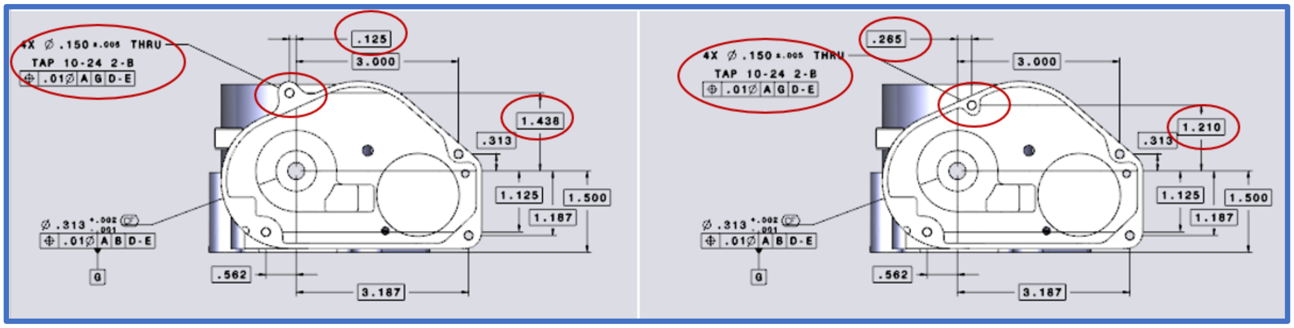


Change Request is submitted to engineering. This request can be anything including paper drawing or even a napkin rendition. The engineer assigned to determine the validity of the request looks at reason and if determined to be viable then a change proposal is created, and the scope of the change is determined. All aspects of the change are determined and documented on the ECP. The ECP is presented to the ECB and they will approve or disapprove the change. If the change is accepted, then the process flow begins to transition the change into the production environment.

The actual ECN used to be represented like the form shown below. The complete ECN includes an assigned ECN number along with the ER and ECP data and what was changed and why.

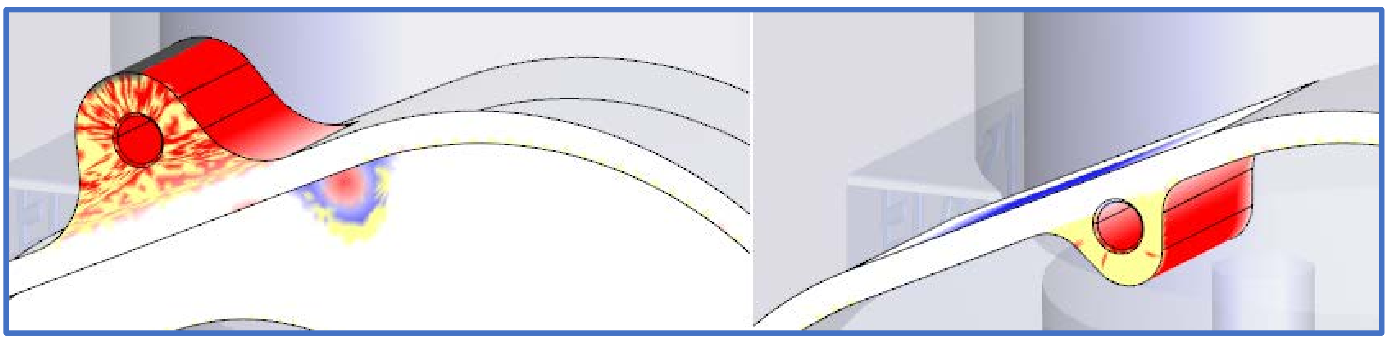
Engineering Change Notice			
Effectivity Date	Effectivity Serial NO.		ECN NO.
ORIGINAL Part Number/Name	REV NO.	PART Description	
NEW Part Number/Name	REV NO.	PART Description	

