Proceedings of the ASME 2012 International Manufacturing Science and Engineering Conference
MSEC2012
June 4-8, 2012, Notre Dame, Indiana, USA

MSEC2012-7344

STATISTICAL PROCESS MONITORING WITH MTCONNECT

Sri Atluru
University of Cincinnati
Cincinnati, OH, USA

Amit Deshpande
TechSolve Inc.
Cincinnati, OH, USA

ABSTRACT

Statistical Process Control (SPC) techniques are used widely in the manufacturing industry. However, it is sometimes observed that a deviation that is within the acceptable range of inherent process variation does not necessarily conform to specifications. This is especially true in the case of low volume; high precision manufacturing that is customary in aerospace and defense industries.

In order to study the limitations posed by conventional SPC techniques in such manufacturing environments, a study was undertaken at TechSolve Inc., Cincinnati to develop a standalone SPC tool. The SPC tool so developed effectively communicates with an on-machine probe and analyzes the collected data to carry out a statistical analysis. MTConnect, a new-generation machine tool communications protocol, was used in developing the communication interfaces with the on-machine probe on a Computer Numerical Control (CNC) machine. The XML (eXtensible Markup Language) code used to extend the MTConnect schema to include the data obtained from the probing routines is also presented.

The statistical analysis was developed as a Graphical User Interface (GUI) in LabVIEW. The statistical analysis was carried out as a case study by producing a widget. Real machining was carried out to produce 48 of these widgets using a combination of end mills and face mills. The data obtained during the subsequent quality testing was used to carry out the statistical analysis.

The limitations of conventional SPC techniques during the developmental and analytical phases of the study are discussed. The presence of a chip during an on machine probing routine, the variations due to disparities in tool macro geometry, and the demand for conformance to requirements are studied in the view of a statistical process monitoring standpoint. Various alternatives are also discussed that aim to correct and improve the quality of machined parts in these scenarios.

INTRODUCTION

Quality is quintessential to the success of every organization. The most popular way to study and analyze the quality in an organization is through the use of a set of statistical tools. The correct application of these tools in a manufacturing scenario is fundamental to good process management and reduces process variation.

The American Society of Quality defines quality as a subjective term for which each person has his or her own definition. Prominent professionals in the field of Quality have defined it as fitness for use (Juran) and conformance to requirements (Crosby) [Summers 2006]. However, in the current scenario, quality has been concentrated solely upon process improvement and reduction in process variation by way of statistical analysis.

This paper examines the limitations of relying exclusively on commercial Statistical Process Control (SPC) methods, and aims at providing alternatives and making improvements that would aid in improving quality in a manufacturing environment. The propositions are tested on the manufacturing shop floor and a case study is presented. Specific tools were developed in conjunction with MTConnect, a manufacturing data communications protocol. A detailed approach on the development of these tools to aid in the statistical monitoring on the shop floor is presented and discussed.

BACKGROUND

The Smart Machine Program Initiative (SMPI) was established with the aim of improving the productivity in manufacturing processes and delivering a high quality product in low cycle times. The supervisory system is one of the thrust areas of the SMPI program that addresses the need for an encompassing system that would automatically coordinate between manufacturing activities and technologies to achieve the *First Part Correct* philosophy.

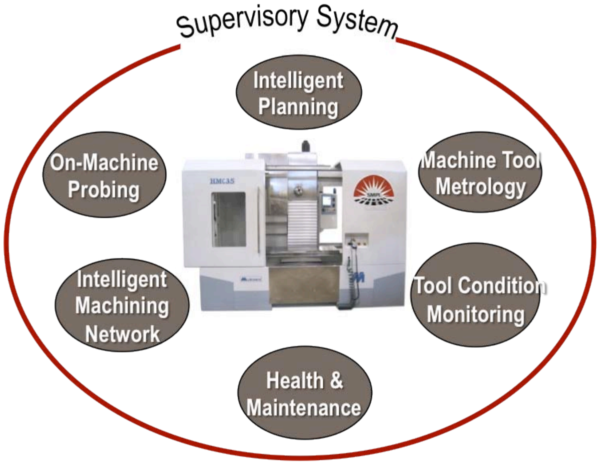

Figure 1: Smart Machine and its thrust areas

The supervisory system needs to ensure that a high quality product is delivered from the machine. To achieve this, it coordinates with one of the SMPI thrust area, namely On Machine Probing, and make use of statistical analysis techniques to determine the quality and control variation with in the process.

