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## Web-enabled, Real-time, Quality Assurance for Machining Production Systems

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### Abstract

In order to maintain the close control of production quality, frequent measurement and process parameter adjustments are desirable. In the discrete parts industry, part inspection is intended to be a metric for the process quality but quality control is typically done long after the part has been machined. The long latency between machining and quality assessment makes it difficult to incorporate quality feedback into production. Quality assurance relies on continuous real-time quality feedback, which is not a complex concept. However, the collection and representation of the necessary process data and quality measurement data is challenging. This paper discusses Web-enabled, real-time quality data and statistics based on the integration of two manufacturing open specifications: MTConnect and Quality Measurement Results (QMResults). A pilot implementation that integrates the two technologies and produces Web-enabled, real-time quality results in a standard XML representation from Computer Numerical Control (CNC) machine tool inspections will be discussed.

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### 1. Introduction

Intuition, ‘rules of thumb’, and educated guesses are ineffective ways to guarantee quality. Quality goods can only be manufactured using hard knowledge derived from ongoing and continuous collection and evaluation of production data. In discrete parts manufacturing, the understanding of the factory processes has been difficult, due primarily to closed, proprietary Computer Numerical Control (CNC) architectures that make any potential analysis expensive. MTConnect is an open, free specification aimed at overcoming the “Islands of Automation” quandary on the shop floor, and with broad industry support has resulted in cost-effective tools for factory floor data acquisition, process measurement, and

production analysis [1–3]. With fact-based analysis, manufacturers can improve production to become lean, efficient, and effective.

Recently, there has been interest in applying the Web-based, data acquisition concepts of MTConnect to the real-time acquisition of quality data. Quality of a product may be defined as “its ability to fulfill the customer’s needs and expectations” [4]. Quality is defined in terms of performance requirements, which vary from product to product. For discrete parts, the primary performance requirements, commonly referred to as characteristics, are dimension (e.g., length, diameter, thickness or area), geometric tolerances (e.g., flatness, cylindricity, etc.), and appearance (e.g., surface finish, color or texture). To ensure overall quality, delivered parts must meet the required quality characteristics. Thus, part quality is measured by its conformance to the performance requirements.

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Since uncontrolled machining process variability can hinder manufacturers in their effort to maintain acceptable part quality, inspection is used to provide insight and visibility to potential production problems so that they can be rectified in a timely manner. However, if adjustments are made based on historical inspection data rather than immediate monitoring, then the analysis is vulnerable to unexpected changes in factors, such as tool performance, thermal characteristics, or operator changes in feed and speed overrides, which can render the inspections useless. Real-time inspection results characterizing the manufactured parts and reported in an easily-accessible, standardized format can lead to better and more optimized performance of the manufacturing processes. This can be difficult as inspections done on-machine are not easy as off-machine, due to problems in controlling the environment, e.g., temperature, debris, and measurement equipment accuracy and access.

The focus of this paper will be on the use of MTConnect to provide Web-enabled real-time communication of Quality Measurement Results (QMResults) inspection data and results. In conjunction with this goal, the development of a prototype Web-based real-time implementation was done using a National Institute of Standards and Technology (NIST) shop floor machine tool with inspection and measurement capabilities. However, the same principles to implement Web-enabled real-time quality results for machine tools could be used for any number of physical inspection systems such as coordinate measuring machine (CMM), laser, optical, and digital measurement devices, or hand held devices. The purpose of this pilot project was to validate whether the Web-based real-time quality paradigm using MTConnect is feasible, assuming that all necessary on-machine inspection data is available, and if not, was it possible to fill in the missing pieces and to guarantee that QMResults is complete and consistent with the functional measurement constraints of machine inspection. The implementation scope was end-to-end – from on-machine part inspection to Web-based client access of the measurement results, including implementations for all the subsystems.