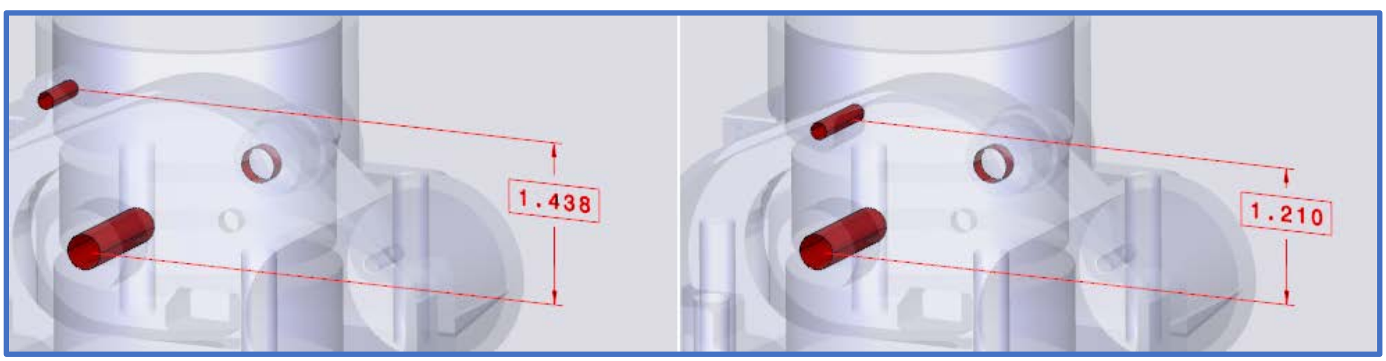
An important aspect of the ECN is showing difference of the before and after definitions of the part or assembly. In the past a “Red-Line” drawing was used to depict before and after images of the part or assembly.



Thanks to the V&V requirements for TDP derivative file definition, we have an automatically generated set of graphical and attribute list of changes that took place within the change process. The image above is being used to represent a “Red-Line” representation of the proposed change. It is an automatic generation of the completed change. The Red annotations were added to depict the desired changes of the ECP.

Below are more of the visuals that are available for the ECN. These graphics clearly represent the changes to the CAD model and the associated PMI. Old part is on left side,





new revision on right.

Name	Diff	V5R26-TBM-MBD-R00	V5R26-TBM-MBD-R01
Part number	Diff	V5R26-TBM-MBD-R00	V5R26-TBM-MBD-R01
Revision	Diff	00	01

Being able to clearly show the changes of an ECN permits all downstream activities to complete their processes faster, cheaper and more accurately. Time will be saved in interpretation of the completed change which should aloe easier modification of processes that were designed for the previous revision without starting from scratch.

Unintended changes will also be discovered while using V&V routines to check that the change was completed as defined. The user who tested this process found that in the case of ECNs unintended changes are quickly evident when strict modeling practices are not followed. The more precise and better controlled practices used by the designer the better results. It is also a good idea to run the ECN documentation (V&V) routine at the designer level to keep unintended changes in check. When we did drawings on the board we had human checkers to flush out this issue. The authors of this document also have examples available to demonstrate how easy it is to have unintended changes propagate the MBD model at the end of the change.

The report from what was the V&V process can be modified to be the ECN document using a special template in the PDF generation process. We think the cost improvement will be small in the grand scheme of things related to the change incorporation process. Sometimes a handful of small improvements will help to make the entire process better.

There is an added improvement that sometimes is hard to quantify. Design managers might like the improvement in clarity that is gained using this method.

Barriers to MBD and MBE: Real, Perceived, and Self-Inflicted

Bryan R. Fischer
TDP360 LLC
Sherwood, OR, USA

Executive summary:

Many companies are interested in MBD and MBE and many companies have tried to implement model-based methods. Some implementations have been successful, some implementations have shown moderate success, and some were not successful and abandoned. In many cases, inertia within organizations has stifled even starting meaningful attempts at implementation. Misconceptions about the ultimate goals and benefits of MBE have also played a role in many of these cases.

There are many barriers to MBD and MBE. This should not be surprising, as barriers are usually encountered when trying to introduce or implement any change in a business environment. This is true whether the change seems to be beneficial or not. In general, people don’t like change, or may be hesitant to accept it. One way to help a new process gain acceptance is to clearly lay out the benefits, the value proposition, and if possible, show a win-win for all involved. In the end, MBD and MBE offer benefits to all involved. However, to get there, change is needed. Some changes are minor, some changes relate to software, some changes relate to hardware, some changes affect infrastructure, and some changes are behavioral and perceptual. Overall, besides having a budget, the main changes needed are vision, commitment, and recognizing and accepting the goals of MBD and MBE.

