INVESTIGATION OF COMPUTERISED INSPECTION TECHNIQUES IN CNC MANUFACTURING SYSTEMS

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Abstract

In discrete part production with CNC machine tools it is becoming more prevalent to use process control to close the manufacturing feedback loop by integrating design, manufacturing and inspection. Review of the literature suggested that coordinate measuring machine and on-machine measurement are two most common inspection techniques adopted by industry in CNC manufacturing systems. This paper presents a systematic approach to compare the capabilities of two most common computerised inspection techniques namely, On-Machine-Measurement and Coordinate Measuring Machine in a typical CNC manufacturing enterprise. In addition, in order to close the CNC manufacturing feedback loop, the requirements of each technique have been identified.

Keywords: CMM, on-machine-measurement, CNC machining

1. INTRODUCTION

The globally competitive nature of manufacturing combined with the growing expectations of customers for quality assured parts at minimum cost has increased the importance of process control in manufacturing systems. Generally process control is related to all manufacturing processes where materials undergo chemical or mechanical transformations [1]. In the context of Computer Numerical Control (CNC) manufacturing, the definition of process control is to monitor a process to increase the quality of finished parts by controlling input parameters. Process control has been introduced as an option to increase the quality of manufactured parts in addition to the typical approach of employing more accurate machine tools. Generally, process control is divided into two sub-sections namely monitoring and decision making. Recent developments in computer control and software has made it available to automate the components in CNC manufacturing. However, these components remained as isolated automated islands due to lack of communication [2].

Due to the nature of the CNC manufacturing, real time monitoring of the geometries of components during machining is not possible. Thus, the inspection unit of the process control is introduced between or after the machining operations. To inspect the geometrical quality of the machined components in CNC manufacturing two methods are common namely using Coordinate Measuring Machine (CMM) and On-Machine Measurement (OMM).

While the CMM is one of the most accurate inspection facilities, it is also one of the most expensive components of the CNC manufacturing system. In addition, due to its accuracy, it requires continual maintenance and attention which is not desired in shop floor. On the other hand, in OMM, the CNC machine is employed as an inspection unit. Thus, it would be busy during inspection operation which is not considered as value added time. Furthermore, the accuracy of the measurements in OMM is limited to the accuracy of the machine tool.

In this paper a systematic approach based on National Aerospace Standard 979 [3] and a series of BS ISO standards is introduced to compare the capabilities of these two inspection systems in a typical CNC manufacturing system in conjunction with commercial Computer Aided Design (CAD)/ Computer Aided Manufacturing (CAM)/ Computer Aided Inspection (CAI) software packages. In addition, the requirements to integrate inspection process with machining process are identified. As shown in figure 1, this integration is proposed to provide feedback information from the machining process to the CAD/CAM components of the CNC manufacturing system.

2. CURRENT GEOMETRICAL INSPECTION TECHNIQUES IN CNC MANUFACTURING

In this section OMM and CMM methods are reviewed as the most common automated inspection methods in CNC manufacturing systems. Both these methods enable data to be collected from inspection to be used as input parameters for decision making in process control loop in order to compensate geometrical errors of the machined parts.

