FINAL PROJECT REPORT

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Introduction

Digital manufacturing requires models, but today's manufacturing machines are controlled by codes that describe linear and circular motions. The details of these codes are unique to each machine and cannot be shared. They are hard to optimize because they do not describe the design requirements being met, or any but the most basic form of the solution. The "Mind the Gap" project has filled this gap with standards to describe tolerances and tooling. This new information allows new cloud services to be developed. Mind the Gap has shown that these services can operate in real time and make manufacturing 15% more efficient. Table 1 summarizes.

"Mind the Gap – Filling the Gap between CAD and CNC with Engineering Services"

Goal:	
Barrier	Machining codes do not carry sufficient information for real time optimization.
Method	Enable new cloud services for optimizing machining in real time with information about the tolerances and tooling.
AVM Participation	AVM iFAB to demonstrate a NC Code Generation service. AVM VehicleForge to demonstrate a 3D Process Monitoring service. AVM SBIR to demonstrate a Tooling Optimization service.
Commercialization	The services are hosted by a new product called the DigitalTwinServer®.
Business Advantage	The cloud services reduce costs by 15% or more in a market worth $75bn per annum by making machining more efficient.
Standardization	MTConnect for connecting the cloud services to the manufacturing machines. STEP for defining the manufacturing tolerances and tooling, QIF for reporting manufacturing quality.

Three services developed in the DARPA AVM program were demonstrated at the Boeing Wide Body plant on October 5, 2016. Together with a service to measure results that is being implemented by the DMDII 14-06-05 program, they were shown to enable model based manufacturing. The following video explains their operation.

https://www.youtube.com/watch?v=Mjzg5nku5Lg

The new services operate on manufacturing data in real time. They are enabled by loading CAD data into a twinning server and connecting it to manufacturing machines. The machines can be located anywhere in the world, and the services show their results to smart phones and browsers located anywhere in the world.

Mind the Gap connects design, to planning, to manufacturing to inspection using a digital thread. Each discipline adds its data to the thread. The thread is defined by apps on open, public standards. Mind the Gap refreshed the thread from changes on the machine tool at 100 time per second. With the technology developed by Mind the Gap, the tier 1 and tire 2 members of the DMDII can host threads for their supplier chains. With a thread, every supplier can immediately see the impact of changes. With a thread, software vendors can develop automations to make manufacturing at least 15% more efficient. These include apps to better manage tool life, enable adaptive programming, automate on-machine measurement and implement advanced operator functionality. With a thread, machining can be controlled by intelligent apps instead of machine codes. Mind the Gap proved its thread by developing and testing the three services shown in Figure 1.

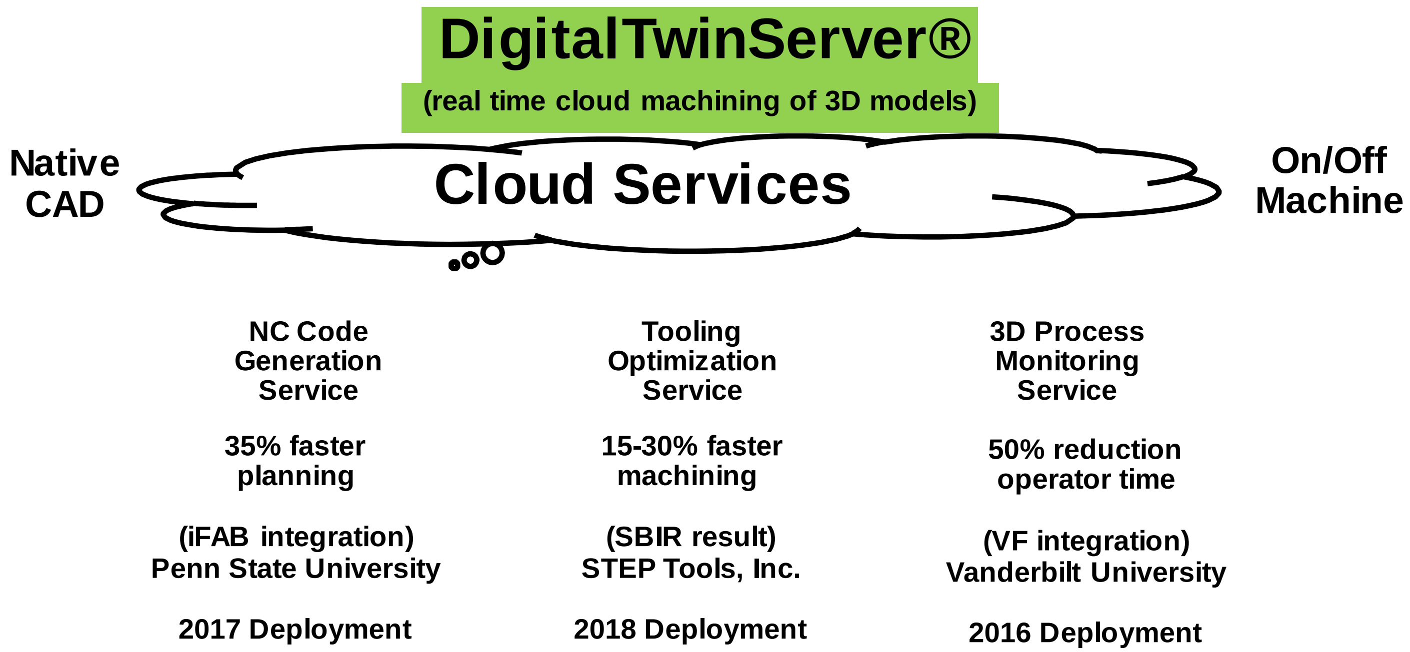

Figure 1 the three services and their industry benefits

The first service is the 3D Process monitoring service. This service is ready for deployment. The service connects the server to a machine tool using MTConnect, and shows the current state of the machining in a browser or on a smart phone.

The second service is the NC Code Generation Service. This service makes more aggressive use of advanced technology and is the reason why the program was submitted under the DMDII AVM 02 project call. The NC Generation Service is being made available to the DMDII members as open source.

The third service is the tooling optimization service. This service is being developed as an App. It uses the current engagement between the cutter and the workpiece to compute an optimum feed for the machining. The computation is continuously updated by the simulator at 100Hz.

Summary of Findings and Recommendations

The key finding of "Mind the Gap" is that it is now possible to construct and maintain a 3D machining model in real time. Therefore, a new digital manufacturing framework can be constructed in which intelligent apps measure, monitor and optimize machining from real time models using smart phones and browsers. This was not possible before Mind the Gap because the necessary computing power was not available.

The three Mind the Gap services are the first examples of apps. US industry should deploy them and similar apps in an open digital thread for their supply chains. STEP Tools has developed a new product to host the digital thread. This product is called the DigitalTwinServer®. It has been evolved from the STEP-NC Machine product that existed at the start of the program. It uses standards to describe its inputs and outputs, and enables integrated machining and measurement by maintaining a real-time simulation of the machining results.

The standards are MTConnect for connecting manufacturing machines to cloud services. STEP for defining models of the tolerances and tooling, and QIF for reporting manufacturing quality results. Mind the Gap has shown that these three standards enable a digital thread that can deliver model based data across the supply chain. Mind the Gap has developed a server to host the thread. Mind the Gap has shown that real time modeling makes manufacturing at least 15% more efficient.

Project Review

Manufacturing data usually lacks context. This makes it difficult to share across the digital enterprise. Today nearly all designs are completed as 3D models. In the ideal, the required tolerances are then added to the models and sent to manufacturing. In practice, they are attached to a drawing. The drawing is then given to manufacturing for interpretation.

A manufacturing engineer uses information on the drawing, and prior knowledge, to determine how to create a part. Data is usually entered into a CAM system and toolpaths are generated as Gcodes. When the chosen machine is set up correctly, the part is machined from a stock that must have exactly the right dimensions. For high volume assembly, the whole process may be repeated for hundreds of technologies and thousands of parts, with millions of copies being made or purchased.

To save costs many parts are made by specialist sub-contractors. Mistakes are easy when the input is a drawing. Therefore, most parts are inspected before and after delivery. The received parts are then assembled. Even with tight tolerances, some assemblies fail and require rework. Lack of communication is a major issue. At the best enterprises, design and planning share an expensive, integrated CAD/CAM system. Other enterprises and many sub-contractors rely solely on drawings. All enterprises lose the digital model when they begin machining because the machining systems only know about codes. Some aspects of the model return after inspection but the digital thread has been lost. Table I summarizes the as-is situation.

Table I. Gaps in the Digital Thread for Machining

Exchange	Missing functionality
Design to planning	3D Model of the tolerances
Planning to manufacturing	3D Model of the process plans
Manufacturing to inspection	3D Model of the machining results
Inspection to assembly	3D Model of the part quality

Mind the Gap has developed a system for manufacturing using models defined as digital twins. The new thread starts as design models. The solution requirements are then added as tolerances. The models are then integrated into processes plans. The process plans are then sent to manufacturing for direct execution. Manufacturing makes parts while producing digital twins. The digital twins are inspected and used for assembly simulation. Any necessary changes are identified across the disciplines because everyone is sharing a model. Optimizations are made in real time because they can be tested in real time.

Project Scope and Objectives

The goal of Mind the Gap is for all aspects of manufacturing to be included in a standards based digital thread. STEP was chosen because it is extensible, and because it has definitions for the necessary tolerances and tooling. STEP gives data context so that it can be understood by each discipline. Therefore, the consequences of design decisions are shown in the manufacturing process. The difficulties of meeting tolerances are shown in the planning process. The impact of tool wear is shown in the machining processes, and so on.

Figure 2 and Table II show how Mind the Gap completes the digital thread. Design requirements are communicated using the STEP AP242 protocol. Manufacturing solutions are communicated using the STEP AP238 protocol. A digital twin is built from an MTConnect stream delivered from the machining system. The twin is measured for conformance to its design requirements by a metrology service. Quality results are sent to customers as QIF files. The thread is explained in a video: https://www.youtube.com/watch?v=Mjzg5nku5Lg

Three services were demonstrated on October 5. The Smart Machining Service was started under the DARPA AVM program and further refined in Mind the Gap. This service integrates the design requirements into the planning solution. The Twin Service builds a digital twin using the MTConnect data stream emitted by a machine tool. This service was started under a DARPA SBIR and enables the real-time modeling of the machining. The Smart Metrology Service measures the digital twin for conformance to the design requirements. This service is being implemented under DMDIII 14-06-05. The tooling optimization is being developed as an app that will be available in 2018.