Section 2 of the paper describes related inspection and quality reporting standards and methodologies. In section 3, a background on QMResults information model is presented. Section 4 describes the implementation of the Web-based real-time quality data at NIST on a shop floor machine tool. Section 5 discusses the benefits of Web-based real-time quality data, as well as the problems encountered developing on-machine QMResults quality feedback and the future work envisioned in this area.

## 2. Related Work

Inspection process planning is an integral part of design and manufacturing activities. It determines what characteristics of a product are to be inspected, where and when. With the continued growth of product complexity and variety and the constant demand of reducing product development cycle, industries are in search of more automated inspection process planning for measurement operations and better decision support tools. Determination of the features to inspect is an ongoing research topic. Of interest in our work is the use of standards to facilitate interoperable quality information exchange.

To assess the quality, an actual machined part is measured and Geometric Dimensioning and Tolerancing (GD&T) characteristics are assessed by comparing the nominal values and their actual values. Good parts maintain a fit and form within the specified GD&T tolerance limits. Tolerancing is widely used in industry to define the allowable variation of discrete parts from their ideal shape [5–7]. Today, symbols to represent GD&T tolerances on a part drawing have been standardized under different standards organizations [8–10]. The standard GD&T symbols provide a means for specifying the shape requirements of, and the interrelationships between, part features. Although automated inspection using GD&T technology has become commonplace, the solutions for the planning, programming, and reporting of measuring data is still vendor specific, and as a result interoperability and quality results portability suffers. There has been some work in industry and academia to rectify this shortcoming.

ISO 10303, commonly known as the STandard for the Exchange of Product model data, or STEP [11], offers an attractive option for standardizing quality and inspection data within the manufacturing CAX process chain. Within the ISO standardization effort, STEP AP 219 was defined to cover all important metrology information, including, but not limited to, measurement results [12]. The latest ISO standard version of AP 219 defines only measurement results information. Ali et al [13] introduces a STEP compliant inspection framework to establish standardized measuring and inspection across the total CAX chain. ISO 14649 and STEP AP238, known as STEP-NC, are the set of STEP standards for machining and related activities and the opportunity to add inspection within STEP-NC is appealing [14–16]. Brecher et al [17] discuss the draft ISO 14649 part 16 standard, which introduces the integration of measuring technology into the STEP-NC-based process chain, so that results of the manufacturing quality process can be fed back into the planning process. Zhao et al [18–20] have studied the use of STEP and extending STEP-NC to

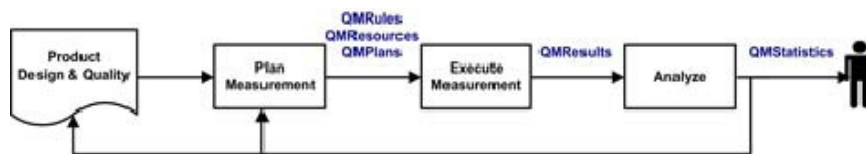


Fig. 1 Quality Information Framework Overview

be an all-encompassing approach for on-machine inspections as well as other aspects of integrating quality and machining. Although the STEP paradigm is popular in academia, STEP-NC and STEP AP238 have found limited success in manufacturing due to the lack of industry support.

The use of quality standards has many proponents in industry who realize the excessive cost and waste from having multiple incompatible solutions. Quality information models described in eXtensible Markup Language (XML) schemas has been developed with the intention to solve interoperability issues among different quality systems. However, those information models only focused on specific areas of inspection and resulted in different and incompatible models to describe quality data. First, Dimensional Markup Language (DML) [21] is a standard developed to represent quality measurement results data in XML format. It was created to transport single part measurement data. Next, Quality Measurement Data (QMD) [22] was developed to handle all types of quality measurement data (not just dimensional) data for statistical process control. Unfortunately, information overlapping and inconsistencies between the two information models prevented interoperability and in fact the variation of feature and characteristic models increased overall complexity.