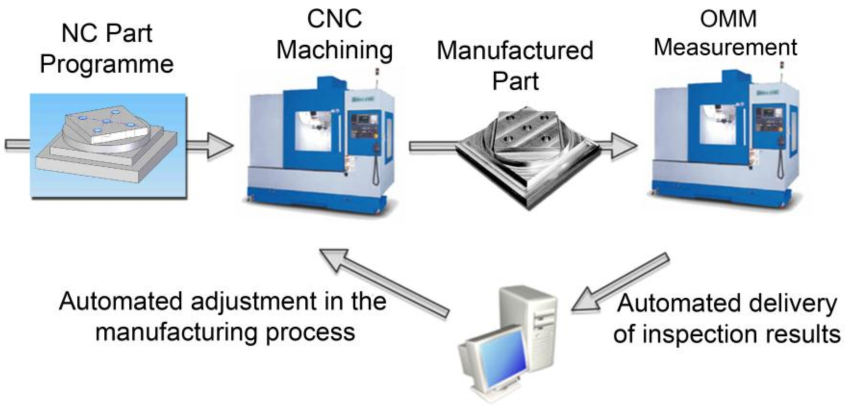

Figure 1 – Desired manufacturing system with feedback loop

2.1 Coordinate Measuring Machine (CMM)

CMMs were developed as flexible and accurate measurement machines to provide automated inspection in CNC manufacturing systems, while reducing inspection time [4]. As inspection results are related to the nominal dimensions of a CAD model, a large body of research has been undertaken to provide integration between design and inspection [4,5,6].

A review by Legge [4] in integration of design and inspection revealed that employing CMMs for inspection has become popular due to the reduction in the inspection time and fixturing requirements. He also found that the use of CMMs in small batch production or individual production would lead to scrap reduction due to unavailability of Statistical Process Control (SPC) methods in small batches. Also in the case of process control, CMMs could be used for process refinement [4] in machining, which requires integration between the CAD/CAM systems, machining centres and CMM.

It is noted [4] that using CMMs for inspection has led to a 90% reduction in inspection time in comparison with traditional inspection methods and concluded that the main reason for popularity of CMMs is their lower inspection time. While CMMs are recognised as highly accurate inspection machines, frequent calibration and error compensation is required to maintain their accuracy and performance. Many researchers have been concerned with maintenance and error compensation of CMMs [7,8,9]. Barakat et al. [7] represented different common types of errors in CMMs. They found that 60-70% of the measurement errors are quasi-static. Quasi-static measurement errors using CMMs were then categorised as geometric errors, kinematic errors, stiffness errors and thermal errors. They noticed that most of these inaccuracies are inherent in the machine and could not be compensated easily.

Like CNC machining, using CMMs for measurement requires an operation plan typically called the inspection plan. The inspection plan defines measurement sequences, probing points or features and probe path planning. Newman and Bagshaw [10] suggested Direct Computer Controlled CMMs for inspection planning and reviewed its benefits through six main categories namely measurement flexibility, reduction of setup time, improved measurement accuracy, increased speed of execution, SPC and the high level of automation. Much research focused on CMM path planning and defining appropriate probing point for different features. Previous inspection path planning was based on heuristics and manual collision checking after simulation [11] also determination of probing points in traditional methods was manual. In this regard, some researchers tried to integrate manual knowledge based probing point modification and computerized facilities [10] through a set of macros [12] or CAD-Directed programmes which have been introduced by Fan and Leu [13] for basic geometrical features.

2.2 On-Machine Measurement (OMM)

While CMMs are known as the most common inspection method in CNC manufacturing systems, the On-Machine Measurement (OMM) method has become popular recently for inspection as an alternative to the CMM. In OMM the same machinery used for machining the parts would be employed for inspection. To use a CNC machine for inspection, an inspection probe is mounted in the spindle of CNC machine. Whether inspection probe-compatible software is available on a CNC controller or not, different methods are defined to use the CNC machine for inspection [14]. Zhou et al. [14] reviewed different available inspection probes for OMM and introduced their requirements in integration with a CNC controller. As CMMs are expensive machines and require environmentally controlled rooms to work they are considered as off-line inspection units in CNC manufacturing systems. Therefore, Kim et al. [15] suggested the OMM method as an alternative for inspection in CNC manufacturing line. In addition, they noticed the reduction in inspection time as a reason for popularity of the OMM. The OMM is believed as a shop-floor inspection method that does not require unclamping and non-value-added movements from machining to environmentally controlled room for inspection [15]. They studied different sources of errors in OMM and evaluated measured results by comparing measurement results of the OMM and CMM. Cho and Seo [16] integrated CAD/CAM and Computer Aided Inspection (CAI) for On-Machine inspection of dies and moulds. They used two measuring point selection methods namely by the prediction of cutting errors and by considering cutter contact points to avoid measurement errors caused by cusps. In this approach, they modelled the component to be machined in a CAD system. In addition, the manufactured surface was modelled by considering the contact point between the tip of the cutting tool and the material. These two models were then used to predict the measurement inaccuracies due to height and depth of cusps. Cho and Seo [16] introduced OMM as an in-line inspection approach to control machined parts after roughing operations and before finishing. Their CAD/CAM/CAI integration concept predicted measurement errors and changed the finishing process plan to correct undesired deviations. As the OMM inspection method is carried by same CNC machine used for manufacturing, the accuracy of inspection results is highly dependent to CNC machine accuracy [17]. Another report [18] noticed the complexity of part setup procedure for re-machining of rejected parts and introduced OMM as an in-process inspection method before finishing operation of parts. In this approach, the part would be inspected after machining and be inspected before unclamping. Thus, correction operations would be executed without new setup requirements. In addition, Kwon et al. [18] presented OMM errors and suggested to conduct post-process inspection to verify the OMM results. Kim et al.[15] classified different sources of errors in the OMM method as: inspection probe installation error, repeatability of the CNC machine tool, settling error in setup of the work piece. They also noticed that the main source of inaccuracy in OMM is settling error of work piece due to clamping forces. A similar comparative analysis among inspection results from the CMM and OMM methods revealed measurement errors in the OMM method due to positional error and thermal errors of the CNC machine tool [18]. This report identified thermally induced errors due to machining operations as the main source of error in machine mounted inspection probe method.