Most people don’t understand the goals of MBD and MBE, at least not the ultimate goals. Many people see the small steps or incremental improvements possible as their goal. In the author’s opinion, a significant failure mode of MBD and MBE is where interim short-term goals are confused with the final goal. The perceived value of these interim goals falls short of what’s possible and may provide insufficient perceived benefit to justify moving toward or continuing implementation.

This presentation will address barriers to implementing MBD and MBE:

- Real and perceived barriers
- Causes of barriers – real and perceived
- Understanding barrier timeframes
- The crystal ball dilemma
- Looking back at the past
- How to plan for MBD and MBE
- How to be successful with MBD and MBE

On-machine Measurement Use Cases for Digital Thread standards

John Horst
NIST
Gaithersburg, MD

The application of quality operations at all points in the manufacturing process, including on-machine, has a long history. Manufacturers worldwide continue to perform quality measurement activities on parts and equipment at select points throughout the product lifecycle, wherever and whenever it seems best to do so, optimizing throughput, quality, cost, safety, and responsibility. Measurements performed within the physical workspace of a machine tool, which we define as on-machine measurement (OMM), has been shown to reduce machining time, scrap, and other costs for certain important use cases, for example, where there are high cost materials and complex parts.

Since OMM operations are here to stay, it is expected that in the digital age, digital thread standards organizations would require information unique to OMM use cases that is accurate, relevant, comprehensive, and detailed, ensuring that OMM information will find its way into the relevant interoperability standards. In particular, two standards groups, one in machining – the MTConnect Institute – and one in metrology – the Dimensional Metrology Standards Consortium (DMSC) – have formed a joint working group that is currently active to identify and model OMM information. The MTConnect Institute's MTConnect specification and the DMSC's ANSI Quality Information Framework (QIF) standard, both defined in XML Schema, are currently providing cost saving benefits through their implementation in many manufacturing operations worldwide. To satisfy this requirement from the standards organizations, we offer detailed descriptions of many OMM use cases, which expose the information required to execute each use case. For example, information elements, such as machine tool offsets, G-code modifications for OMM, raw stock measurements, cleaning & cooling system commands, swarf measurements, temperature measurements, humidity measurements, and interim part models, are necessary to OMM use cases.

In terms of the type of manufacturing operation, a depth-first approach is taken, limiting the scope to milling and turning machine operations. The MTConnect Institute and the DMSC have created a joint working group to define, test, and disseminate OMM models within their respective digital standards, MTConnect and QIF. OMM processes have already been implemented to varying degrees by a wide variety of manufacturers and solution providers, and all with the lack of a standard information model widely adopted. The same semantic information for OMM is written in multiple proprietary digital languages, causing a confusion of language that is costly to both end users and solution providers, and calling for OMM information defined in a widely-adopted digital thread standard.

Computer Aided Inspection and Quality

Toby Maw
Manufacturing Technology Centre (MTC)
Coventry, Warwickshire, UK.

David Ross-Pinnock
Manufacturing Technology Centre (MTC)
Coventry, Warwickshire, UK.

James Whicker
Manufacturing Technology Centre (MTC)
Coventry, Warwickshire, UK.

Effective quality control requires the combination of design, manufacture and measurement domains. Throughout industry, data across these areas are currently being handled and processed by individual departments that each focus on their own domain expertise. This lack of integration limits the creation of usable knowledge from the process chain and makes it difficult to make global process improvements.

Digital technologies now cover the full process chain and those that can share information between stages can enable workflows that are of significant value to industry. One of the critical enablers to this is Model Based Definition (MBD) making use of CAD and product manufacturing information (PMI), which provides the downstream metrology and manufacturing processes with traceable 3D design information.

One of the aims of the digital engineering team at the MTC is to begin to unlock the potential benefits from combining inspection results with design and manufacturing data. Over the last 5 years, the MTC has run several collaborative projects in this area, working with a large group of industrial end users, software providers, standards agencies and research partners around the world. This presentation will focus on efforts towards the integration of the product lifecycle using data standards, such as the Quality Information Framework (QIF) and MTConnect. It will also discuss implementation challenges, which lead to development opportunities for the software and standards communities to raise the suitability of CAD and PMI to facilitate the industries' future requirements for Digital Measurement Planning.