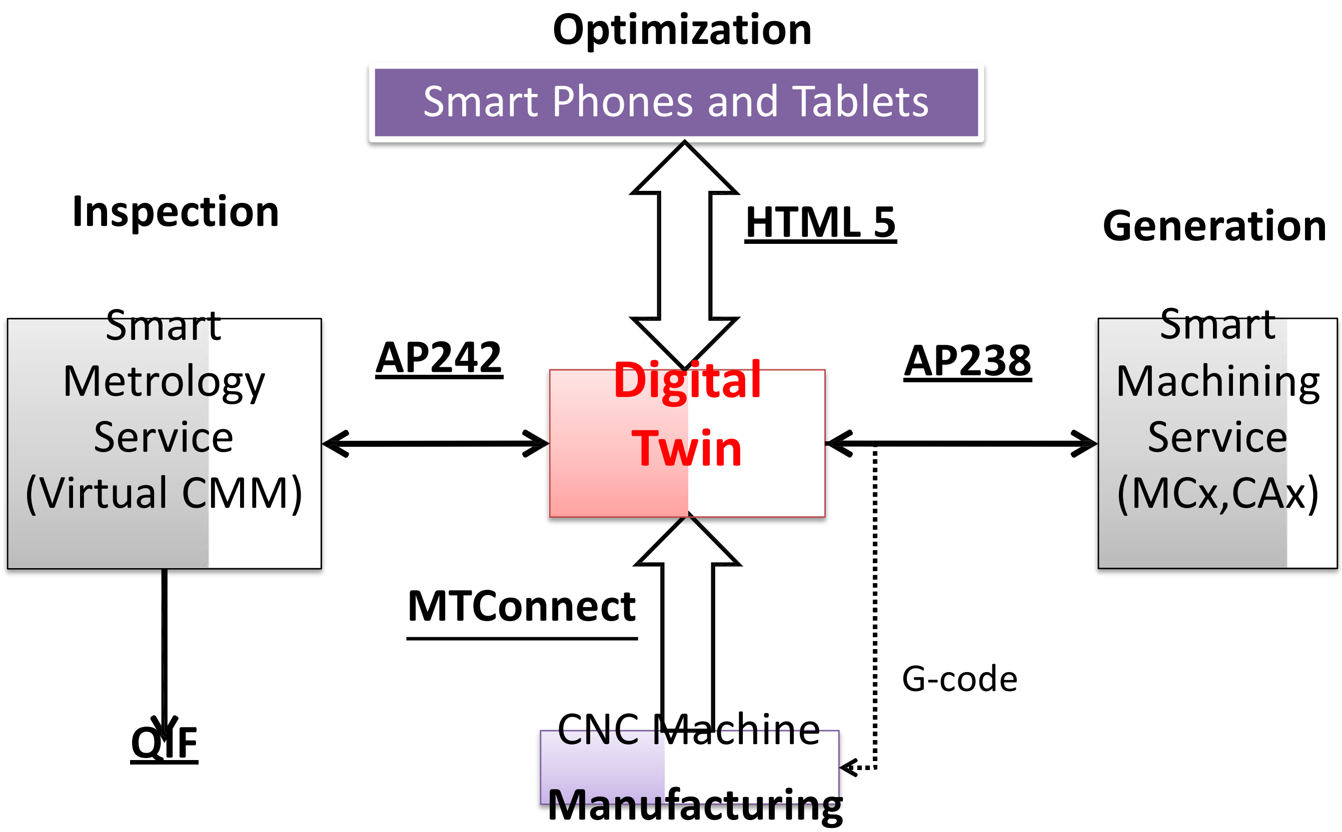

Figure 2 Digital Twinning System

Table II. Filling the Gaps in the Digital Thread for Machining

Exchange	Gap	Standard
Design to planning	Semantic tolerances on the model	AP242
Planning to manufacturing	Machine independent process plan	AP238
Manufacturing to inspection	Model of the machining results	MTConnect
Inspection to assembly	Model of the part quality	QIF

The state of the art is to send a drawing from design to manufacturing describing the requirements for a machined part. The requirements are stated as tolerances which are shown on the drawing as leader lines and symbols. Both the designer and the planner may have trouble understanding the intent and consequences of the lines and symbols leading to increased costs.

The ISO STEP AP242 standard allows semantic tolerances to be put directly on the design as semantic constraints that can be interpreted and validated by intelligent systems. However, planning is not the only function impacted by tolerances. Manufacturing must organize and maintain its systems to meet those tolerances. Inspection must verify their compliance, and assembly must deal with the consequences when the tolerances are not met. Therefore, the tolerances must be available throughout the digital thread.

The STEP AP238 protocol allows a manufacturing plan to be described as a series of AP242 stage models. Each stage describes the tolerances that must be met by that model. Each stage describes how its start state is transformed into an end state. A high-level description can be parameters such as the width and depth for a drilling operation. A low-level description is a series of tool movements and cutter requirements that achieve the operation. The high-level description is often solution specific and enables direct optimization by systems that understand the parameters. The low-level description can be executed by any machine that has the necessary capabilities (bed size, cutter sizes etc.) and enables machine tool interoperability.

The digital twin is a model made during the manufacturing. The input data is supplied by MTConnect or another protocol such as AutomationML or OPC/UA. Each of these protocols reports on what was actually done by the machine as raw movements, feeds and speeds. Additional sensors may send additional information such as spindle load. The Digital Twin Service combines this data with the manufacturing plan to create the most accurate possible digital twin model. The digital twin includes the tolerances so it can be inspected. The quality of the final twin is reported as a QIF file. Key advantages include:

- The digital twin enables cloud services that reduce costs
  - Services to generate and optimize solutions
  - Services to select machines and cutters
- The digital twin enables scientific shop floor control
  - Machine faster if the schedule is tight, or with less tool wear if the schedule is open
  - Validate results against previous results using the same material and tolerance
- The digital twin enables real-time adjustments and measurements
  - Adjust processes, validate changes, close the loop
  - Send digital results to assembly for verification before machining ends
- The digital twin enables product enhancements using seamless communication
  - Designers, planners and machinists share results and see each other's solutions
  - Maintenance and third parties see requirements and help optimize solutions

Figure 3 shows an image of a digital twin being machined in real time in a web browser. A demonstration that operates on planning data or execution data depending on current interest is at: http://www.steptools.com/demos/mtc/

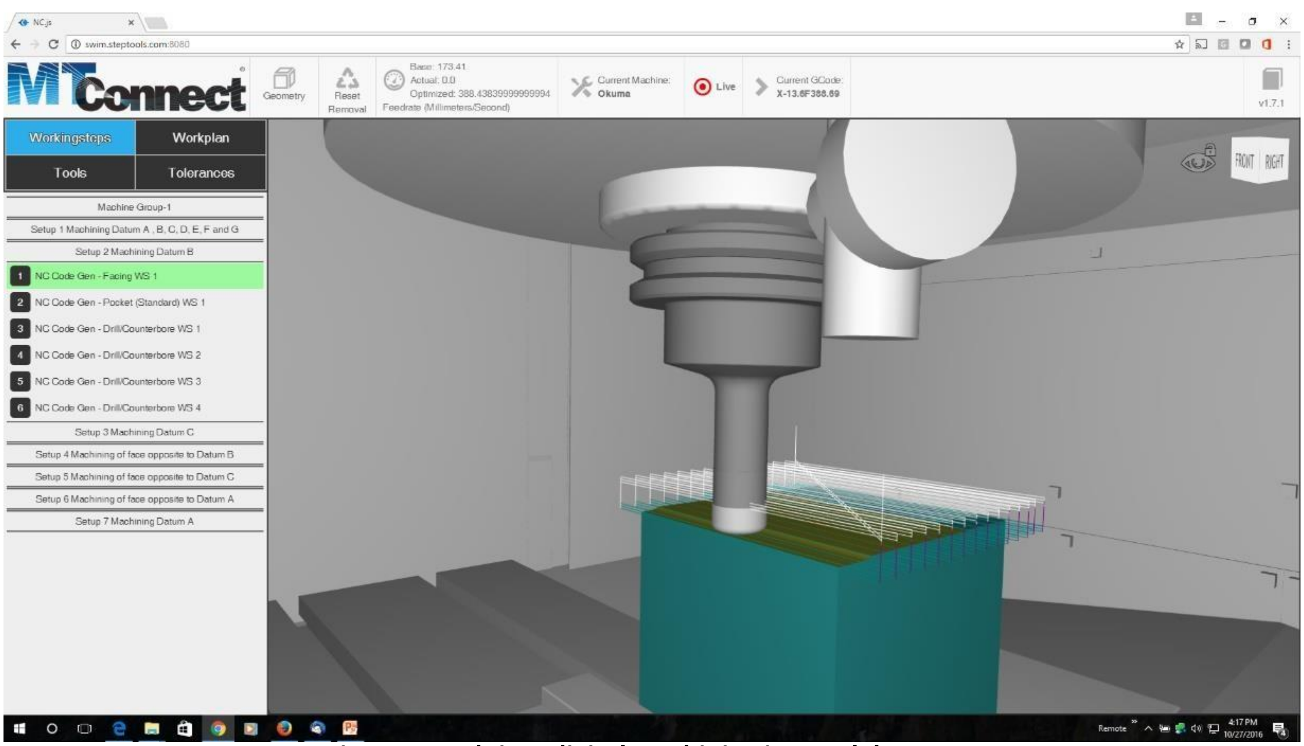

Figure 3 Real time digital machining in a web browser

Technical Approach and Planned Benefits

A digital twin demonstration was given at the Boeing Wide Body plant on October 5, 2016. The purpose was to prove measurable machining models can be made in real time. Machining taking place in the Boeing Renton plant, 30 miles away, was used to construct a digital twin model from MTConnect data. The digital twin model was measured in real time in the room where the demonstration was taking place, and in the basement where a CMM had been installed for that purpose. The model included design requirements and process plan data. At each stage of the process, the machining results could be checked against the design requirements using the metrology service.

As shown in Figure 4, the machining was tracked and the model updated at a rate of 100 times a second (100 Hz). This compares to the 60 times a second that a typical computer screen used to be refreshed. Not all the operations were tracked at this rate. For example, during the spiral in for the pocketing, the model update rate dropped to 70 Hz because of all the complex calculations. The digital twin caught up when more conventional machining resumed and there was no impact on final accuracy.

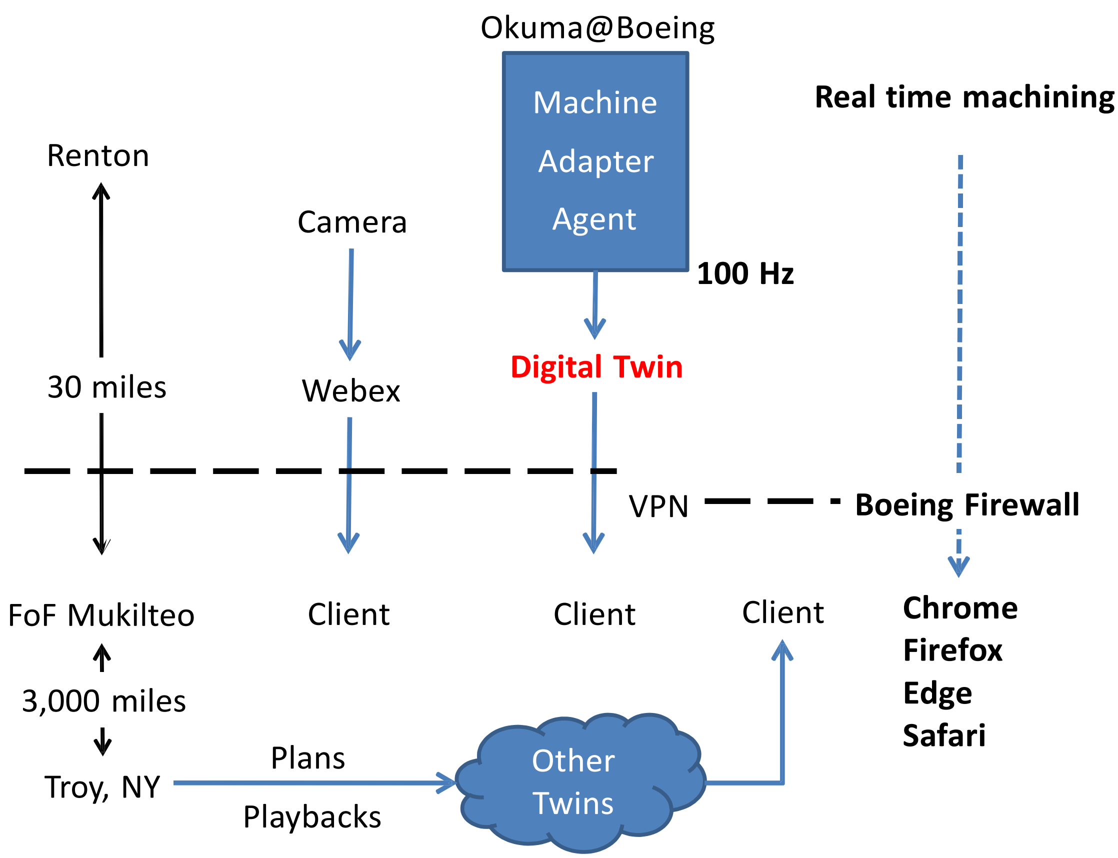

Figure 4 Configuration of the digital thread demonstration of October 5, 2016

The digital twin showed the following benefits:

Table III. Benefits of a Digital Thread for Machining

Benefit	Reason
15% more efficient machining	Better tool wear management
50% reduction in inspection costs	Virtual screening of in-process models
35% reduction in planning costs	Intelligent reuse of similar models
10% increase in enterprise efficiency	Completion of the digital thread

To manage a 100 Hz refresh from a distance of 30 miles, the server was placed on the same subnet as the machine tool. The server had an i7 processor with four cores because it had to perform many intersection calculations very rapidly.

Putting the server on the same subnet also eliminated possible security concerns. The client at Mukilteo accessed this server over the internet using the Boeing VPN. The server constructed a digital twin model that was displayed on local and remote screens. The display was managed using the same HTML 5 technology as other web systems. Results were shown in Chrome, Edge, Firefox and Safari. Additional results from Troy, NY were shown by replaying previous machining tests. The real-time was validated using a camera on the machine tool which showed the same movements, at the same time, as the digital twin.

Metric Analysis and ROI

Three KPI's tables are shown for the Digital Twin service, the Smart Machining Service and the Digital Thread.

The first KPI in Table IV is the range of model refresh rates. A faster rate makes the model more accurate. A slower rate makes it possible to twin with machining systems that only deliver at 10Hz such as a Haas mini-mill. Faster processing is relatively easy because processors with sixteen or more cores will soon be widely available. Responding properly to low MTConnect refresh rates is more challenging. If the cutter is moving rapidly and there is a corner, then the direct path between two sampled points may result in a spurious collision. The planning data shows how to avoid / override these collisions.

The second KPI is to improve the accuracy and enable real time machining correction. The adoption of curved triangles allows the facet density to be more dynamic. Algorithms can be written to detect and eliminate the differences between the as-machined and as-planned geometry. These algorithms can continue the machining until the as-machined model has all the features of the as defined B-rep geometry.

The third KPI is closely related to the second. Making better models enables better optimizations. A 3D model of the additive or subtractive volume defines the work being performed very precisely. Computations of the third KPI can factor in tool bending. Sensors such as lasers can track the tool tip. Databases can predict tool locations for different materials, tools and tolerances. By optimizing the as-machined results that occur at the time of the machining, instead of the as-planned results predicted by a CAM system days, weeks, months or years earlier, digital twinning can make machining easier to program, faster to execute, and more accurate.

Table IV. Digital Twin KPI

Digital Twin Service KPI	Present State	Desired State
Model Refresh Rate	[10Hz, 100Hz]	[10Hz, 200Hz]
Model Accuracy	Flat facets	Curved facets
Model Optimization	2D cross section	3D removal volume

The second set of KPI in Table V relate to the Smart Machining Service. First, we must improve the coverage of the operations so that we can use the system for turning. Second, we must extend the range of materials that can be processed to include aluminum and steel. Third, we must fully integrate the Smart Machining Service with the Digital Twin Service. This requires the replacement of desktop technology with HTML5 user interfaces. The software requires the customer to have licenses for ACIS and Mastercam, but only the latter is strictly necessary.

Table V. Smart Machining KPI

Smart Machining Service KPI	Present State	Desired State
Operations	3, 4, 5-axis Milling	Mill, Turn and Mill-Turn
Materials	Titanium	Titanium, Steel & Aluminum
User Interface	Desktop	Desktop and Cloud

The third KPI set relates to the components of the digital thread. The thread deployed by Mind the Gap uses MTConnect to connect machine tools to a server, STEP to define product models for the server, and QIF to report the results of the server. MTConnect allows the computations to be performed on any platform. STEP is extensible and already has the definitions necessary to support tolerances and tooling. QIF is also extensible and already has schemas for many types of manufacturing quality reports.

An alternate architecture is to deploy OPC/UA on the machine tool and use that API to connect the machining to an integrated CAD/CAM system. If the CAD system is defined by a standard such as JT Open, then applications may be shared between systems. In this alternate, results are reported to the enterprise in an ad-hoc format using a protocol such as I++.

Table VI. Digital Thread KPI

Digital Thread KPI/Metric	Mind the Gap	Alternate
Machine to Server	MTConnect	OPC/UA
Product Model	STEP	JT Open
Quality reports	QIF	I++

The alternate architecture places the app on the same platform as the machine tool. Therefore, machine tools of the future will have to have very powerful processors which is usually not the case today. The alternate architecture raises security concerns because a vendor's machine tool will know all about the part being machined. The alternate architecture uses JT Open to define the machining model. JT Open has strong support from a powerful vendor. It is widely used in the automotive industry and is being promoted as an open standard with multiple options, including ones that do not require the vendor's software. STEP is an open standard that has been supported by a community of vendors for many years. STEP has already published specifications for semantic tolerances (AP242) and tooling (AP238).

The alternate architecture uses I++ to communicate the results of the machining. QIF is an open standard with a rich and growing set of definitions. There are many kinds of results that need to be reported. Because it is working in an open forum, QIF adds schemas as they become necessary. I++ is a more closed forum with difficult membership requirements. The relative merits of QIF and I++ are being further evaluated by the DMDII 14-06-05 "O3" program.

In summary, the Mind the Gap architecture allows the digital twin to be hosted anywhere. The Mind the Gap architecture allows applications to be written as web apps which can be tuned to the specific requirements of a part or machine from smart phones and browsers. The Mind the Gap architecture uses a standard library to report outcomes which can be programmed for response across the enterprise.

Technology Outcomes

System Overview

Mind the Gap has produced a Digital Twin Service and a Smart Machining Service. The Digital Twin Service simulates the current state of a machining process as a real-time 3D model. The Smart Machining Service makes machining plans so that they can be simulated in the digital twin service. The machining plans are described by the STEP AP238 standard and can be produced by the Smart Machining Service, or by a conventional CAM system.

Figure 5 shows the architecture of the digital twin service. The service reads MTConnect streams and STEP models. The service uses the MTConnect streams to keep the twin current with the current machining state. The service supports apps that are written as JavaScript clients. The first app enables remote viewing of the machining in browsers and on smart phones. The second app is being developed under DMDII 14-06-05 and enables measurement of the digital twin by CMM software. The third and fourth apps for adaptive programming, and tool wear optimization, will be released in 2018.

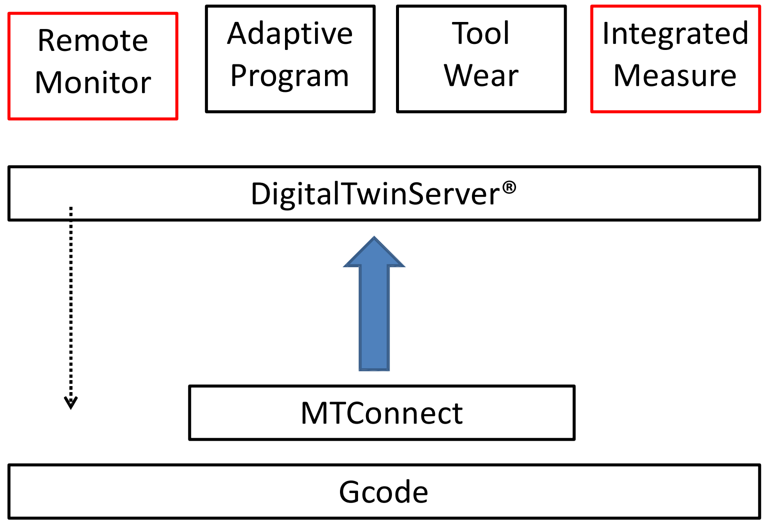

Figure 5 system overview of the Digital Twin Service

Figure 6 shows a system overview of the Smart Machining Service also known as the NC Generation service. This service creates and optimizes machining solutions from STEP models. There are two modes of operation. In the first mode, it generates a new solution from AS-IS and TO-BE product models. In the second mode, it optimizes an existing solution for a new material or tooling.

In the available time, we were able to use the service to generate new solutions for titanium from existing solutions for aluminum. The service works as a desktop tool and requires ACIS and Mastercam to be installed on the same box. ACIS is not necessary but there was insufficient time to replace this component. The service should understand and generate solutions that are appropriate for the GD&T constraints of the input, but this also was not possible in the time available.

Because the Smart Machining Service is not yet ready for commercial deployment, STEP Tools plans to continue using the direct translators. The direct translators allow the necessary planning data to be loaded directly into the DigitalTwinServer where it can be used for the four applications. The Smart Machining Service is being delivered to the DMDII as open source.

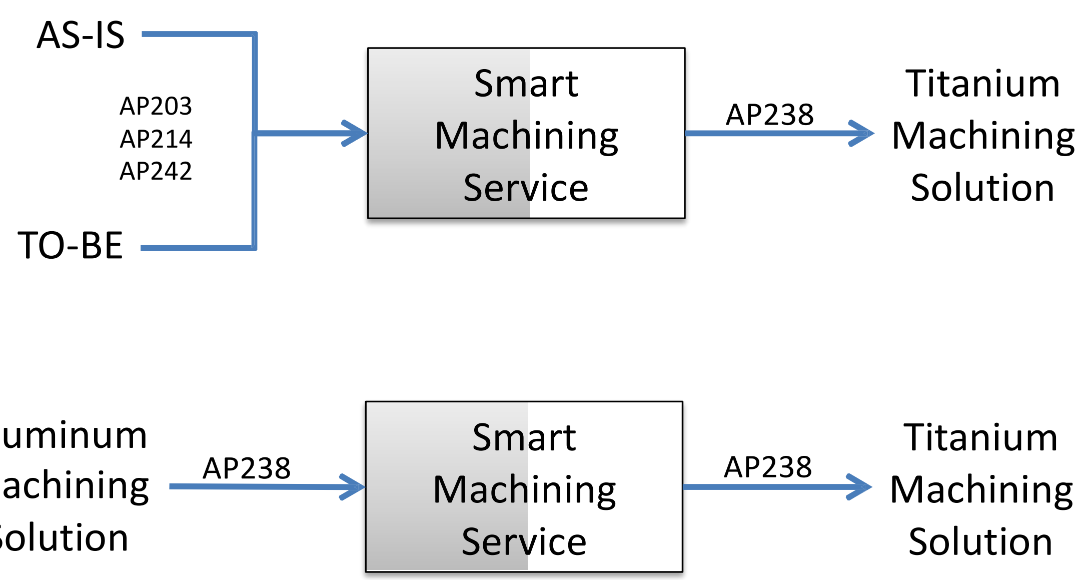

Figure 6 system overview of the Smart Machining Service

System Requirements

The digital twin service is divided between a client and a server. The client is an open source application that can run in any JavaScript browser that supports WebGL. This includes Chrome, Edge, Firefox and Safari but **not** Internet Explorer.