An experiment was conducted by Ali [19] to compare inspection results of a prismatic part using a CMM and the OMM method. He employed a 1990s 3-axis CNC machining centre (WADKIN CNC) and a state of the art 3-axis CNC 3-axis CNC machining centre (Bridgeport) for on-machine measurement. He noticed that the results obtained from the CMM are more accurate than OMM while inspection process planning with the older WADKIN CNC machine tool is more difficult and time consuming in comparison with CMM and Bridgeport. Also he [19] claimed that inspection time using a CMM is approximately equal to the inspection time using Bridgeport CNC machine.

3. STANDARDS ASSOCIATED WITH EXPERIMENTAL MEASUREMENT AND MACHINE TOOL INVESTIGATION

One of the common standards in machine tool investigation is the NAS 979 [3] which was established by the Aerospace Industries Association of America on April 1966 and revised on January 1969. The aims of this standard was to "provide a standard for the selection of cutting tests required to evaluate the performance of conventional and numerically controlled machine tools, excluding drilling and turning machines, and to provide a standard format for recording and reporting actual performance results." [3].

The standard contains several methods to investigate machine tool accuracy in terms of dimensional, geometrical and surface finish quality of manufactured parts during different machining conditions. Specified tests for machine tools evaluation are classified as: maximum torque-low speed, maximum rated horsepower, high speed, low speed, maximum feed rate-low speed, overshoot and undercut, composite cutting test, transverse tilt cutting test, longitudinal tilt cutting test, profile - cone frustum cutting test, boring test, bore and counter bore test, accuracy and repeatability cutting test, flatness and mismatch cutting test.

To standardise the evaluation tests, machining parameters were defined by NAS 979 for each type of test in terms of spindle speed, feed rate, depth of cut and tool characteristics. This approach to machine tool evaluation provided a standardised comparison among different machine tools and simplified test processes. However this methodology is described as a time consuming technique due to requirements for machining and measurement of the machined test pieces [20].

Different test pieces were introduced in the NAS 979 for different customer requirements; one of these test pieces is generally known as Square-Circle-Diamond which is a major test part of the standard. This standard outlines how to evaluate machine tool capabilities under different cutting conditions. The test part introduced for the cutting test contains all CNC manufacturing features and makes it available to investigate machine accuracy in terms of positioning, parallelism, flatness, etc.