Rule Model for Feature Inspection and Resource Selection in Dimensional Measurement

Shaw C. Feng
NIST
Gaithersburg, Maryland
USA

ABSTRACT

Process plans are important elements in Model-based Enterprise (MBE) to ensure that the designed part can be manufactured and inspected to conform design specifications. For example, manufacturing process plan guides shop-floor operators how to manufacture parts, and dimensional measurement plan guides metrologists how to inspect dimensions and geometric characteristics of manufactured parts to meet tolerances. During process planning, product Manufacturing Information (PMI) are used for generating dimensional measurement plans. Product design and inspection planning are closely corelated. In a model-based enterprise, design and process plan information should be sharable with suppliers in a supply chain. One major component of an inspection plan is a set of rules. Process planning includes dimensional measurement strategy and measurement resource selection. Rules are used in dimensional measurement planning to make plans consistent across time spans and among different planners. Rules also enable automation and minimize uncertainty, i.e., same conditions result in same action(s). Rule types have been developed in the Quality Information Framework (QIF) standard to enable sharing and exchange rules between customers and suppliers. Rules types in this presentation are templates to ensure interoperability among design, dimensional measurement planning, and inspection execution systems. A proof-of-concept demonstration will show how feature inspection rules and dimensional equipment selection rules are created. These rules conform to standardized rule types for interoperability. Difference systems included in the demonstration are an inspection planning system, a resource modeling system, an uncertainty estimation system, and a computer-aided design system. More detailed information is as follows.

As measurement resources are getting more capable, accurate, and complex, manufacturing industry needs to have deeper knowledge on selecting measurement resources so that measurement resource selection can be automated. In this presentation, the presenter will also discuss the main concept of the selection of dimensional measuring equipment used in dimensional measurements based on the part design and measurement requirements. Dimensional measuring equipment is any type of hardware used in a measurement process, for example, coordinate measuring machines, fixtures, gages, probes, probe extensions, styli, and probe tips. Measurement devices include instruments having all the components needed for measuring parts, e.g., scanner, laser tracker, and theodolite. Gages include block gages, go/no-go gages, depth gages, and bore gages. The selection is based on geometric and dimensional characteristics, tolerances, and datums of the part to be measured. Furthermore, an activity model has been developed to describe activities of determining what characteristics and features to be measured, measurement resources selection, and conformity. Dimensional measurement equipment selection rule types will also be presented. The activity model represents key operations and information flow in dimensional measurement. Rule types provide industrial users with standard formats to capture, exchange, and share equipment selection rules with their collaborators, based on design information and measurement requirements. This presentation will also provide examples of rules that users can use to plan a measurement process using functionally complex and highly capable dimensional measurement equipment. This activity model provides a basis for developing rule types as a part of the Quality Information Framework (QIF) standard.

Automatically Calibrated & Collected 3D Scan Data used for Quality Control (QC) across Supply Chain

Mingu Kang
ARIS Technology
Batavia, IL, USA

Scott Kruse
UI LABS - DMDII
Chicago, IL, USA

Project Description:

- ARIS has performed automated robotic 3D scanning at UI Labs for the die casted, CNC machined, and additive manufactured real-life production parts. The studies were performed in a way that one automated robotic 3D scanning system emulated manufacturing QC to verify and validate the quality of manufactured components before shipping, and supplier QC to verify and validate the quality of sourced components pre-machining or assembly. This exhibits the relationship between a Tier 2 manufacturing supplier with a Tier 1 OEM.
- The manufacturing QC results showed highly precise measurement, which can be replicated when the measurement is repeated, implying the flexibility, stability, and portability in utilizing automated robotic 3D scanning for inspection. The manufacturing QC results also showed 75%+ cost savings in engineer hours to setup the first article inspection (FAI) compared to CMMs. The manufacturing QC was performed by comparing the automatically collected 3D scan data against the annotated CAD design data. To make this entire process fully automated, the original CAD was annotated using the 2D prints shared by the OEM.
- The supplier QC results at the Tier 1 OEM can use the same measurement process to collect 3D scan data on the sourced part from the Tier 2 supplier. By collecting measurement data with the same process, the Tier 1 OEM can reliably compare the QC inspection data provided by the Tier 2 manufacturer side by side with QC inspection results they have created.
- The original CAD and the raw 3D scan data is saved at the edge of the Tier 2 for security, and the QC results in a form of QIF and visual PDF are available to be transferred to the Tier 1 OEM via secure cloud. The supplier QC results showed that the manufacturing QC data can be easily saved on a secure server and be accessed remotely from the component buyer's perspective. From the Tier 1 OEM side, this measurement can be connected to MES (Manufacturing Execution System), so that supplier QC results can inform the supply chain decisions in real-time.
- It is an important note that both incoming inspection (supply QC of die cast parts) and outgoing inspection (post-machined die cast parts) were measured using one system, showing the seamless connectivity of data not just inter-companies, but intra-company.