Coordinate measuring machines and on machine probing are being extensively used in the inspection of mechanical components for statistical process and quality control to assess trends in manufacturing processes [Dowling et al. 1997]. Research in academia and industry has been directed towards various statistical issues and methods used to determine geometric features during inspection with Coordinate Measuring Machines (CMM) [Dowling et al. 1995]. Though statistical analysis of data has been predominantly used for subsequent analysis of the process, it is acknowledged that for certain manufacturing environments, like short production runs, it becomes necessary to refine traditional statistical methodologies to suit the requirements of the shop floor [Wasserman et al. 1994].

Variations to traditional SPC methods by means of data transformations have also been discussed through the introduction of the Q-statistic [Quesenberry et al. 1991] and its improvements [Del Castillo et al. 1994]. This is due to the fact that in short production runs, traditional SPC methodologies that are constructed on the basis of within-subgroup variability, measured after the process has been set up, adjusted, and brought into statistical control; do not recognize the ongoing volatility in the sequences of setups and production runs [Kim et al. 2000]. It is also very important that we need to understand how parts are out of tolerance and why they have been signaled as a special cause of variation; and simply not whether they have been accepted or rejected [El Maraghy et al. 1990].

STATISTICAL PROCESS CONTROL

Statistical Process Control (SPC) has evolved out of traditional quality control methods. It aims at preventing poor quality rather than putting an emphasis on the inspection and detection of poor quality subsequent to manufacturing. The most significant difference between traditional quality control approaches and modern day SPC methods is that the process is monitored, controlled and adjusted in latter while the former deals with the monitoring of the product.

There are a number of advantages for using statistical process monitoring. Some of the main advantages are (and not limited to):

1. Helps to interpret the consistency and variability associated with a process.
2. Helps in identifying patterns and preventing scrap
3. Ability to inspect for changes in features is viable
4. Ability to make decisions based on statistical process patterns is feasible

SPC uses certain process performance indicators and statistical methods to monitor for changes that might affect the quality of the product and adjust the process accordingly. The control charts are the basis for every performance analysis done by SPC methods. They form the economic basis for making decisions concerning the produced parts. They also help to provide a statistical basis on which to formulate the improvement actions that need to be taken. Some of the popular performance indicators on the control charts are *Out of Control*, *Trending*, *Shifting*, etc. These performance indicators are explained below.

Out of Control: A process is said to be under control, or in a state of control, when the performance of the process falls within the statistically calculated control limits. The control limits are calculated based on $\pm 3\sigma$, which describe the spread of the process. There have been various kinds of control charts being used in day-to-day quality management methods, depending on the economic control of quality to be accomplished.

Trending: This is a performance indicator that is observed when the control points show a steady and progressive change in the location where the data is centered on the chart. The key to identifying a trend is to recognize that the control points show a steady increasing or decreasing movement from one level of the chart to another.

Shifting: This is another SPC performance indicator that is also similar to trending, but with the exception that shifting is a result of control points being accumulated on one particular side of the mean due to presence of a bias. Some of the commonly used rules to detect patterns in SPC are the Western Electric rules and the Nelson rules.

Process Capability: This is a concept used within quality control that determines the ability of a process to produce parts that meet the specifications laid out in the requirement. It must be understood that while there might be inconsistent variation exhibited by the control charts, the process might still be capable of meeting the requirements of the customer.

MTCONNECT

MTConnect is a manufacturing communications standard developed at the University of California, Berkeley, with the support of The Association of Manufacturing Technology (AMT). It aims to providing the standard through which communication can be established among various control systems within the hierarchy of a manufacturing process. MTConnect makes use of eXtensible Markup Language (XML) to create a tag based communication network between component control systems.

MTConnect was implemented at TechSolve Inc for a Milltronics HMC 35 with a Fanuc Oi-mc controller [Atluru et al. 2009]. A smart energy monitor based on MTConnect is also implemented to study the effective energy consumption during discrete part production. [Deshpande et al. 2011] The data collection methods using MTConnect compared very favorably with traditional methods used on legacy machines [Deshpande et al. 2011].

AUTOMATING SPC FOR MANUFACTURING

While CMM's and more lately, on-machine probes are being used regularly to maintain quality standards in manufacturing environments, there is a need for automating the data collection and processing for statistical quality monitoring.