The test part consists of an outer square, a circle, a 45 degree canted square, two ramp cuts of 5 degree and two taper cuts. Each of these features was designed for particular test requirements which are identified by the standard and represented below:

- Outer square:
  - Dimensional accuracy
  - Parallelism
  - Flatness
  - Squareness (perpendicularity)
- Circle:
  - Dimensional accuracy
  - Diameter inspection
  - Centre point inspection
  - Concentricity
- 45° Centre canted square (Diamond):
  - Dimensional accuracy
  - Integrated axis parallelism
  - Integrated axis squareness (perpendicularity)
  - Flatness
- Ramp cuts of 5° plunge and raise:
  - Angular deviation inspection
- Taper cuts:
  - Visual observation of uniformity of servos response and slide stiction

The material of the test part is aluminium 7075-T6 as suggested by National Aerospace Standard body.

In addition to the NAS 979 the experimental investigations were developed based on some other standards defining the experiment condition. Based on BS ISO 5725-1:1994 [21] in the context of precision measurement, many factors may assign to the variety of the measurement results namely the operator, the measurement equipment, the measurement environment (temperature, humidity, air pollution, etc.) and the time elapsed between measurements. In addition, four most important factors that may influence the precision of the results were defined as time, calibration, operator, equipment [22]. Changes of each of these factors during the experiments would be a potential source of uncertainty in measurements and should be considered in DoE for measurement. The standards provide a method to design an experiment for precision measurement and defining the accuracy of the measurement by considering all potential functions which may affect the measurements results. In addition, [23] defines different requirements to investigate the accuracy and repeatability of a CMM.

According to [21] in the context of measurement, accuracy is defined as closeness of agreement between a measured value and its nominal value. However, due to characteristics of measurements, accuracy is separated into trueness and precision. The term trueness is 'the closeness of agreement between the average value obtained from a large series of test results and an accepted value' [21]. In addition, precision is defined as closeness of agreement between independent test results. In other words, precision is the standard deviation of the trueness [24]. Precision is separated into repeatability and reproducibility. However the term repeatability of measurements is different from repeatability of measurement equipment. The repeatability of equipment is the ability of the equipment to produce similar results for different single measurements of an identical test. However, the repeatability of a measurement is the standard deviation of the measurements taken under similar condition namely same operator, equipment, environment, calibration and short elapsed time between measurements [21]. In addition, reproducibility is the precision while measurements are executed with different operators and measurement equipment for an identical item using the same method.

4. METHODOLOGY AND DESIGN OF EXPERIMENTS

For this experiment, due to testing on a 3-axis CNC machining the NAS 979 test part was modified to a prismatic component called "Bath Modified NAS 979 (B-NAS 979) Test Part". Thus, the two 5˚(degree) ramps of the component were removed. In addition, the taper side of the component was removed as it was defined in the standard for visual observation during machining and not for measurements. Furthermore, four holes were added on top of the component which would be used to investigate the positional accuracy. Finally, the B-NAS 979 test part was generated and specialised for prismatic part measuring machines investigation. Figure 2a shows the isometric pictorial view of the component.

Prior to measurement operations, inspection features of the B-NAS 979 test part were generated in terms of lines, planes, circles and cylinder which are shown in figure 2b. Based on the [23], circles would be used to assess the positioning and form accuracies while lines and planes would be inspected to investigate the dimensional and angular accuracies. Thus, diameter and position of the centre point of the circles was defined as output parameters of the inspection process. In addition, the length of the lines and their angles were measured. Furthermore, the distances and angles between the planes and the reference plane were evaluated. It should be noted that [21] was taken into account to conduct the measurement operations.

Each component was proposed to be measured five times to compensate the repeatability error of the measuring equipment. Measurement results would then be mapped to the measurement features and developed in order to compare the capabilities of CMM and OMM based on ISO 10360-2: 1996 standard.

5. EXPERIMENTATION

Four B-NAS 979 test parts were machined using a Dugard's Eagle 850 vertical CNC machine. Each test part was measured five times on the machine tool after machining and prior to unclamping based on the measuring plan. It should be noticed that measurement operations in OMM were limited to point inspection therefore feature-based inspection was not applicable. Thus, measured coordinates were then analysed using other software packages to represent features characteristics.