Impacts to the Digital Transformation with an Integrated Lifecycle:

- Manufacturers can simply and cost-effectively validate and verify model-based artifacts and processes by utilizing automated robotic 3D scanning
- Link design, manufacturing, and quality by performing automatically calibrated non-contact measurements (in various measurement environments), resulting in the storage and analysis of 3D measurement data sets, which can be directly compared across the supply chain
- Create high-value, high-impact workforce in automation, robotics, 3D, and data science, while minimizing the complexity of training and education

Contributing Parties for the Study: Stanley Black & Decker, Siemens, NADCA (North American Die Casting Association), Chicago White Metal Casting, Mitsubishi Electric, Creaform, Solutionix

MBD ROI Case Study: CMM Automation from MBD

Mark Nielsen
TechAzul
Hermosa Beach, CA, USA

Daniel Campbell
Capvidia
Sugar Land, TX, USA

CMM programming is currently a tedious, time consuming, and error prone process which requires the active involvement of a highly skilled quality engineer. The GD&T product requirements need to be manually transcribed into the CMM programming software from the product drawing or model. This takes an enormous amount of time, and involves a high risk of transcription or interpretation errors. A further risk is that the quality of the CMM program created is heavily reliant on the skill, knowledge, and expertise of the CMM operator. The time spent and risks involved in this process add up to enormous unnecessary cost to manufacturing industry.

By leveraging a direct machine-to-machine interface between CAD and CMM software, this process can be automated and optimized. Using semantic PMI in the CAD model, CMM measurement uncertainty simulation, and state-of-the-art CMM programming tools, it is possible to highly automate these tasks. This automation lowers costs by *significantly* reducing time spent creating CMM programs, and eliminating some of the risks identified previously. It also frees up the skilled engineer to add value to their organization in ways other than data transcription. The results would be a CMM program, created with minimal user assistance, which is optimized according to measurement uncertainty requirements and corporate best practices. Overall benefits are: less time spent, less reliance on unpredictable human-in-the-loop, and greater reliance on encoded organizational processes.

The time for this technology is now. This presentation will show how, using commercial, off-the-shelf software tools, highly automated CMM workflows are ready for industry. Pilot projects at large manufacturing enterprises will be explained, including comparisons of traditional workflows to this MBE workflow, and estimated cost savings due to process time reduction.

Model-based Operational Control Methods for Smart Manufacturing Systems

Timothy Sprock
National Institute of Standards and Technology
Gaithersburg, MD, USA

Conrad Bock
National Institute of Standards and Technology
Gaithersburg, MD, USA

ABSTRACT

Performance of smart manufacturing and logistics systems is impacted by the quality (optimality) of decisions made by the operational control system. Operational control methods, such as scheduling, are responsible for optimizing the flow of items through a system, such as jobs, products, and materials, and utilization of system resources. Performance can be measured by metrics such as throughput, cycle time, on-time delivery (or tardiness), and cost.

Designing and optimizing operational control for smart manufacturing and logistics systems is challenging due their scale, including many control decisions based on a large quantity of system feedback, and additional precision and detail needed to support automation. Implementing smart operational control systems is often hampered by heterogenous information sources, execution mechanisms (shop floor actuators), and decision-support tools. Operational control design and execution methodologies are limited by lack of accessible and integrated simulation-based decision-support tools.