Current approach and limitations: The current statistical quality monitoring approaches employed in manufacturing often relate to the use of a commercially available CMM software, such as PC-DMIS, to capture and process the data obtained from a CMM or an on-machine probe.

The CMM software is used to develop the probing routines for the required features to be monitored. These probing routines are then transferred as CNC sub-programs to the machine. The data generated during these probing cycles is stored within the macro-variables on the controller, which are obtained back by the CMM software and displayed to the operator or the user. The data obtained by the CMM software is often displayed directly to the user. File support for storing this data is given in Windows-compatible formats (Excel or Access). Often, the ability of the CMM software to conduct statistical monitoring based on the data obtained is given as a separate feature that needs to purchased as an add-on to the CMM software.

The use of this conventional approach for SPC monitoring (by using commercially available CMM software) has the following limitations.

1. There is a need for heavy investment in commercial CMM software and its add-on packages
2. Manual execution is required to compute feature compliance for each manufacturing run
3. Manual supervision is also necessary to monitor and detect patterns
4. Most importantly, there is no real-time supervisory control to check for discrepancies in the probing routines (probe accidents), machined surfaces (presence of chip on machined surface), or to take responsive action in the event of the occurrence of a quality-deriding indicator.

Proposed approach and advantages: To overcome the limitations of the current approach of using CMM software, it is proposed to develop a probing application in-house, capable of

- Capturing probing data from the machine
- Converting probing data into relevant measurements about the concerned feature
- Monitoring the process statistically, using the individual measurements obtained
- Having the ability to detect patterns in the statistical process monitoring without manual intervention
- Identifying possible causes for 'out of control' process, and
- Take responsive action, if possible.

The advantages of using in-house developed CMM software are numerous. There is no manual intervention required to process the data obtained from the CMM or the on-machine probe. Additionally, the use of MTConnect in obtaining probing data ensures plug-and-play connectivity across various CNC machines and the organizational hierarchy. Automated SPC approach also means that the in-house developed CMM software is capable of automatic detection of process patterns, and more importantly, also be capable of taking appropriate adaptive actions, as necessary.

CASE STUDY

To study the implications of using automated SPC on the manufacturing shop floor, a case study was modeled on a 'bore and boss' widget. The design of the widget is shown below.

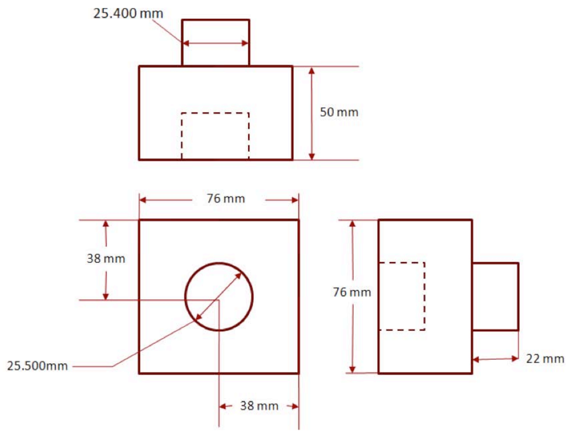

Figure 2 : Design of Widget used in case study

The process plan to cut the widget from the stock piece incorporates the common milling procedures like face milling, end milling and drilling to create a bore and boss interface on the roughed surfaces. 48 parts were machined for the purpose of analysis, using a face mill and an end mill on a stock piece. Every part was subsequently subjected to quality testing using On Machine Probing (OMP).

Figure 3 : Picture showing the machining of widget

OMP uses commercially available technologies like PC-DMIS to generate the appropriate probing routines and subsequently determine the circularity of the boss and the bore directly on the machine. It eliminates the need to move the part from the CNC to the CMM thereby reducing the time and effort required for traditional quality inspection using a CMM.

DEVELOPING STATISTICAL PROCESS MONITORING SOFTWARE

As an alternative to commercial CMM software, a MTConnect based Statistical Process Monitoring application was developed to replicate the functionality achieved through using technologies like PC-DMIS. The MTConnect based application obtains the data from an on-machine probe by the use of MTConnect schema and computes the radius of the boss and the bore features on the widget. Some of the important approaches used, in the development of the MTConnect based Statistical Process Monitoring application, are discussed below.