Based on the [21], same operator, devices and measuring setups were used to execute all the measurement operation. In addition, the elapsed time between each measurement procedure was reduced to less than 30sec to reduce the possible changes in environmental condition. Furthermore, tool calibration operations were executed before all measurement operations and the calibrations were not changed during measurement operations, thus same calibration was used for all measurements.

By considering the defined features, a measurement strategy and programme were developed using Modus™ CAI programme. A Brown & Sharp's Global Status CMM with "1.5 + L/333" μm accuracy was used to measure the test parts. Similar to OMM, each part was measured 5 times in order to compensate the repeatability error of the CMM. As a result a total number of 40 measurement result batches were generated for further analysis.

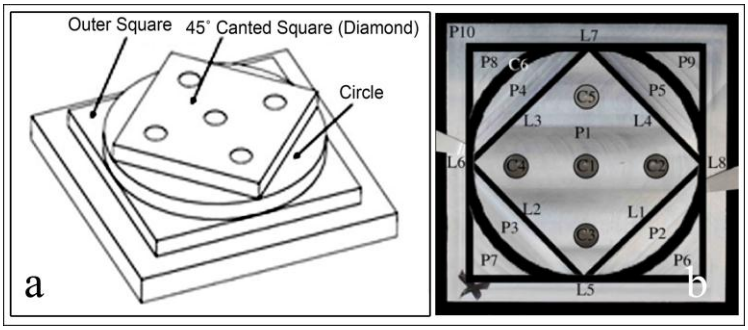

Figure 2 – a) Pictorial and b) inspection features of the B-NAS 979 test part adopted from [3]

6. RESULTS AND DISCUSSION

In order to analyse the measurement results they were categorised into six classes namely form inspection, positioning inspection, length measurement in X-Y plane, Length measurement along the Z-axis, angular inspection in X-Y plane and 3D angular inspection [23]. For instance, figure 3 illustrates a comparison of the measurement results obtained from OMM and CMM and repeated five times. As the measurement results of the OMM were limited to the coordinates of the inspection points, the coordinates were developed based on the geometrical characteristics of the inspection features to be used in analysis. This is one of the main weaknesses of the OMM technique that most CNC controllers cannot recognise the inspection feature and are limited to probing points coordinates.

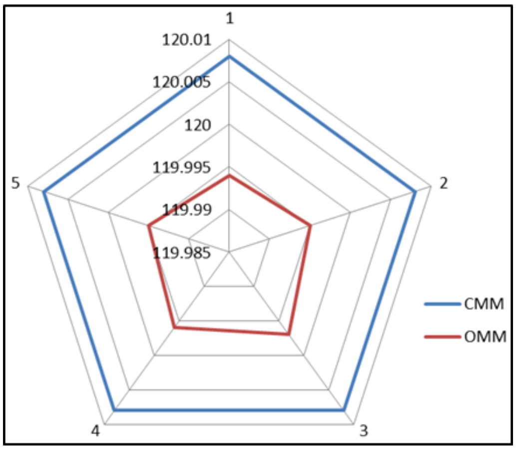

Figure 3 – Measurement results of circle 6 (C6) of the test part 1 obtained from OMM and CMM

According to [25], quality assurance for the measuring equipment standard, a true value of a measurand is inherently indeterminate. Thus, the standard mentioned that the true value is a value obtained from a perfect measurement. In this case, the true values of the measurements were assumed as the average value of the measurements obtained by the CMM as one of the most accurate measuring facilities. The average values of the measurements obtained by the CMM are referred to as true values in the literature.

For each of the four B-NAS-979 components, the mean value of the measurement results was defined as the measured value. The deviations of measured values from true values were then presented as measurement accuracies of OMM for the particular component and feature while the deviation of the true values from nominal values was defined as machining accuracy. Finally, mean of deviations were calculated as accuracy of OMM in measurement of a particular parameter according to [23] as it is shown in table 1. As it could be understood from table 1, the measurement accuracy of the machine tool is reasonably higher than its machining accuracy although this is not the case for the features which are not parallel to the machine tool axes (form and bi-axial length) where the probing operation cannot be conducted perpendicular to the feature. This indicates that in most cases, machine tools have the capability to be used for inspection to a higher accuracy than their machining accuracy.