In recognition of the impact and larger presence of the Information Technology (IT) world and understanding that XML has become the de facto Internet specification language, the Quality Information Framework (QIF) is a standardization effort aimed at producing an all-inclusive set of quality measurement XML specifications required in manufacturing systems [23]. QIF standards sponsored by the Dimensional Metrology Standards Consortium (DMSC) will allow users to assemble interoperable quality software systems in their plants using solutions from multiple vendors. QIF consists of a set of five standards to address the major facets of manufacturing quality systems namely: QMPlans, QMRules, QMRResources, QMStatistics, and QMResults. Figure 1 shows the relationship of these five standards.

1. **Product Design and Quality** – define the part quality metrics by identifying features critical to fit

and function. The output is a list of features associated with tolerances and datum.

2. **Plan Measurement** – uses the features and the corresponding characteristic tolerances to assign nominal measurement points for the inspection device to probe (number and location of feature points to measure) based on type of feature and the specific characteristic tolerance.
3. **Execute Measurement** – performs the part inspection, in which the actual measurement points are saved, with each actual point corresponding to the planned nominal points.
4. **Analyze and Report** – compares the measured dimensions to the nominal dimensions and based on the allowed tolerance will report the nature of the errors, sometimes over multiple parts, associated with each measured feature.

Within QIF, QMResults is the standard that was developed to model quality measurement results information. It consists of information about parts, features, characteristics, and inspection results data. QMResults contains digital (computer-readable) definitions for all GD&T elements within the ASME Y14.5 standard. QMResults provides a mechanism to record measurement data generated from one or more inspections. Elements include but are not limited to Assembly Information, Part Information, Features, Characteristics, Nominal Data, Actual Data along with Traceability information that is collected during the inspection process such as Operator ID, and Inspection Environment attributes.

QMResults represents parts as collections of manufacturable knowledge, which includes design, manufacturing, and inspection data. For example, a hole can be expressed with geometric design data for the hole location, diameter, and depth. A hole can also be associated with GD&T data to ascribe the tolerance of the hole location, diameter, and depth as well as relationships to other features. The two primary QMResults modeling concepts of interest for our Web-based real-time quality feedback include:

- **Features** – for quality, features are defined to be parametric shapes associated with attributes such as intrinsic geometric parameters (length, width, depth, etc.), position and orientation, geometric tolerances,

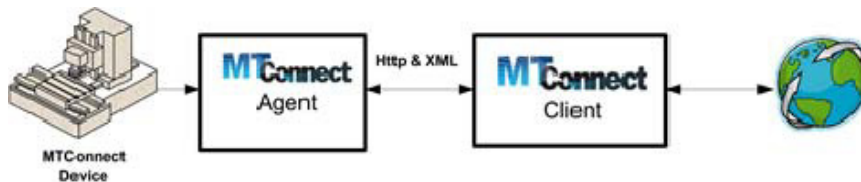


Fig. 2 MTConnect Overview

material properties, and references to other features [24].

- **Characteristic** – an attribute of a material, process, or part (includes assemblies) whose variation within the specified tolerance has a significant influence on product fit, performance, service life, or manufacturability.

### 3. Prototype Implementation

Integration of factory floor CNC information has been difficult, if not impossible, as traditionally, factory floor equipment have been “Islands of Automation.” Closed architecture machine tools make the gathering of production knowledge difficult. Further, it is difficult to improve systems if they cannot be accurately measured and quantitatively characterized. In order to reduce costs, increase interoperability, and maximize enterprise integration, the MTConnect standards have been developed to “open” machine tools and factory floor devices for the manufacturing industry. MTConnect is based upon prevalent Web technology including XML and Hypertext Transfer Protocol (HTTP). Using prevailing technology and providing free software development kits minimizes technical and economic barriers to MTConnect adoption.