The server is a Node.js application. The Node.js application makes the functionality of the STEP-NC DLL available in JavaScript. The server delivers JSON objects describing this functionality to thin clients. The DigitalTwinServer requires the STEP-NC DLL which is BIP supplied by STEP Tools, Inc. The STEP-NC DLL libraries are available for Windows, Linux and Mac platforms.

The DigitalTwinServer computes a new simulation model for each MTConnect update. For the Boeing demonstration, in which the model was updated at 100Hz, this required the server to run on an i7 processor with 4 cores. In subsequent demonstrations, the server has been run on an i5 processor with 2 cores when the MTConnect refresh was 10Hz. A 10Hz refresh rate is usually sufficient for three axis parts.

The Smart Machining Service is being delivered as source code. The Smart Machining service requires licenses for Mastercam, ACIS and the STEP-NC DLL. The Smart Machining Service has been tested for Windows platforms only.

System Architecture

Figure 7 shows the architecture of the system. The Digital Twin Service is connected to the CNC machine by the MTConnect XML. The digital twin service is connected to the Smart Machining Service by the STEP AP238 protocol. The Digital Twin Service is connected to the web clients by JSON objects. The Digital Twin Service is connected to the Smart Metrology Service being developed by the DMDII 14-06-05 project by the STEP AP242 protocol. The results of the Smart Metrology service are reported as QIF.

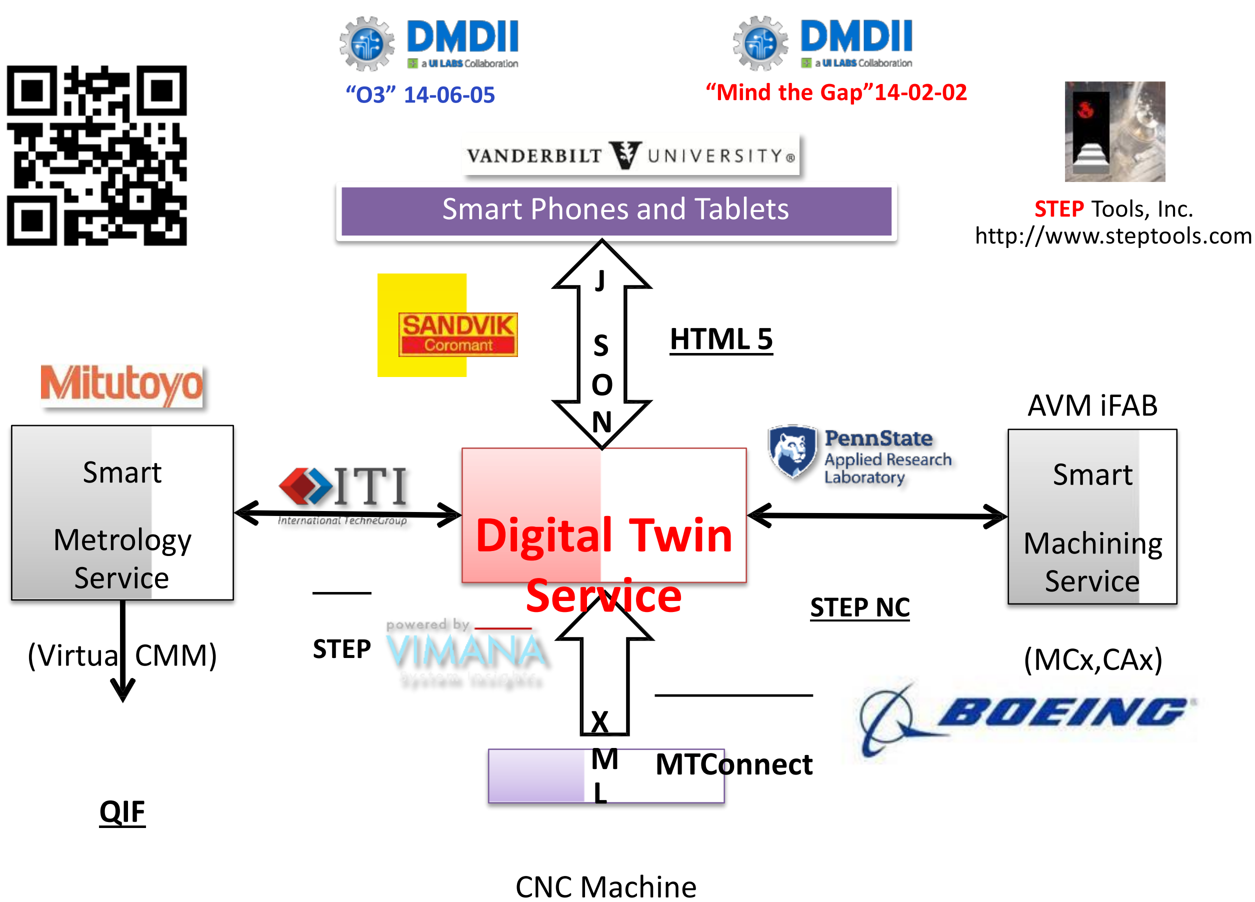

Figure 7 system architecture

Features and Attributes

The system measures machining in real time for milled parts which may be three, four or five-axis. The real-time measurements enable real time tool wear management, and real-time adaptive programming. The real-time measurements enable the development of apps to manage machining for different kinds of parts and tooling.

Modes of Operation

The Digital Twin Service has three modes of operation.

1. **In machining mode**, the digital twin server simulates live machining directly from the MTConnect stream.
2. **In planning mode**, the digital twin server simulates as-planned machining from STEP AP238 data.
3. **In analysis mode**, the digital twin server mixes as-planned and as-machined data by projecting the as-planned results of the next operation onto the as-machined results of the previous operation.

Software Development Documentation

The software development documentation is on GitHub and as detailed in the Appendix.

https://github.com/steptools/NC.js

Use Cases

The **first use case** is to monitor machining results from remote locations. The results can be observed using a browser or smart phone and they can be evaluated by writing applications to process the following three data formats

1. MTConnect - this format reports the machine results. It can be checked to make sure that the process is running within its limits.
2. STEP – this format reports the machined results as a 3D model with GD&T. It can be checked to make sure that the tolerances are being met.
3. QIF – this format reports how key characteristics were verified. It can be checked to make sure that the part is in compliance with pertinent regulations.

The **second use case** is for on-machine probing. This use case is being developed by the DMDII 14-06-05 "O3" program. The part can be measured from the virtual model and the results can be confirmed by using a probe or scanner to touch the physical part. Depending on the situation the results may be used to adjust the setup, compensate for tool wear, or determine final part conformance. If there is doubt about the measurement results, then the same tolerances can be verified on a traditional CMM.

The **third use case** is better tool wear management. A real-time simulation delivers a real-time model of the chip thickness which can be used to better regulate the feeds and speeds during machining. If the part is not urgently needed, then the feeds can be reduced to minimize tool wear. If there is a deadline, then the feeds can be increased to the maximum that can be supported while still meeting the tolerances.

The **fourth use case** is adaptive programming. If the stock size changes, or if some features are already on the part, then the machining can be adjusted to eliminate redundant processes. The adjustments can be made by loading an as-is model of the part into the simulation server. Operations that are redundant can be detected and eliminated. Operations that need to be modified can be given new feeds depending on the actual size of the stock and cutter.

The **fifth use case** is simplified machining. Apps can be written to guide the operator through the setup processes. Apps can be written to make checks at different stages to confirm that the machining is operating within its boundaries. Apps can be written to substitute tooling and make various process changes depending on what is available in the shop on the day of the machining.

The **sixth use case** is resource optimization. Model based machining can be sped up or slowed down depending on the available tooling. A database can be built of the range of parts that can be manufactured on each machine. Analyses can be performed to determine use cases for purchasing new machines which include the option of moving work to new machines to make more optimal use of the available equipment.

Implementation

Technology	Start of Project TRL	End of Project TRL
Digital Twin Service	5-6	7-8
Smart Machining Service	3-4	5-6

The Digital Twin Service was developed by STEP Tools, Inc. from technology developed under an AVM SBIR. In Mind the Gap a simulator developed for this SBIR was given a web user interface using technology developed by Vanderbilt University.

The Smart Machining Service was developed by Penn State University, first under the DARPA AVM program, and then under Mind the Gap. The AVM program enabled development of the basic algorithms and Mind the Gap focused the solution on stage model generation. The tool was used to generate solutions for a cloud service, but has not yet been deployed as a cloud service.

Technology Transition

Future Plans

The Digital Twin Service will be marketed to OEM's as a solution for modeling and optimizing machining results in real time. When the system reaches maturity, it will be saving customers approximately 15% annually in a $75bn market.

Market Assessment

The current market is limited to early technology adopters. A new customer must meet two requirements:

1. It must have machine tools that stream MTConnect.
2. It must have product models made using a CAD system.

The second requirement is optional when the machining is for a basic three axis part. If the requirements are met, then the server can be loaded with the CAD models and connected to the machine tools for real time simulation. The server will then allow the machining to be observed from remote locations using web browsers and smart phones. In the future, the server will allow the machining to be measured and optimized in real time leading to a 15% reduction in costs.

Because of the complexity of system integration, the pricing model is as for ERP systems. We are planning for 3 customers in 2017, 5 customers in 2018 and 20 customers in 2020. Each customer will host a thread that may be connected to hundreds of machines that are making thousands of parts.

We predict competitors will join the market in 2018. Reliable apps will become available in 2019 and sales will depend on cost benefits analyses starting in 2020. After 2020, machine tools will become available with the necessary software already loaded. Organizations should think about their business models. Today many first world countries assemble parts from kits made overseas. The digital thread allows kits to be machined in factories that are more like silicon foundries so this work can be returned to the USA.

Barriers to Adoption

The time required to complete the digital infrastructure and write the first apps is the major barrier to adoption. Therefore, in the early years, the market is limited to organizations with the vision necessary to understand the advantages of a standards based digital thread. Figure 6 shows stages for the adoption. Stage 1 has been completed and enables the remote monitoring of machining from smart phones and browsers. Stage 2 is in progress and enables the automated measurement of the machining results. This is the second application and a critical gateway because you cannot make optimizations without being able to measure the validity of the necessary changes. Stage 3, in 2018, is when the first apps become available. After this, the thread will start to deliver value that can be measured as ROI and the deployment will become easier.