The standard deviation of the measurement results was calculated in order to identify the repeatability of the measurements from the CMM and OMM. Similar to accuracy, repeatability is presented by different components based on the [23] for different components as it is shown in table 2. Similar to accuracy results, except bi-axial measurements, other repeatability components are within a reasonable interval.

Table 1 – Measured accuracy components of OMM in comparison with CMM

Accuracy Component	Unit	OMM Accuracy	Machining Accuracy
Form	mm	0.01188	0.008
Positioning	mm	0.0037	0.0071
Centre point distance	mm	0.0037	0.0071
distance along Z	mm	0.00072	0.0019
3D angle	deg	None	0.0029
Uni-Axial X-Y Length	mm	0.0038	0.0271
Bi-axial Length	mm	1.737	0.0267
X-Y Angle	deg	0.001875	0.0062

Table 2 – Measured repeatability components of CMM and OMM

Repeatability Component	Unit	CMM	OMM	Machining
Form	mm	0.0003	0.0010	0.0017
Centre Point Positioning	mm	0.0005	0.0012	0.0059
Uni-axial Length	mm	0.0001	0.0005	0.00091
Bi-axial Length	mm	0.0001	0.3	0.00094
X-Y Angle	deg	0.0003	0.002	0.00087
Z Length	mm	0.0010	0.002	0.0034
3D Angle	deg	0.0015	None	0.0021

It is noteworthy to mention that measurement time excluding setup time was 7min and 12.5min for CMM and OMM respectively whereas CMM provides a lot more information based on the measurement features while the results obtained from OMM was limited to the probing coordinates which requires further analysis. As in OMM the machined part will be inspected during or just after the machining operation literally no setup time is required for OMM. As a result, the measurement results could be used for error compensation and re-machining operation. This is supported by reasonably high repeatability of the machine tool. In contrast to OMM, the software interface of the CMM was capable of comparing the measurement results with nominal dimensions thus helping in approving or rejection of the components in an inspection process. This indicates the requirements for more integration between CAD/CAM/CAI software systems with machine tools to make CNC machine tools more capable facilities for online inspection during machining processes.

7. Conclusion

Demands for higher quality products at lower costs have increased requirements for process control in CNC manufacturing systems [19]. CMM and OMM are known as the most popular solutions for inspection in the CNC manufacturing process control. While there have been valuable efforts to integrate different components of CNC manufacturing systems, it is mostly concentrated on the integration of a computer based programme and a component of the manufacturing system. As a result, most components in the CNC manufacturing systems are driven or programmed by software programmes but the system suffers from lack of communication between individual components. In this paper, a systematic method based on a series of standards has been developed in order to evaluate the accuracy and repeatability of OMM as compared to CMM. Based on the methodology and literature a series of experiments were conducted and following conclusions have been drawn:

- From the literature CMM has been identified as the most accurate inspection device in CNC manufacturing systems, but can vary from sub-micron level to 10 microns dependent on the environment. In addition it also is known as one of the most expensive components of the system.
- OMM is an alternative inspection technique to the CMM which could be used during or after machining operations for compensating geometrical errors of the machining or inspecting machined parts
- Whilst accuracy and repeatability of OMM is in an angle with the results obtained from CMM, it has a potential to be used as an in and post process inspection technique.
- OMM suffers from lack of direct communication with measurement software programmes which are capable of developing inspection plan, inspection programmes and analysing the measurement results.
- While OMM provides the capability to measure machined parts just after the machining operation and prior to unclamping, the machine tool will be busy for measurement operation which is considered as a non-value added time. However, in some cases such as mould and die manufacturing, this time could be compensated by prevented scrap machining.
- OMM has the capability to be integrated with CAD and CAM programmes in order to close the CNC manufacturing loop by providing feedback from machining process. The information provided from OMM during or after machining operations could be used to improve the geometrical accuracy of the machining operations by compensating the probable and unquantifiable inaccuracies inherent to machining processes.

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