The U.S. National Institute of Standards and Technology (NIST) is addressing the need for model-based operational control methods in its Systems Analysis Integration (SAI) for Smart Manufacturing Operations project. The project is delivering models and methods for unifying discipline-specific engineering analysis information, and integrating it with existing unified systems modeling techniques, enabling manufacturers and solution providers to design and operate smart manufacturing systems faster and cheaper. Model-based operational control methods use a common representation of the system under control (system model) to integrate multiple sources of information already defined and/or represented in other ways, often from heterogenous systems in incompatible formats, to create an integrated model of the system. System-analysis methods integrate system models with many kinds of analysis models, such discrete event simulation.

The project identified three components of successful development and deployment of model-based operational control: a standard model of operational control, analysis models and tools properly implementing that standard, and system-analysis integration methods providing automated, inexpensive access to those analysis tools.

Standard models of operational control support design of cyber-physical system components that execute complex control tasks, as well as integration of logic/algorithms to support control decision-making. These standard operational control models identify: the kinds of control decisions required, which control actions are allowed/permitted, and information and algorithms required (or available) to make decisions. Standard system models can be used to define standard integrations of predefined analysis methods and algorithms (SAI libraries). These libraries include methods addressing common issues such as information availability, resolution, and fidelity, as well as balancing trade-offs between algorithm run-time and solution quality.

Standard system models and supporting analysis methods will enable simulation-based methods to be routinely applied during the (re-)design process to test and validate control logic (algorithms) in a high-fidelity simulation before deploying to the system. Simulation also can be integrated with optimization and heuristic methods to provide online decision support.

While most simulation-based methods require significant time and expertise to manually construct analysis models, especially the simulation models themselves, the vision of this project is to use automated model-based methods to enable routine and inexpensive simulation-based analysis to support operational control design and decision-making processes.

QIF and the Future of Digital Metrology

Jennifer Herron
Action Engineering
Denver, CO, USA

Curtis Brown
Honeywell FM&T *
Kansas City, MO, USA

Daniel Campbell
Capvidia
Sugar Land, TX, USA

Modern metrology systems consist of a patchwork of various individual software packages, each of which produce and/or consume massive amounts of data. The efficacy of these software systems is severely encumbered by the lack of interoperability between its components. Transferring data between software packages is costly both in terms of time required of the human expert to manually process the data, and number of errors involved in manual transcription of quality data.

This presentation will describe the ANSI Quality Information Framework (QIF) and will explain how it can provide the information format necessary to master the challenges of interoperability and data traceability. QIF is an XML-based ontology for quality and manufacturing data, all built on semantic links to 3D model data. This solution arose organically via a body of industry experts ranging from manufacturers (end users), software vendors, research organizations, and National Measurement Institutes, all coordinated by the Dimensional Metrology Standards Consortium (DMSC).

See example QIF workflows that show how a large quantity of product, manufacturing, and measurement information interoperate to beget: automation, optimization, traceability, and data analytics.

* *The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839*

Proposal of a Data Processing Guideline for Realizing Automatic Measurement Process with General Geometrical Tolerances and Contactless Laser Scanning

Atsuto Soma
ELYSIUM Co., Ltd
Japan

Hiromasa Suzuki
The University of Tokyo
Japan

Toshiaki Takahashil
3D+1 Lab
Japan

Executive Summary

Measurement and testing is one of the largest arena where 3D CAD data is not utilized well, and can be regarded as a bottle neck in realizing MBE throughout manufacturing processes. We propose a guideline to realize automated process of manufacturing and testing utilizing annotated 3D CAD data (MBD).

In product design phase, geometric tolerance is the best method to define tolerances of 3D shape unambiguously. It is important to define geometric tolerance for all features in 3D CAD data effectively, and we propose a new way of general geometric tolerance for that purpose. Our approach is based on surface profile tolerance with referring a datum system. Tolerance value for each feature is determined by distance from a datum system. With this approach, we can minimize number of annotations with representing tolerances that can be achieved by usual manufacturing process. Current general geometric tolerance in ISO, ISO 2768-2, is well known to have technical problems and now considered to be withdrawn.

Contactless measurement methods like laser scanning or X-ray CT are desirable to evaluate 3D shape, especially for features specified by general tolerance. This is not only because contactless measurement can evaluate overall surface of a part, but also because it doesn't require many arrangements of measurement that are necessary for other methods. On the other hand, measurement and data processing procedures of contactless measurement are

not standardized, so point cloud data itself and result of evaluation based on it are considered to be unreliable for testing purpose.