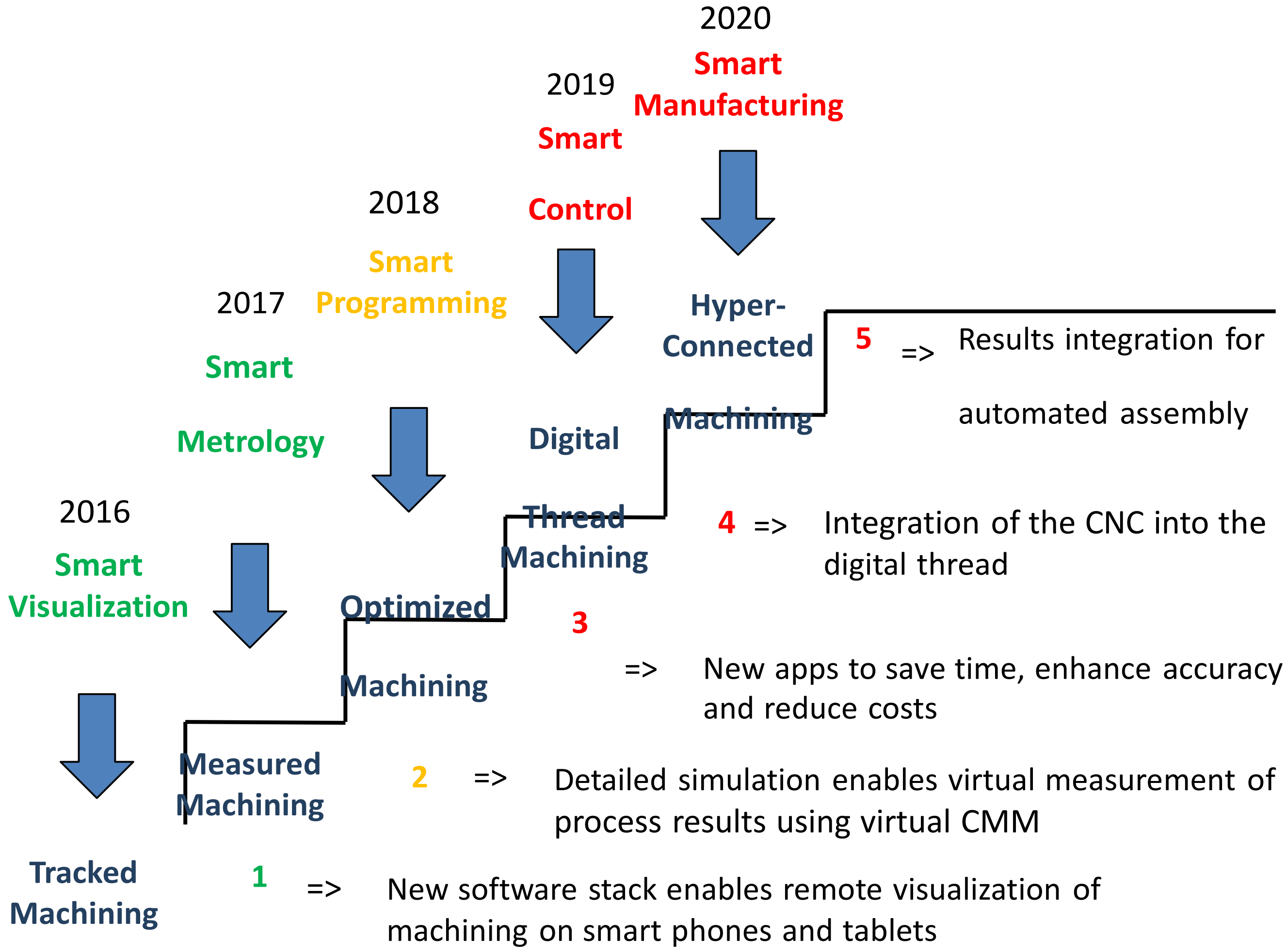

Figure 8 technology development plans

Workforce Development (WFD) and Education

At its core the digital thread is a JavaScript programming environment that uses of a stack of new technology. This technology requires skilled programmers. Today machining is performed using codes that were designed to be stored on paper tape. This technology requires skilled machinists. There is a significant gap between the two technologies.

Since 2015 STEP Tools has been giving digital manufacturing courses to engineering students and computer science students at RPI. The engineering course is for graduate students and focuses on the functionality of the digital thread and how to connect systems. The computer science course is for seniors and focusses on how to program web apps for machining. Trying to mix the two is difficult but becoming easier as the first systems become available. In the first year getting a machine to emit MTConnect data was a big issue. In the second year, the engineering students were able to connect a Haas machine tool to a DigitalTwinServer. In the third year, they will measure and compare results from the machining using a real and virtual CMM.

During these years, the computer science students have been writing progressively more complex applications. In the first year, they learnt how to program a solid model in C++. In the second year, they wrote the first JavaScript applications. In the Spring of 2017, they will develop apps for machining and measurement that can be used by the engineering students. In the fourth year, they will start programming the first apps and there will be some kind of merger between the two courses so that the engineering students can help the computer science students understand what is needed in the apps.

Digital Twin Courses

Date	Location	Notes
Engineering Course	Boeing, Seattle Wide Body	Immediately following an ISO or MTConnect meeting
Computing Course	NIST, Gaithersburg	Immediately preceding or following MBE summit
Engineering Course	DMDII, Chicago	Immediately preceding or following a demonstration
Computing Course	STEP Tools, Troy NY	Immediately preceding or following a demonstration

Conclusions / Recommendations

There are three recommendations:

1. **US industry should adopt a digital thread.**

Mind the Gap has shown that a digital thread can deliver real time machining data to web browsers and smart phones.

Mind the Gap connects a real-time simulator developed for the DARPA SBIR program to a machine tool. The simulator is updated at 100 times per second (100Hz). The 3D model based simulation is then broadcast to web browsers and smart phones. As part of the simulation the engagement between the cutter and the workpiece is also computed. This engagement allows new optimizations to be implemented including tool wear management and real time adaptive programming. These apps and others enable savings of at least 15% in a manufacturing market estimated as $75bn per year.

2. **The digital thread should be defined by open standards.**

The digital thread should be defined by open standards to enable a new market.

Mind the Gap has shown that an open thread can support real time machining. Standards allow the thread to be connected to all the potential users across the supply chain. These include users in design, planning, manufacturing and inspection. Standards reduce costs by allowing many organizations to develop applications. The standards chosen by

Mind the Gap are: (i) MTConnect so that the simulation server can be connected to the millions of legacy machines; (ii) STEP so that the product model data can be supplied by any CAD system; and (iii) QIF so that quality reports can be sent to any enterprise.

3. The digital thread should be nurtured by the DMDII members

The digital thread will allow US manufacturing to compete with low cost enterprises but not until the new automation applications are completed.

Like any new platform, the thread is currently not very rich. The iPhone platform started as a better digital music player. The Windows platform started as a better compute operating system for hobbyists. The SAP ERP system started as an accounting application for relational databases. The digital thread is starting as a solution for monitoring machining from remote locations. Many new functions can be implemented on this base. The DMDII should assist by nurturing their deployment with its tier 1 and tier 2 members.

Ending Financials and Labor Hours Assessment

DMDII Authorized Cost	DMDII Actual Cost	Difference
$1,010,052	$1,012,311	$2,259 (excess cost was not billed)

DMDII Authorized Cost Share	DMDII Actual Cost Share	Difference
$1,099,329	$1,226,901	$127,572

DMDII Authorized Hours	DMDII Actual Hours	Difference
6,840	8,480	1,640

Lessons Learned

Problems Encountered

It was anticipated we would have difficulty updating a 3D machining model at 100Hz but this was not an issue.

It was anticipated that follow on funding would become available to complete the commercialization of the Smart Machining Service but to date no funding has been found. Therefore, STEP Tools, Inc. will continue using direct CAM translators.

Work Scope Deviations

None.

Risks

The digital thread can be defined by commonly available, and widely supported open standards, or by closed alternates. The closed alternates will be of strategic advantage to a small number of vendors, and will get considerable support in the short term. An open thread allows many participants and vendors to contribute and will play to the traditional strengths of the USA.

Appendix

Document Deliverables

Figure A1 show the components in the software stack of the simulation server. The Maker package and everything below are BIP. Everything above the Maker and all client packages are being delivered as source code.

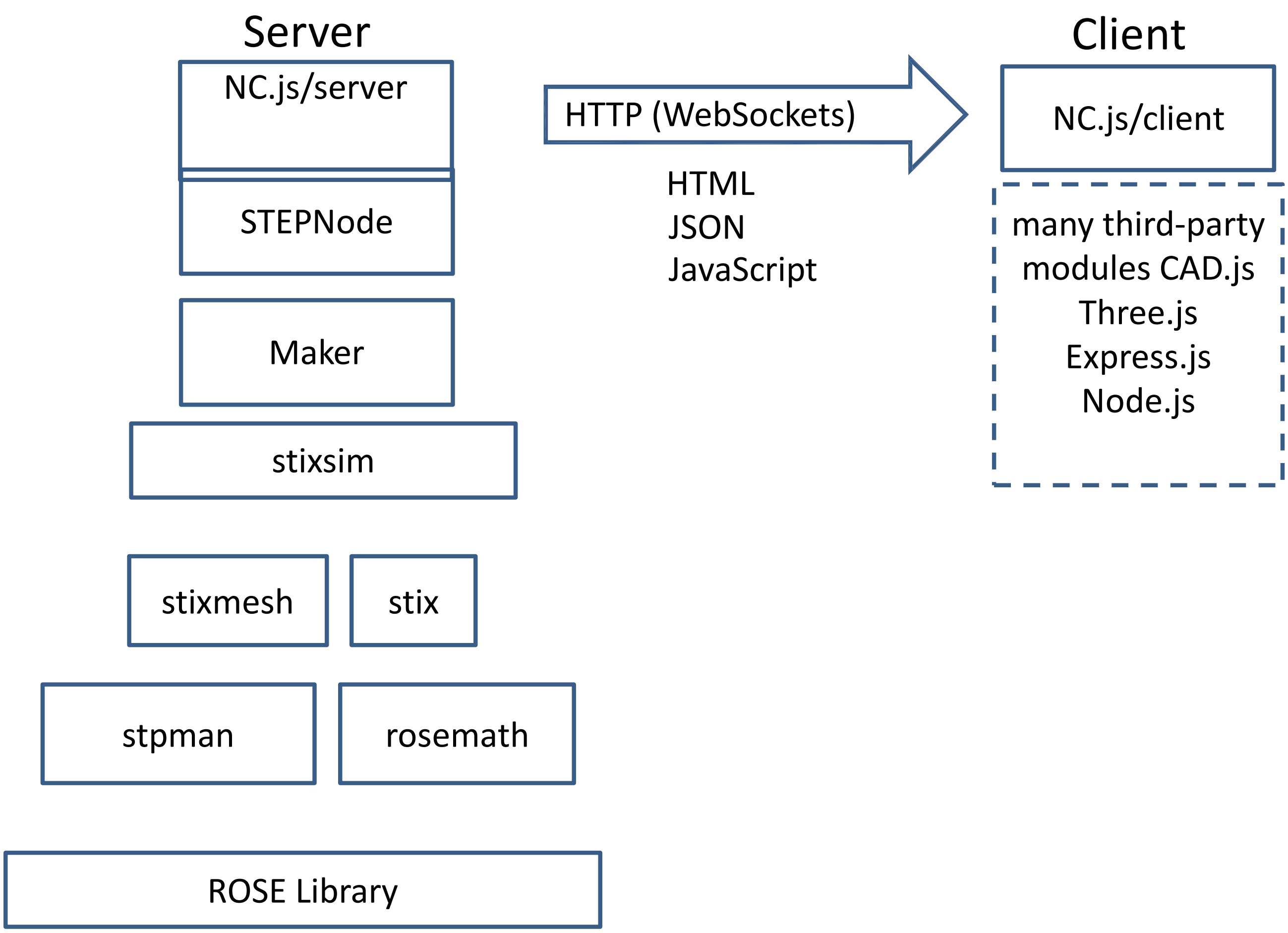

Figure A1 components of the software stack

The following web sites document these components.