Using MTConnect to obtain data: The use of MTConnect as a communication protocol enables the easy parsing of X-, Y-, and Z-coordinates of the probe. The X-, Y-, and Z- coordinates of the probe, so obtained, can subsequently be used to determine key quality indicators on the machined part. The probe coordinates were custom-defined as Xp, Yp, and Zp tags in the MTConnect schema, which refer to the X-, Y-, and Z-coordinates of the probe respectively.

The data to these custom XML tags is obtained from the macro-variables in the controller. These are the same macro-variables that are setup to store the X-,Y-, and Z-coordinates of the commercial probing systems. This is done in order to ensure a foolproof fail back mechanism in the case of any eventuality arising out of the in-house developed MTConnect application. Additionally, the use of the same macro-variables also ensures that simultaneous computing can be done with commercial CMM software (PC-DMIS). This can be used to validate the approach adopted during the in-house development.

All changes in Xp, Yp, and Zp, are monitored through MTConnect and recorded. The appropriate values of Xp, Yp, and Zp, are subsequently extracted from the recorded set for computational purposes during process monitoring.

Calculating radius of boss/bore: The radius of the geometric feature was determined by using the orthogonal least squares curve fitting method on a 2-dimensional plane. The least squares algorithm is deemed to be more accurate than other methods like minimum zone method [Dowling et al. 1995]. A sample of 8 points was taken to compute the radius. It is generally agreed that in practice, a sample size of 4-8 points is necessary to fit a circle feature to accommodate for machine drift and measurement time [Dowling et al. 1997].

```
- <MTConnectDevices xsi:schemaLocation="urn:mtconnect.com:MTConnectDevices:1.0 http://www.mtconnect.org/schemas/MTConnectDevices.xsd">
    <Header creationTime="2010-04-19T17:31:45" sender="localhost" instanceId="1270662751" bufferSize="131072" version="1.0"/>
  - <Devices>
    - <Device id="d4" iso841Class="6" name="Testbed" sampleRate="10" uuid="000">
        <Description manufacturer="Milltronics"/>
      + <DataItems></DataItems>
      - <Components>
        - <Axes id="d5" name="Axes">
          + <DataItems></DataItems>
          - <Components>
            + <Spindle id="d10" name="S"></Spindle>
            - <Linear id="d7" name="X">
              - <DataItems>
                  <DataItem category="SAMPLE" id="xp15" name="Xp" nativeUnits="MILLIMETER" subType="PROBE" type="POSITION" units="MILLIMETER"/>
                  <DataItem category="SAMPLE" id="x14" name="Xact" nativeUnits="MILLIMETER" subType="ACTUAL" type="POSITION" units="MILLIMETER"/>
                  <DataItem category="SAMPLE" id="x15" name="Xload" nativeUnits="PERCENT" type="LOAD" units="PERCENT"/>
                </DataItems>
              </Linear>
```