Figure 2 shows the high-level system architecture of the MTConnect standard. An “MTConnect Device” is a piece of equipment organized as a set of components that provide data. The core of MTConnect is the “Agent”, which is a process that acts as a “bridge” between a factory device and a “Client Application”. The MTConnect Agent receives and stores single or a time series of data samples or events that are made available to the Client Application. An MTConnect sample is the value of a continuous data item at a point in time. An MTConnect event describes an asynchronous change in state. Web-enabled refers to content that can be accessed via the Internet and uses http for communication. In order to realize real-time quality data, the use of the Internet is important for several reasons, including its distributed architecture, world-wide accessibility, and reliance on open standards. Since MTConnect leverages the software and hardware Internet paradigm, and

because of the systemic prevalence of the Internet, there is an abundance of tools to ease MTConnect deployment.

MTConnect has the ability to incorporate and transport standardized XML data developed independently from the core MTConnect information models. In this case, MTConnect defines “assets”, which use an associative array of key/value stores to store the XML [25]. This allows the ability to collect and report entire XML documents as they change within applications. Below, the XML shows how an AssetChanged tag with an asset type Part and INSPECTION value that would be updated within the MTConnect XML query to indicate new quality results from an inspection.

---

```
<AssetChangeddataItemId="dev_asset_chg"
timestamp="2011-09-08T19:42:16.855924Z"sequence="46"
assetType="Part">INSPECTION</AssetChanged>
```

---

For our implementation, the QMResults XML Schema was used to develop the the XML that is then accessible via the Internet with the following query to an MTConnect agent:

---

```
http://xxx.xxx.xxx.xxx/asset/INSPECTION?type=Part
```

---

where xxx.xxx.xxx.xxx is the IP address of the MTConnect server and which returns an QMResults XML “web page”, outlined by the following snippet of QMResults:

---

```
<Part timestamp="2011-07-25T13:55:22" assetId="INSPECTION">
<Inspection><!--thisisthestartoftheQMResultsspecification-->
  <MeasurementResults>
  ...
  </MeasurementResults>
</Inspection>
</Part>
```

---

Figure 3 shows the system architecture of the various components that were used to implement the Web-enabled, real-time quality feedback. The implementation used a machine tool located in the NIST machine shop that also has a multi-directional (3D) touch-trigger probe

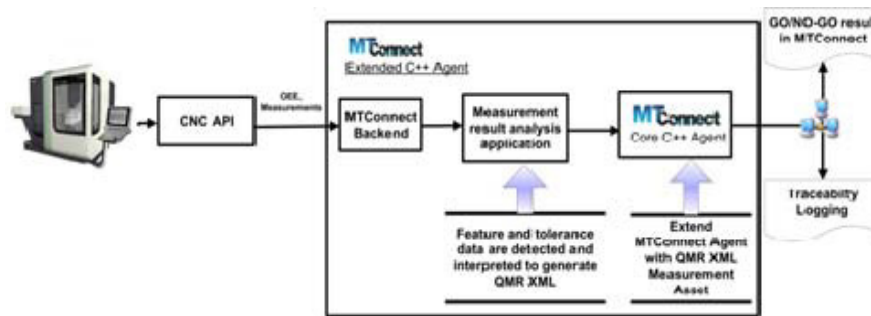


Fig. 3 Implementation Architecture

to perform the part inspections. The CNC provides measuring canned cycles for various part features (i.e., point, hole, shaft, slot, inside/outside rectangle, boss, and surface) and characteristics (e.g., position, diameter, straightness). For each measuring cycle, the inputs include a nominal setpoint value, an inspection characteristic, and upper and lower tolerance limits as measurement parameters. For example, to measure a hole, the center of a hole is set as reference setpoint. The probe is then positioned at approximately the center of the hole and measuring depth. The measurement cycle moves the probe to sample four points on the inner surface of the hole. After the probing, the CNC outputs the actual measured feature value, and the dimensional differences.