ROSE: http://www.steptools.com/support/stdev_docs/roselib/index.html

Stpman: http://www.steptools.com/support/stdev_docs/stpman/html/index.html

Rosemath: http://www.steptools.com/support/stdev_docs/rosemath/index.html

STIXmesh: http://www.steptools.com/support/stdev_docs/stixmesh/index.html

STIX: http://www.steptools.com/support/stdev_docs/stix/index.html

Stixsim: Not yet available

Maker: http://www.steptools.com/support/stepnc_docs/ncapi/AptStepMaker.html

STEPNode: https://github.com/steptools/STEPNode

NC.js: https://github.com/steptools/NC.js

Demos

The following web site hosts demos.

http://www.steptools.com/demos/mtc/

The following web site explains the operation of the system.

https://www.youtube.com/watch?v=Mjzg5nku5Lg

Validation and Testing

The validation and testing will be via a series of demonstrations.

Since 2000, the STEP Manufacturing team (ISO TC184 SC4 WG15) has been hosting a continuous series of technology demonstrations to verify the standard, drive implementations of STEP-NC machine controls and give organizations experience with the STEP-NC standard. The lessons learned in these demonstrations are fed back into the ISO working group for use in future editions of STEP-NC AP238 standard.

The first demonstrations were held by STEP Tools, Inc. as part of the Super Model project. These focused on higher level operations as well as integration of STEP CAD data with STEP-NC process data and provided important feedback while the standard was being drafted.

The later demonstrations have been hosted by ISO STEP-Manufacturing. They have attracted a wide range of industrial participants and focused on deployment, machining interoperability, integrated machining and measurement, optimization, and simulation.