We propose a standard method of processing point cloud data acquired by contactless measurement method. Outline of the procedure is:

1. Measure workpiece by digitizer
2. Remover outliers
3. Filtering
4. Register point cloud and CAD data with best fit
5. Extract point cloud for datum calculation with removing unreliable data around sharp edges, small fillets and so on.
6. Calculate datum features composing datum system with applying a filter
7. Register point cloud and CAD data with using datum features
8. Evaluate general geometric tolerances of surface profile
9. Evaluate individually specified geometric tolerances

We prepared test pieces and measured them by three different commercial laser scanners, one X-Ray CT and CMM. The measurement results are compared, and concluded that difference among measurement methods above can be within 20 μm by following the proposed procedure.

Next steps are:

(1) Test proposed method with practical parts

(2) Create guidelines or collect best practices of measurement processes

(3) Contribute to international standardization activities of this arena with our achievements

This activity is based on Japanese electronics industry group called JEITA (Japanese Electronics and Information Technology Industries Association) and funded by Japanese Ministry of Economy, Trade and Industry.

Transitioning to Model-Based Quality ignited by Persistent Model-Based Product Characteristics

Curtis Brown
Honeywell FM&T*
Kansas City, MO, USA

Mark Nielsen
TechAzul
Manhattan Beach, CA, USA

ABSTRACT

Product acceptance from a Model Based Definition (MBD) has been one of the primary inhibitors for moving towards Model-Based Enterprise (MBE) implementation. Assurance that product acceptance can be performed from an authorized part defining model is a critical driver toward achieving maximum MBE return on investment. Furthermore, determining an end-to-end model-based quality solution will enable the manufacturing quality function to become a primary advocate for MBE.

Streamlining your MBE process from Design to Inspection by intelligently mapping persistent product characteristic that can be evaluated in first article and production inspections is a critical enabler. Using MBD, with a semantically correct product & manufacturing information (PMI), we will show the ability to easily organize dimensional and geometrical tolerances into a Bill of Characteristics (BoC), listing each tagged product characteristic as a line item for inspection. Further refinement is made by defining and displaying the critically level (e.g., safety, manufacturing, function) and the criticality area of definition using special symbology in the model.

Once the requisite product characteristics are properly presented in the 3D model with appropriate references and confirmed to be represented as semantic, machine readable data elements, then a complete inspection report can be produced automatically. A common excel spreadsheet can be produced with images of the model showing the tagged annotations for each line item in the BoC to create the framework of a First Article Inspection (FAI) report.

Using the Quality Information Framework (QIF) standard, intelligent mapping with QIF Rules can be implemented to define specific techniques and sampling plans. The specific verification method such as visual, manual, point scan, CMM probe or CT can be automatically associated to each line item in the FAI or Initial Sample Inspection Report (ISIR) that is generated. These methods can be colored and organized to simplify and streamline the quality process in-house or sent to an external supplier in an easy-to-use format for fabrication and inspection.

Finally, the definition of inspection or product characteristics are all over the map based upon industry, company, or function and there is no known standard that defines product characteristics for a MBE approach. This presentation will continue the progress toward defining a common MBE lexicon for product characteristics and review recommendations for both a digital persistent identification and a human readable symbology.

* *The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839.*

Machine Readable Semantic PMI for Pattern Definition

Ryan Gelotte
Action Engineering

Products across all industries include parts with patterns of features where the quantity of pattern members can be extremely large. Following accepted MBD semantic annotation standards, a dimension or tolerance quality characteristic that applies to a pattern must be semantically associated with the model topology of all pattern members. While all of the CAD applications offer selection capabilities to efficiently gather the surfaces in order to meet the MBD standards, many quality and inspection applications that can read and use the semantic PMI are not able to recognize that there is one characteristic, patterned many times. In fact, semantically linking the entire pattern topology is often times undesirable due to additional tasks to deconstruct the pattern definition and redefine using the native application pattern definition tools. One work around to this issue is to not annotate the model as a pattern but rather have each member annotated independently of the rest of the pattern. Then each pattern member is assigned it's own characteristic to be validated. This is also not desirable especially when working with large patterns. A standard definition for machine readable semantic PMI that recognizes pattern members is necessary to fully leverage CAD models for downstream consumption across all industries.

Index of Authors