To enable Web-enabled, real-time feedback, the CNC was connected to the Internet via MTConnect technology. The MTConnect Institute provides an open-source C++ Agent implementation that was used to integrate the various software components. An MTConnect Back-end adapter was embedded within the Agent to communicate with the CNC to retrieve measurement results. In our case, this CNC communication was done using OPC [26], but it could be any open-architecture communication technology, or indeed, proprietary interfaces for which there is a software development kit. The MTConnect Back-end used synchronous communication to cyclically read the status of the CNC variables in order to update the MTConnect data. The MTConnect Back-end also sampled measurement-related variables based on detection of the execution of a measurement cycle. There are two strategies for achieving this.

1. Canned Cycle Detect – (1) Wait for a measurement canned cycle block in the running part program, (2) Read the cycle parameters, (3) Wait until the canned cycle has completed (detect a new program block), and (4) Read the latched x,y,z measurement values.
2. Subroutine Detect – (1) Use a special Cylinder Probe 840D subroutine with all the feature and tolerance

information passed in as parameters and (2) Repeat the same as above in Canned Cycle Detect, but with more feature/probing knowledge available to be read from the subroutine calling parameters.

The additional canned cycle with richer quality-related content would clearly be preferable, but may be impractical in the real world. Manufacturers would be required to adopt this canned cycle into their Computer-Aided Design (CAD)/ Computer-Aided Manufacturing (CAM) and machine tool post processors, which is a major undertaking. For our purposes, to detect a hole measurement, the MTConnect Back-end monitored the current CNC executing block for the occurrence of a measuring cycle, e.g., matching “CYCLE977”. This block matching was possible since the probing cycles are slow enough for detection. Upon completion of the measurement cycle, the input and output measurement variables are read.

A software module was written to interpret the CNC measurement variables and translate the data into QMResults XML representation. XML has many industry software tools to help parse it into a Document Object Model (DOM) that renders the XML into a navigable tree of elements, attributes, and child elements. DOM is powerful, especially when combined with the XML Path Language (XPath), which is a query language for selecting nodes from an XML document. However, although the DOM approach is powerful in reading XML, it is time-consuming in generating XML as it requires hard-coding the XML output.

In lieu of XML DOM hand coding, the implementation used XML schema (XSD) to native language code generation tools to simplify the software development. Our implementation relies heavily on XML serialization and deserialization that was based on an QMResults XSD mapping to native language data structures. Deserialization means reading the XML and then mapping it into a native language (e.g., C++/C#) data structures. Serialization takes the native source representation and produces an XML in output stream.

Date	Part	Characteristic	Feature	Status	Target	Actual	Lower Tolerance	Upper Tolerance	Error
9/13/2011 13:27:52		DiameterCharacteristicInstance	CrkMeasurement5283	GO	44.0000	44.0002	44.0000	44.0000	0.0002
9/13/2011 14:27:53		DiameterCharacteristicInstance	CrkMeasurement5284	GO	44.0000	44.0004	44.0000	44.0000	0.0004
9/13/2011 15:27:55		DiameterCharacteristicInstance	CrkMeasurement5285	Fail	44.0000	43.9996	44.0000	44.0000	0.0004
9/13/2011 16:27:55		DiameterCharacteristicInstance	CrkMeasurement5286	Fail	44.0000	43.9988	44.0000	44.0000	0.0012

Fig. 4 QMResults Client Sample Display

The code generation is quite efficient and we developed software to interpret the quality data results into native C++ data structures and then into XML. The generated code can also provide the capability to use XPATH and the native XML DOM representation. XPATH was useful searching the QMResults XML for unique “pointer-like” attribute identifiers, which are used by various QMResults feature and character constructs as references to associated data.

Data visualization of quality results in a time-line fashion can help analyze and compare the data to the expected outcome. Intuitive and useful visualization of Web-enabled real-time quality results would help in understanding the association between quality events and production, and form the basis for a more immediate responsiveness to problems. Equally as important an outcome of Web-enabled real-time quality, is the simplification for archiving the data with mainstream IT tools. In this manner, traceability and reporting can be accomplished, in turn will allow more sophisticated analysis, such as statistical process control (SPC), discrete event simulation, and data mining.