STEP-NC demonstrations so far:

```
2016 – RPI, Troy; Digital Twinning on a Haas mini-mill
2016 – Boeing, Mukilteo; Optimization using cloud services
2015 – SC4, Baltimore; Machining in the cloud
2014 – IMTS Chicago; Machining simulation in real time
2012 - KTH, Stockholm: Machining Accuracy Prediction
2010 - Renton, WA: Setup Compensation
2010 - NIST, Gaithersburg: Networked Machining and Simulation
2009 - Bath, UK: Many Sites, Multiple Setups
2009 - Renton, WA: Mold Machining at Multiple Sites with the Same Part
2008 - Hartford, CT: Closed-Loop Impeller Machining, Feed Optimization, and Measurement
2008 - Sweden: Feed Optimization, HSM, Closed-Loop and Traceability
2007 - Ibusuki, Japan: Machining and Measurement
2006 - Toulouse, France: International Aerospace Machining Testing
2005 - EASTEC: Closed-Loop Machining
2005 - Orlando FL: Five Axis Testing Forum
2003 - JPL: Multi-axis milling
2002 - Troy NY: STEP-NC milling
2000 - Watervliet NY: First in USA
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Benet Laboratories, Watervliet, NY
November 30, 2000

First Year Demonstration

The first demonstration was held on November 30, 2000 at the Benet Laboratories of Watervliet Arsenal. The Arsenal is the oldest manufacturing arsenal in the USA. Founded in 1812 as the USA's response to the better cannon of the Royal Navy, the Watervliet Arsenal can claim to be the oldest high tech manufacturing facility in the United States.

From CAM to Controller

The demonstration featured an FB Mach CAM system being used to make the STEP-NC data, and a Bridgeport Machine Tool controller being used to make the part. FB Mach is a Computer Aided Manufacturing system developed by Honeywell FM&T for the Department of Energy. In the demonstration it read a STEP file from a CAD system, an operator used its advanced feature recognition capabilities to compute a manufacturing plan, and the result was written as a STEP file containing all the information required to make a part. The Super Model read the data written by FB Mach and added the information to its database. A Bridgeport Controller modified by Electro-Mechanical Integrators (EMI) used the Intelligent Interface to read the manufacturing data. The Intelligent Interface found the information necessary for a milling machine to make the part, and it presented that information in a form that is easy to process on the PC based control.

Experimental Machine Tool and Plating Company Inc., Troy, New York
February 20, 2002

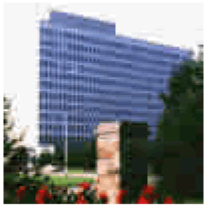
On February 20-21, 2002, STEP Tools hosted live demonstrations of STEP-NC technology for CNC milling operations at Experimental Machine Tool & Plating Company (Troy, NY), a local manufacturer specializing in precision machining and electro-plating services. This was the second of three planned demonstrations of the Super Model Project, and as part of this event the fifth Industrial Review Board Meeting was held to discuss results and plans for further development of STEP-NC technology.

Multi-Axis Machining at JPL and NIST

On January 29-30, 2003, STEP Tools Inc. held its 6th Industrial Review Board (IRB) Meeting at the NASA Jet Propulsion Laboratory (JPL) in Pasadena, CA. STEP Tools worked with JPL to demonstrate the machining of a part using full fidelity STEP-NC product data as direct input to a multi-axis CNC milling machine. JPL is testing the new technology as a participant in the STEP-NC Phase One Implementers program.

STEP Tools and JPL rapidly converted AP203 (STEP) models into AP238 (STEP-NC) CNC-independent control data with tolerances using JPL crib sheets, and presented an automated set-up wizard for defining setup and fixtures. The ultimate goal of the STEP-NC initiative is to serve as direct input to a CNC machine tool, thus eliminating post processors, G & M codes, data redundancy, multiple CAD files, and more. During the demonstration, STEP Tools also

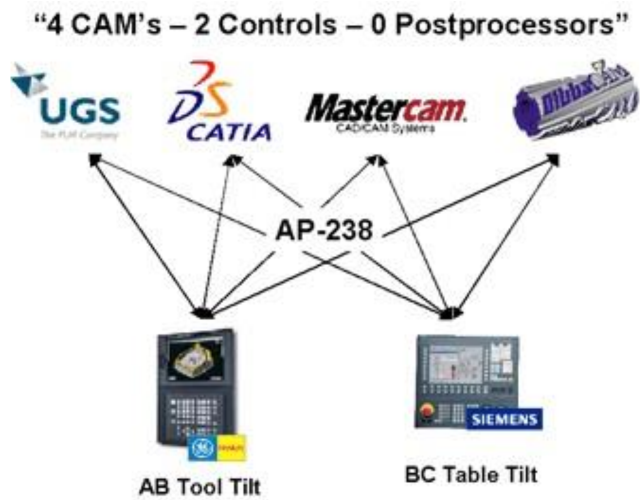
showed how feature recognition and [STEP-NC Machine] can enable the manufacturing process by managing and automating machining and planning operations.


NIST Gaithersburg, MD

The next STEP-NC demonstration was held at NIST in Gaithersburg, MD, on June 4-5, 2003. For the first time, the STEP-NC demonstration focused on a complex surface model provided by Boeing that was milled on a 5-axis CNC machine tool. STEP Tools and NIST will show the rapid conversion of AP-203 (STEP) models into AP-238 (STEP-NC) CNC-independent control data containing tolerances. Also, for the first time, a STEP-NC Machine plug-in for MasterCam software (CNC Software, Tolland, CT) was featured to generate toolpaths and output CNC code. STEP Tools also demonstrated a STEP-NC Machine plug-in for GibbsCAM software (Gibbs and Associates, Moorpark, CA).

AP-238 CC1 Testing for 5-Axis Machining

On February 3rd, 2005 the OMAC STEP-NC Working Group hosted an AP-238 testing forum in Orlando Florida. The tests were done on 5-axis parts using AP-238 CC1 machine independent toolpaths. In addition to showing CAD/CAM systems producing AP-238 and CNCs processing it.



The Details

Four CAD/CAM systems produced AP-238 machining programs for milling a 5-Axis test part (an NAS 979 circle/diamond/square with an inverted NAS 979 cone test in the center). Each of these was then run on a pair of CNCs configured for completely different machine geometries (AB tool tilt vs. BC table tilt).

In addition to the activities in Florida, Boeing cut actual parts on a variety of machines at the Tulsa facility as well as a machine at NIST in Gaithersburg.

These are two of the machined circle/diamond/square and sample aerospace parts produced during the tests. The walls of the sample aerospace part may look vertical but actually have subtle 1-2 degree inclinations that require 5-axis machining. In addition there are several holes in the walls that must be drilled at odd angles.

AP-238 Testing for Closed-Loop Machining

On May 24-26, 2005, the OMAC STEP-NC Working Group held the latest AP-238 testing forum event at EASTEC 2005 in Springfield, MA. Representatives from Boeing, Unigraphics, NIST, Pratt and Whitney, and STEP Tools were present and Siemens graciously provided us with space in their booth.

This event focused on demonstrating closed-loop machining using touch trigger probes and cutter contact machining driven from STEP-NC. The following slides describe the complete closed-loop scenario. [PPT, 1.4M].

The scenario is to rough and finish a boss on the engine casing test part provided by Pratt and Whitney (see right). After roughing and semi-finishing, a probing operation is used to adjust a final finishing pass. The finishing is done using cutter contact paths To further make things interesting, the roughing paths are created by one CAM system and the finishing paths by another.

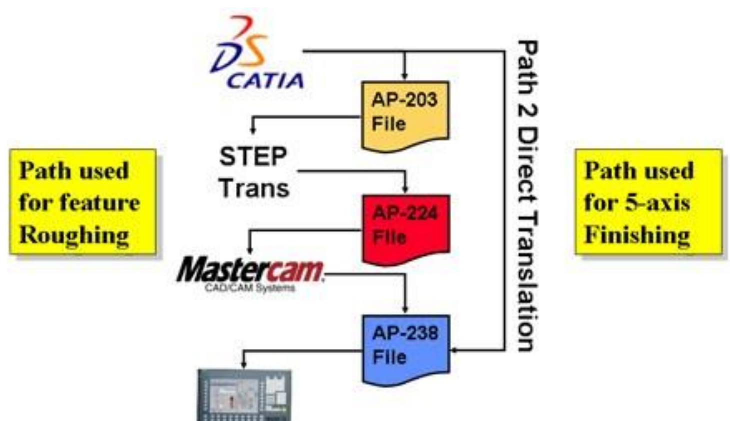
International STEP-NC Testing in Toulouse

On June 28, 2006, a live 5-axis STEP-NC machining demonstration was hosted by Airbus at the Université Paul Sabatier Laboratoire de Génie mécanique in Toulouse. The demonstration and accompanying Manufacturing Industry Day featured:

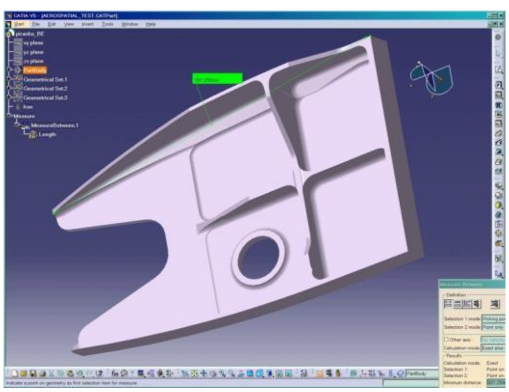
100 attendees
Successfully machined 5-axis test parts
Machining using STEP features
Contributions from France, UK, USA, Sweden, Germany
Presentations from France, UK, USA, Germany, Korea, Japan, Sweden, Spain, Switzerland
Test parts from Boeing and Airbus
Demonstrated use of STEP AP's for design, planning and manufacturing

The Details

For the test part machined during the meeting, two different technology paths were demonstrated. The workpiece was first cut into a rough state using toolpaths computed from STEP manufacturing features by an intermediate CAM system. Second the workpiece was finished using toolpaths directly from the original design system. The final result was a STEP-NC AP238 file containing all geometry, feature, and toolpath information used during the entire process.



Airbus "Fish" and Boeing "Fin"



For roughing, a CAD model of the rough form was first exported from Catia as STEP AP203. This was annotated with STEP manufacturing features to produce AP224 data. Using plugins designed by STEP Tools, the AP224 data was read in to MasterCAM, a workplan with toolpaths was generated from the feature data, and an AP238 file containing all of the geometry, feature, and toolpath data was written out. last-minute changes to the cutting tools were easily accommodated and demonstrated flexibility. (Some slides describing roughing)

For finishing, a CAD model of the final form was exported from Catia, along with APT 5-axis toolpaths describing how to machine from the rough to the final form. These were added to the AP238 file to produce the complete roughing and finishing description. (Some slides describing finishing)

Finally, to cut the part, the AP238 file was then loaded onto a DMG 50 with a Siemens 840D controller located at the Université Paul Sabatier Laboratoire de Génie mécanique. (Some slides describing the implementation tools used)

In addition to the activities in Toulouse, a Boeing-supplied test part was circulated among the participants and cut prior to the meeting at a machine at NIST in Gaithersburg.

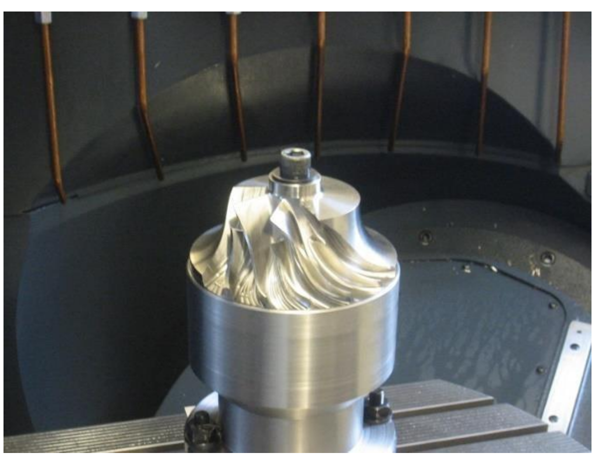
International STEP-NC Demonstration of Feed Optimization, High-Speed Machining, Tolerance-Driven Tool Compensation, and Traceability

On March 10-12, 2008, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) met in Sandviken and Stockholm, Sweden to demonstrate and discuss advanced uses of the STEP-NC AP238 standard. The participants in the demonstrations included Airbus/Univ. Bordeaux, Boeing, Eurostep, KTH Royal Institute of Technology, NIST, Sandvik Coromant, Scania, STEP Tools, and Univ. of Vigo.

Highlights included:

- Feed and speed optimization: Boeing, Sandvik Coromant, and STEP Tools showed how to improve nominal machining process plans to generate optimized process plans just prior to machining by adding cutter cross sectional area information to the STEP-NC file.
- High-speed machining: Airbus/Univ. Bordeaux, Sandvik Coromant, and STEP Tools showed HSM with STEP-NC and demonstrated new approaches for representing large volumes of toolpath curves.
- Tolerance-driven tool compensation: KTH Royal Institute of Technology, Eurostep, Sandvik Coromant, Scania, and STEP Tools showed how STEP-NC machining information can be linked with tolerances, wireless measuring equipment, and ISO 13399 tool descriptions to simplify tool compensation for more accurate machining.
- Traceability: Univ. of Vigo and NIST showed a series of traceability extensions for linking STEP-NC machining programs with sensor feedback and machine state information during execution.
- Contributions from France, Spain, Sweden, and USA
- Test parts from Airbus and Scania.
- Cutting Tools from Sandvik Coromant and Prototyp