Figure 4 : XML code used to extend MTConnect Schema to include Probing Data

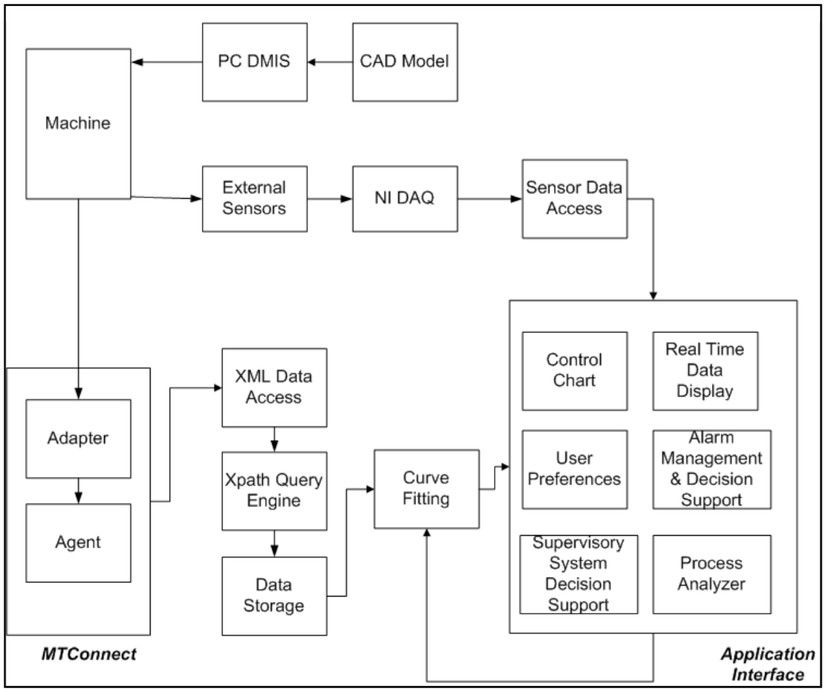

Figure 5 : Flowchart detailing data flow of the SPC application

Compensating probe radius: It must be understood that the probe reports only the center location of the probe sphere but not the actual contact point of the probe with the surface. The reported probing point is then obtained by adding the radius of the probe to the coordinates of the center location reported by the probe. By using this method to determine the contact point of the probe, it is assumed that there is no measurement error (cosine error) associated by the difference between the actual contact point and the reported contact point of the probe.

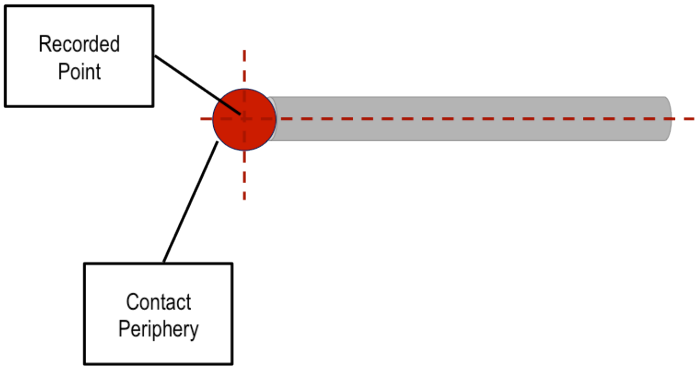

Figure 6 : Figure showing compensation of probe radius

Conventional SPC definitions used: The following definitions were used in the developed of the MTConnect based application.

- Out of Control Process – Point falls beyond the control zone.
- Shifting – 10 out of 12 consecutive points fall on the same side of the Center Line.
- Trending – 5 out of 7 consecutive points show an increasing or decreasing trend over the previous point.

Validating in-house approach against commercial CMM software: To determine the accuracy of the MTConnect based application in obtaining and computing the probe contact points and radius, the raw values and the calculated values were compared with those obtained through using PC-DMIS. The input values and calculated results obtained by the MTConnect based application were exactly similar to the values and results output by PC-DMIS. This was observed in all the 48 cases. The diameter resolution (up to 0.1 micron) is the same in both the applications.

As the number of parts being analyzed is too small to form traditional $\overline{X}$ and R charts, an individuals and moving range chart (based on the first 10 samples obtained) is used to analyze the results obtained. The MTconnect application is capable of flagging and reporting 'Out of Control Zone' points. 'Shifting' and 'Trending' patterns are identified and first point of shift/trend is also reported. The 'Process capability' is also monitored and a monitored product is reported as scrap in case of an out of specifications part being identified.

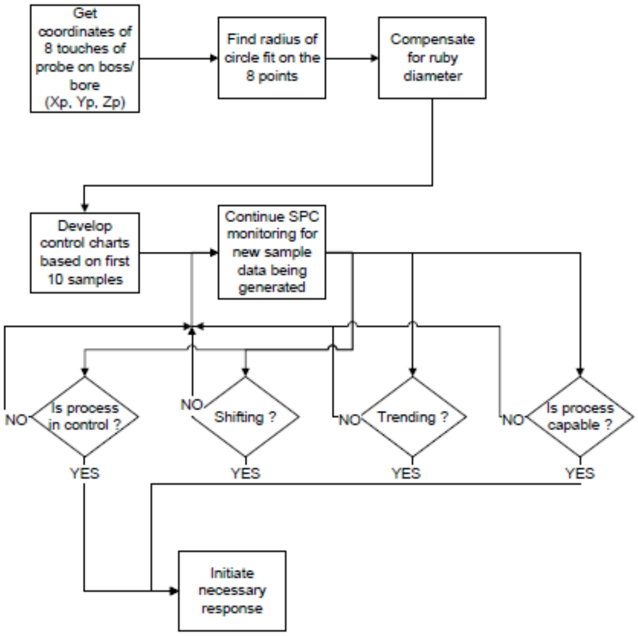

Figure 7 : Flowchart showing architecture of SPC system

DISCUSSION - LIMITATIONS

There were significant limitations observed during using an automated SPC approach to control quality on the manufacturing shop floor. Most of these limitations are concerned about the practicality of using traditional SPC methods in a manufacturing environment. The practical limitations are discussed below.