Figure 4 shows a simple display interpreting the ongoing quality results from a machine tool that is repeatedly inspecting two features on an identical part. In general, clients can simply use XML DOM and XPATH to parse the relevant XML which provides a lightweight but powerful programming paradigm. The client software is a C# application that monitors for new inspection results by reading the XML returned from the MTConnect Agent at its given IP address. The client application integrates Excel automation to build a worksheet of graphical pass/fail/caution inspection results.

The user is given quality results on-line that are continuously being updated. By dealing with quality issues as they occur as opposed to after the fact, parts can be rejected right after being identified as defect(s) in the production process. A significant amount of time and money can be saved harnessing the power of immediacy in the production process.

#### 4. Discussion

In this paper, we discussed the use of MTConnect to realize Web-enabled, real-time QMResults output results. We presented a summary of QMResults, which is a XML standardization effort aimed at improving Computer-Aided Quality operations. The availability of standards such as MTConnect and QMResults holds the promise of time saving and more efficient production while also reducing data quality losses, including data misinterpretation. Further, the use of MTConnect eases the integration of quality results into a production processes with its use of XML and Internet communication Web technologies. Now with real-time QMResults available, identifying variability in production processes is simpler, so that a complete, proactive approach to quality assurance can be undertaken, as opposed to a legacy approach of reactive quality control and part rejection.

An XML Web-based quality feedback system will help improve production. If manual inspection exists, replacement of reporting by the automated MTConnect recording system will lead to easier and more complete tracking of quality data while reducing the frequency of reporting errors. Moreover, with an automated process, operators are able to spend less time on non-value added reporting activities and more on productivity-oriented tasks. Integration of realtime inspections using a common QMResults format will help eliminate inconsistencies and errors and is critical to providing accurate, measurable and actionable quality data. For instance, capturing the entire quality history of a production shift in a standard XML format should allow for easier integration and interpretation. Recording of other related machining activities as well as the quality data can then be used for statistical process control, trend analysis, data mining, and business intelligence.

There are a number of issues related to the real-time quality feedback from a machine tool. Although the advantages of in-process measurement are obvious, it is not a trivial task to accomplish a good measurement within manufacturing processes. One reason for this is

the assorted physical constraints such as the presence of chips or coolant which obscure a location that needs to be inspected. Another issue of concern is the validity of performing dimensional measurement on the same machine that makes the part. While measurements performed by a cutting machine are subject to some of the same error producing factors as the cutting progress, the errors that are most difficult to eliminate through machine maintenance and certification can easily be detected and accounted for with in-process measurement. For example, machine flexing, tool wear, and vibration will all be absent during measurement. Additional error compensation techniques such as laser measurement, ball-screw compensation, and measuring pre-cut proofing parts for future reference can also be applied to compensate for other machine inaccuracies. The ability to rectify manufacturing errors caused by problems such as these has led to the acceptance of in-process measurement as part of a manufacturing system.

Several aspects of the pilot implementation suggest the need for future research. On-machine measuring knowledge provides an incomplete picture of inspection planning and feature models, and a more holistic approach, such as found in QMResults, would be preferable for representing knowledge in the measuring canned cycles. An industry effort to standardize this canned cycle measuring knowledge could make it happen. Further, since on-machine real-time quality assessment is rare, this is a great opportunity to exploit MTConnect capabilities for integrating sensors and other production knowledge, so that process elements such as ambient temperature, humidity, operator, spindle life can be directly correlated and measured against part quality.

In summary, despite the advances in information and communications technologies, it is still difficult to achieve manufacturing information interoperability [27]. The necessary levels of flexibility, efficiency, and responsiveness can only be achieved if standard information technology, such as XML and QMResults, can be melded into manufacturing processes, so that barriers to the integration are removed. Only then can the proactive use of quality information in manufacturing production be feasible and cost-effective.

### Disclaimer

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