International STEP-NC Demonstration of Closed-Loop Machining, Feed Optimization, and Measurement



On October 1-2, 2008, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) met at the Connecticut Center for Advanced Technology, in Hartford, Connecticut to demonstrate and discuss advanced uses of the STEP-NC AP238 standard. The highlight of the meeting was the live 5-axis machining of a titanium impeller.

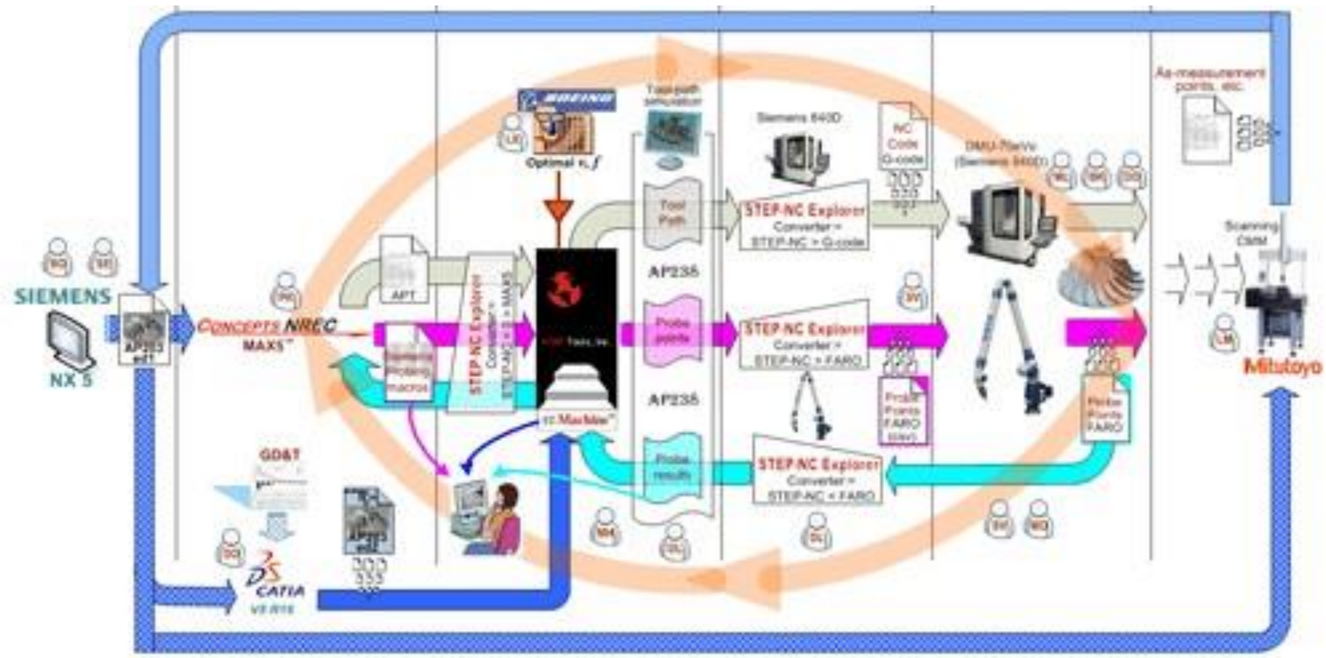
Participants in the machining demonstration and other activities included Boeing, Connecticut Center for Advanced Technology, Concepts NRec, DMG, KTH Royal Institute of Technology, Mitutoyo, NIST, Sandvik Coromant, Scania, Siemens, and STEP Tools.

The meeting was very productive. We were able to show that we can mill an impeller using STEP-NC files containing models of the product, process, fixtures and cutting tools. We showed how the new information can enable on-machine feed-speed and tool life optimization, and we showed how the product tolerance information in STEP-NC can be used to implement closed loop machining using measurement devices such as probes and Faro arms.

Highlights include:

- Live machining of titanium impeller test part from a complete STEP-NC description.
- Measurement using Faro arm or a scanning probe and feedback into STEP-NC
- Correction of toolpaths from probe results and update of STEP-NC description.
- Application of STEP-NC in heavy truck manufacturing
- All presentations from the meeting

The complete flow of the machining, measurement, and feedback is shown below (click for full size):



International STEP-NC Demonstration, Renton, WA 2009

On May 14-15, 2009, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) met in Renton, Washington to demonstrate and discuss advanced uses of the STEP-NC AP238 standard. The key goals for this round of demonstrations were to have multiple sites machine the same part from the same AP-238 data, and to show AP-238 can be used for molds.

Boeing hosted machining demonstrations at their Renton facility and gave the group a tour of the 737 production line. Mitutoyo demonstrated touch probe and laser scan measurements in Kirkland at Micro Encoder. Finally, in the following week, the group held technical meetings with SC4 in Parksville BC and discussed a methodology for representing the kinematics of a machine tool model as STEP data.

The key accomplishments for this round of demonstrations were:

Implementation by Fanuc of AP-238 STEP-NC
AP-203 Edition 2 annotation tolerances read from Catia
Part quality measured at Mitutoyo using laser scanner and touch probe
Moldy parts made from AP-238 data at many locations, on many types of machine.

- Boeing, USA
- NIST, USA
- Connecticut Center for Advanced Technology, USA
- Al's Rod Shop, USA
- KTH Royal Institute of Technology, Sweden
- Scania, Sweden
- University of Bath, UK

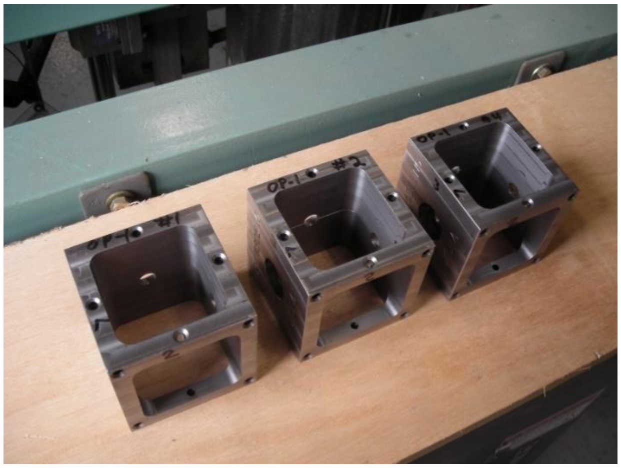
More details are available in the minutes of the meeting [ppt, 450k]

International STEP-NC Demonstration, Bath, UK 2009

On September 21-24, 2009, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) met at the University of Bath in concert with the TC184/SC1 meeting for a new round of STEP-NC international testing.

Over the course of the demonstration cycle, the "Boxy" series of data sets were developed to exercise capabilities with multiple setups. Three different versions were created, each with multiple setups designed for three, four, or five axis machining. Furthermore, each file contains a number of alternative workingsteps for doing operations with different tools. The data sets also contain a full selection of in-process models to display the results of each operation as well as the delta volumes.

International STEP-NC Demonstration, National Institute of Standards and Technology (NIST), Gaithersburg, MD, June 16-18 2010



On June 16-18, 2010, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) net at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland for STEP-NC international testing and demonstration.

This round of demonstrations focused on the use of STEP-NC for tool wear management and machining a part in multiple setups with multiple alternate machining plans for 3, 4 and 5-axis machining. The "Boxy" test part for this round was a simplified gear box that must be machined on all six sides. During the live machining demonstration at the meeting, the tool wear and consequent machine loads were predicted from the STEP-NC data and verified using a dynamometer.

The technical discussions covered a range of topics, such as ways to help the operator understand the "real" tool requirements, process monitoring, machining and measurement, machine resource modeling, and the use of STEP-NC within Mil-Std 31000. Browse the minutes of the meeting for a complete list of all presentations and discussions.

International STEP-NC Demonstration, Boeing Renton Plant, Renton, WA, October 12-13 2010

On October 12-13, 2010, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) met at the Boeing facility in Renton, Washington for STEP-NC international testing and demonstration.

This round of demonstrations applied STEP-NC to setup compensation with on-machine measurement of part and fixture datums using a FaroArm. During the preparation for this round, a series of compensation extensions to the STEP-NC model were discussed and refined, then implemented within STEP-NC Machine for validation and further testing. The resulting model adds several new frame definition and compensation workingsteps as well as associated measurement geometry. Browse the minutes of the meeting for presentations and discussions.

STEP-NC Machining Accuracy Demonstration, Stockholm, June 14, 2012

On June 14, 2012, the STEP Manufacturing team (ISO TC184 SC4 WG3 T24) met at the KTH production engineering labs in Stockholm, Sweden for an Industry Day and demonstration of machine tool accuracy calculation. This was part of a week-long T24 meeting as part of the larger ISO TC184 SC4 group in Stockholm.

The demonstration milled a forged blank for a Crown Wheel Gear on an older Mazak VQC 20. Prior to the demo, the Mazak was measured using laser and a loaded double ball bar. Next, ASME B59.2 software developed by NIST used this information to predict the positional accuracy of the actual tool movements. Finally Cross-section based force calculation software developed by Boeing used cross section information in the STEP-NC machining data to predict the deflection of the cutting tool under load.

These components were combined to predict the machining result, and when the machined article was measured, the shape of the predicted deflection correlated with the observed deflection, but the magnitude of the predicted deflection was larger than what was observed. A second machining test is being planned to repeat the experiment at another facility.

We also discussed STEP kinematics models for machine tools, and showed a model of the tool changer on the Mazak. We had extensive discussions on external reference between STEP files, including cutting tool models built from files on vendor websites, and agreed on the scope and form of a Part 21 extension to simplify references.

STEP-NC at IMTS, Chicago, September 8-13, 2014

We worked with Boeing and Okuma to integrate the simulator onto the machine tool and show a STEP-NC enabled CNC in the Okuma booth at IMTS. We received an Okuma control demonstrator (the machine tool control without attached servomotors) to assist with the integration.

Okuma Machine Control with Live STEP-NC Display

We extended the STEP-NC tools to connect to an Okuma control via the THINC API to query the CNC. It can show the live machine tool state in context with the STEP-NC program and are the simulator can follow along to show the material removal state. We also corrected some initialization issues with the 3D geometry display on the control.

The three machining processes (Boeing baseline, Sandvik optimized, and ISCAR optimized) were tested for live machining in the Okuma booth at IMTS in September 2014. During the preceding months, we revised data sets to incorporate feedback from Okuma for better fixturing and improved spindle speed handling, better process organization, and improved processes from ISCAR and Sandvik.

Live Titanium Machining Demonstration run daily with Boeing, Okuma, Sandvik and ISCAR at IMTS 2014.

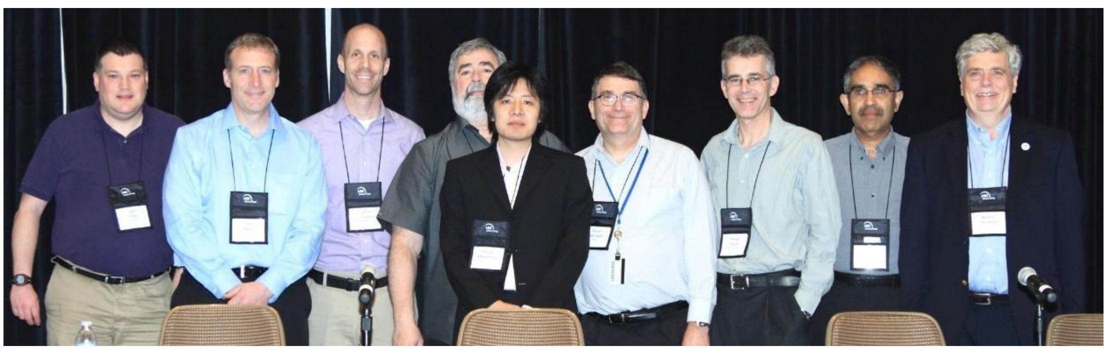
STEP-NC at OMAC, SC4 and MTConnect, 2015

We developed an MTConnect interface and extended the user interface so that you can visualize the machining of a part by just entering the URL of the CNC. We demonstrated the new interface to the Technical Advisory Group of the MTConnect Institute in Tampa on January 22. At the meeting we used MTConnect to connect a laptop to a server in our lab in Troy NY and visualized a part being machined in real time.

We improved documentation for the STEP-NC programming libraries, with updated API documentation, new sample code, and thorough setup instructions. The DLL now has uniquely identifying "strong name" and can be installed into the global assembly cache on a machine. We also tested the COM interface to the DLL for use with tools that create STEP-NC data from Mastercam. This validates that the STEP-NC services can be used from newer .NET applications as well as traditional C++ applications.

We worked with Makino to demonstrate STEP-NC feedback directly from their controls. They produced a STEP-NC monitor using the plugin architecture. After some initial tests, they were able to demonstrate motion and simulation driven by the control. We are currently discussing ways to increase the amount of position data reported back using a stream of recent points or some other mechanism.

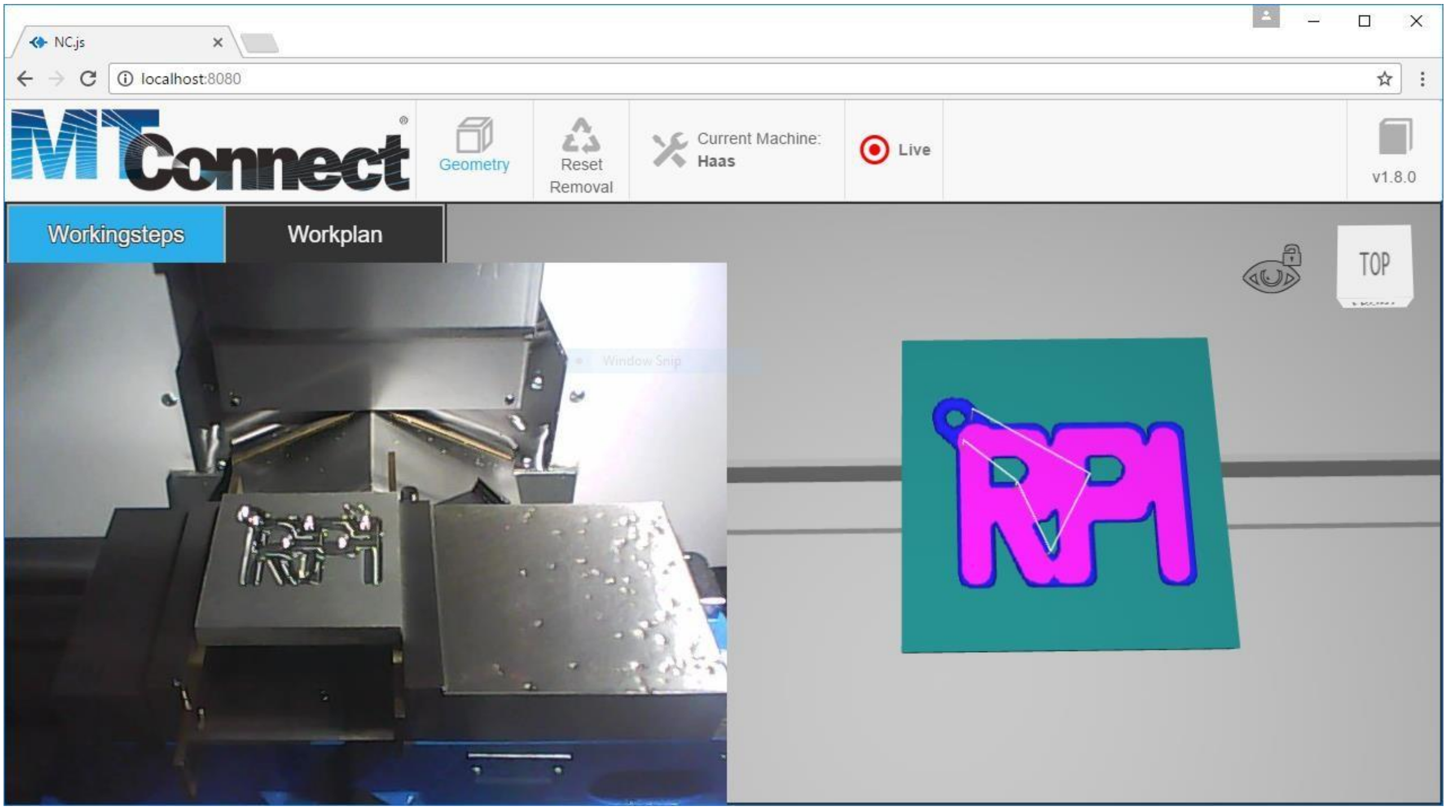
The Second CAM Data Exchange Workshop February 2015 in Orlando had representatives were present from Penn State, Vanderbilt Mitutoyo, Makino, Boeing, Sandvik Coromant, and STEP Tools. Penn and Vanderbilt reviewed the NC planning and visualization services scheduled for the Mind the Gap Project. Mitutoyo used the Simulation Service output for a Virtual CMM proof of concept for a future project.



Second CAM Data Exchange Workshop, February 2015, with Representatives from Penn State, Vanderbilt Mitutoyo, Makino, Boeing, Sandvik Coromant, and STEP Tools

Digital Twinning using STEP, QIF and MTConnect, 2016

We developed a digital twinning system that connect a machine tool to a server in real time. In October, we showed this server being used to twin machining on a high-end Okuma machine tool. In December, we followed this with a demonstration on a low-end Haas mini-mill. The October demonstration showed that the server could maintain a digital twin model at very high rates of refresh. These varied between 70Hz and 100Hz. In December, we showed that the system can also manage a much lower refresh rate of 10Hz.



Real time digital twinning on a Haas at 10Hz