Presence of Chip: One of the foremost limitation of using an automated SPC approach was the failure to detect an outlier in reported contact points of the probe, thereby leading to distorted calculations and the improper flagging of a part as 'inaccurate' or 'bad'. This is usually due the fact that the presence of a chip on the part might lead to the inaccurate reporting of one of the contact points of the probe. This in turn leads to a distorted fitting on the reported contact points and hence the corresponding radius of the fitted circle leads to improper flagging of a part as a 'bad part'

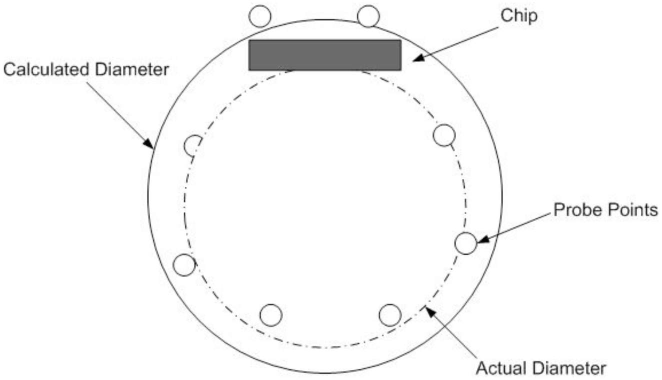

Figure 8 : Effect of chip presence

Tool Macro-geometry: It is also to be noted that certain patterns observed in the control charts, namely, trending and shifting are inherent to manufacturing process. While trending can be attributed to a number of avoidable factors like a slowly loosening work holding device, a gradual deterioration of machine equipment, it is also majorly attributed to tool wear. Tool wear is an accepted and unavoidable cause of variation within the manufacturing process and hence, it becomes imperative that trending is an acceptable pattern in the control charts.

Similarly, it was observed that shifting occurs as a result of tool change. While the technical specifications of a new tool might be the same as those attributed to the worn tool, there is an difference in the macro geometry of the tool that introduces a prolonged bias into the process being monitored. It was observed that this bias was being introduced into the control chart of the case study after every tool change.

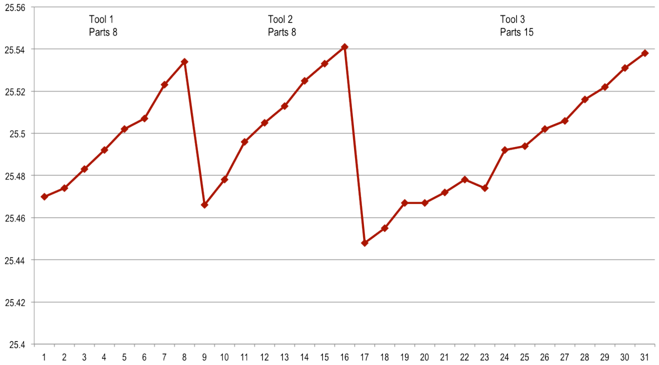

Figure 9 : Trending observed as a result of tool wear

Boss and Bore mismatch: The most important limitation observed by the use of automated SPC in determining the quality is that the computed circularity of the boss and the bore does not guarantee a conformance to requirements, wherein the requirement being that the boss should fit snuggly into the bore.

This observation can be associated with the three lobed defect often referred in academic research [Caskey et al., 1990]. This can be understood by the fact that though a circle is fitted onto a set of 8 probe contact points, there might be a significant difference in the circularity of the points set. This might lead to form differences where in the form of the boss would not fit into the form of the bore. This was observed in almost all the 48 widgets manufactured during the case study.

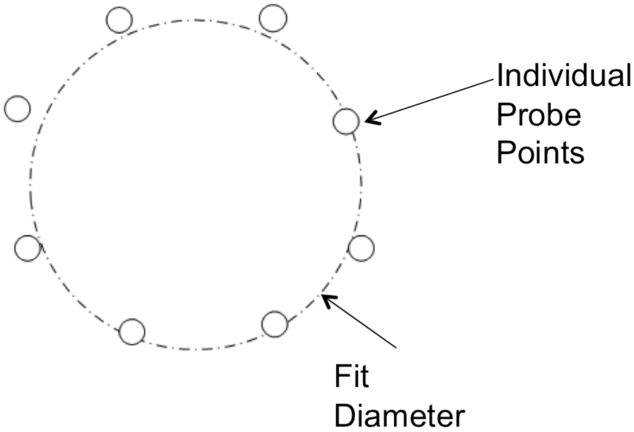

Figure 10 : Circularity determined as a best fit diameter

REVISED APPROACH

The following alternatives are proposed to counter the limitations of using traditional SPC methods in a manufacturing environment.

To counter the effect of an outlier on the overall circle fitting algorithm, the following methodology is proposed. The outlier is identified by studying the 8 probe contact points on an individual basis and is identified as the probe contact point that has the maximum influence on the fitting algorithm. This point is flagged as an outlier and eliminated from the set of probe contact points and the fitting algorithm is used once again on the remaining 7 probe contact points to determine the radius. This has proved to be highly beneficial as it helps in identifying parts that have been incorrectly flagged as 'bad part' due to the presence of a chip during the OMP process.

While accepting that trending and shifting are inherent to the manufacturing process, the MTConnect based application was revised to notify the machine operator about the need to change the worn tool based on the trending patterns observed. Similarly, shifting in the manufacturing process was accounted for opting for a variable control chart with variable control limits based on the difference in the nominal mean.

The 'three lobed defect' on the form feature is the main reason for a non-conformance to requirements in the widgets being produced. To ensure a high degree of conformance, the fitting algorithms is also used to determine the maximum inscribed circle and the minimum circumscribed circle on the set of probe contact points. A simple rule of thumb for the boss to fit snuggly into the bore would be to ensure that the radius of the minimum circumscribed circle of the boss is less than the radius of the maximum inscribed circle of the bore.

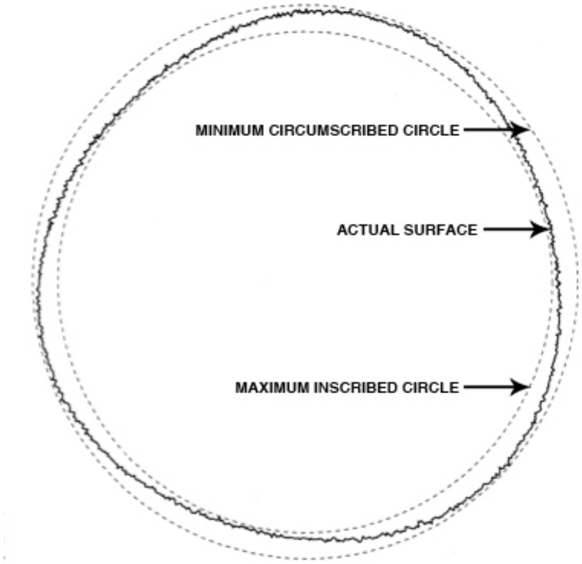

Figure 11 : Minimum Circumscribed Circle and Maximum Incribed Circle

REVISED GUI

The revised approach discussed above was implemented into the existing MTConnect based application. The revised GUI is shown below.

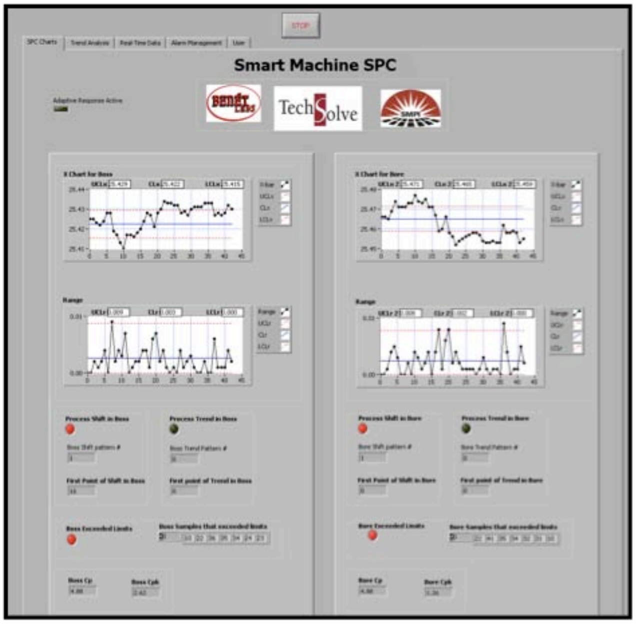

Figure 12 : GUI of the SPC application

RESULTS

The development of an automated statistical process monitoring application based on MTConnect was able to address the limitations of using conventional CMM software on the manufacturing shop floor. The revised MTConnect based application was tested for specific cases discussed in the limitations of traditional SPC.

The application was able to address the limitations due to certain inherent performance indicators such as trending and shifting. The application is also capable of accurately notifying the operator for tool change based on the trending patterns observed previously. Similarly, the application was able to predict with 100% accuracy on all 48 parts manufactured during the case study whether the widget conformed to requirements, which was that the boss had to fit snuggly into the bore.

The presence of chip during OMP process was simulated by deliberately leaving some chip inside the bore and on the periphery of the boss. Whenever, a ‘out of control zone’ indicator is flagged, the presence of an outlier was detected and compensated as the MTConnect application was able to recognize that there was an improper contact point reported by the on-machine probe. In such cases, there was no necessity for an outlier being identified and this was accomplished by the MTConnect based application appropriately.

CONCLUSIONS

The automated quality monitoring in a widget with very tight tolerances, was developed and implemented as part of the efforts of the supervisory system of the Smart Machine Program Initiative. The deployment of traditional SPC methodologies on the shop floor were identified to have some limitations especially in areas of control chart patterns and a general conformance to requirements.

These limitations were addressed by modifying the traditional SPC methods to include acceptable and unavoidable causes of variation in the manufacturing process like tool wear, and tool change. Similarly, a customized approach was used to ensure quality as a conformance to the prescribed requirements.

FUTURE WORK

During the course of this work on the automated handling of quality in the Smart Machine, it was observed that the variation in the process was more or less similar to the variation observed in the machining parameters like power, temperature etc. Current and future work is directed at establishing a process consistency by correlating the process variables with machining parameters to establish a prediction function. This can be extended to include an overall optimization function to realize the *First Part Correct* philosophy.

ACKNOWLEDGMENTS

Research was sponsored by the U.S. Army Benet Laboratories and was accomplished under Cooperative Agreement Number W15QKN-06-2-0100. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of U.S. Army Benet Laboratories or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation heron.

REFERENCES

Atluru S, Deshpande A (2009) “Data to Information: Can MTConnect Deliver the Promise?.” 37th North American Manufacturing Research Conference, May 19-22, 2009, Greensville, SC.

Deshpande A, Pieper R, Wang X (2011), “Legacy Machine Monitoring using Power Signal Analysis.” (In preparation) Sixth Annual ASME International Manufacturing Science and Engineering Conference (MSEC), June 13-17, 2011- Oregon State University, Corvallis, OR.

Deshpande A., Snyder J., Scherrer D. (2011). “Feature Level Energy Assessments for Discrete Part Manufacturing”, 39th Annual SME North American Manufacturing Research Conference (NAMRC), June 13-17, 2011 - Oregon State University - Corvallis, OR.

Del Castillo E.D., Montgomery D.C. (1994), “Short- run statistical process control: Q-chart enhancements and alternative methods,' Quality and Reliability Engineering International, 10, 87-97

Dowling M.M., P. M. Griffin, K.-L. Tsui, C. Zhou, (1995) “A comparison of Orthogonal Least Squares and Minimum enclosing zone methods for form error estimation”, Manufacturing Review, 8, 120-138.

Dowling M.M., P. M. Griffin, K.-L. Tsui, C. Zhou, (1997) “Statistical Issues in Geometric Feature Inspection Using Coordinate Measuring Machines”, Technometrics, Vol. 39, No. 1, 3-17.

El Maraghy W.H., El Maraghy H.A., Wu Z. (1997), “Determination of actual geometric deviations using coordinate measuring machine data”, Manufacturing Review, 3, 32-39.

Kim G.C., Schniederjans M.J. (2000), “Use of Short-run Statistical Process Control Techniques: A Comparison of US and Japanese Manufacturing”, American Journal of Business, Vol. 15, No. 1.

Quesenberry, C. P. (1991), “SPC Q charts for start-up processes and short or long runs”, Journal of Quality Technology, Vol. 23, No. 3, 213–224.

Summers D.C.S. (2006), Quality, 4th edition, Pearson Prentice Hall.

Wasserman G.S. (1994), “Short run SPC using Dynamic control chart”, Computers Industry Engineering, Vol. 27, No 1-4, 353-356.