Statistical Process Control (SPC) in a High Volume Machining Center: Gage Repeatability and Reproducibility Study

by

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Bachelor of Engineering in Mechanical Engineering
Tsinghua University, 2014

Submitted to the Department of Mechanical Engineering
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Abstract

The purpose of this project is to set up a statistical process control (SPC) system in a high volume machining center to reduce the scrap rate and improve the manufacturing quality. The system is demonstrated on a machining center at Waters Corporation as part of a team internship project. This thesis focuses on the gage repeatability and reproducibility study (Gage R&R study) for the implementation of the SPC system. Based on the knowledge about the machining processes and the gages available, we select the proper gages for different dimensions to conduct the Gage R&R study. Gage capabilities are analyzed and root-cause analysis for incapable gages is performed. Related reaction plans are developed and implemented in order to improve the gage capabilities. Discussion about tolerance redesign leads to the adjustment of specifications in the manufacturing area. As a result of these efforts, we find that the existing measurement system is capable for the SPC real time inspection system. As for the final result for this entire project, we demonstrated that with the SPC system, we successfully reduce the scrap rate by half and thus offer substantial cost savings as well as improved product quality.

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Chapter 1. Introduction

This thesis focuses on the methodology and the benefit of the gage repeatability and reproducibility study ("Gage R&R" study) for implementing a statistical process control system ("SPC" system) in a high-volume machining center. This thesis is based on research conducted at Waters Corporation, an analytical instrumentation company located in Milford, Massachusetts [1]. The Waters Global Machining Center is the largest supplier to Waters Corporation for machined and fabricated components. It has experienced a significant growth rate of staff over the last few years, in excess of ten percent per year since 2010. The rapidly increasing percentage of new hires and the lack of standardized inspection procedures has led to concerns about potential drops in yield and growths in cost associated with diminished quality. This problem offers an opportunity to improve and maintain the overall production quality by introducing standardized inspection plan protocols. Therefore, a group of MIT students, who are part of the Master of Engineering in Manufacturing Program, were introduced to the company to build a statistical process control system for the machining center.

In this case, the implementation of the statistical process control is split into three major stages. To ensure the accuracy and the reliability of the data collected in the future, a proper gage repeatability and reproducibility study is the first step to begin with. After the demonstration of gage capabilities, the standardized operating procedure ("SOP") is developed and the operators are trained accordingly. Hereafter, valid data can be collected and control charts are plotted. Based on the analysis of the data, assignable causes for process variation are identified and reaction plan is taken accordingly. This thesis focuses on the first part of the statistical process control implementation in a high-volume machining center: the gage repeatability and reproducibility study. For more details about the other parts of the statistical process control implementation, please refer to the related theses [2, 3].

Chapter 2 will provide a brief introduction to the company and its Machining Center. Following the issues in the Machining Center, the problem statement will be presented. Chapter 3 will introduce the theoretical basis of the SPC method and the Gage R&R study. Chapter 4 will explain how the product is machined and what measurement devices are used for its inspection. Chapter 5 will concentrate on the Gage R&R study analysis. Chapter 6 will discuss the Gage R&R results and the benefits of the methodology. Chapter 7 will draw conclusion and outline recommendations for the company to achieve further improvements.

Chapter 2. Background and Problem Statement

In this chapter, a brief introduction to the company and its Machining Center will be presented and current issues in the Machining Center will be brought up. The problem statement follows up and our overall approach is discussed at the end of this chapter.

2.1 Background on Waters Corporation

Waters Corporation is an analytical instrument manufacturer that primarily designs, manufactures, sells and services high performance liquid chromatography ("HPLC") and ultra performance liquid chromatography ("UPLC") and mass spectrometry ("MS") technology systems and support products, including chromatography columns, other consumable products and comprehensive post-warranty service plans [1].

HPLC's performance capabilities enable it to separate and identify approximately 80% of all known chemicals and materials. With a specialized instrument to accommodate the increased pressure and narrow chromatographic bands that are generated by smaller particles, UPLC enables researchers and analysts to achieve more comprehensive chemical separation and faster analysis times in comparison with many analyses performed by HPLC. Together, they are referred to as liquid chromatography ("LC"). MS is a powerful technology used to identify unknown compounds, to quantify known materials and to elucidate the structural and chemical properties of molecules. Waters Corporation has successfully developed integrated LC-MS systems and become one of the world's largest manufacturers and distributors of LC and LC-MS instrument systems, chromatography columns and other consumables and related services.

Waters' products are widely used by pharmaceutical, life science, biochemical, industrial, nutritional safety, environmental, academic and governmental customers working in research and development, quality assurance and other laboratory applications. The company's LC and LC-MS instrument systems are utilized in this broad range of industries to detect, identify, monitor and measure the chemical, physical and biological composition of materials, and purify a range of compounds. The primary consumable products for LC are chromatography columns. These columns are packed with separation media used in the LC testing process and are typically replaced at regular intervals. The retail price for each column package varies from $750 to $1500. It has become a major part of the company's total revenue [1].

2.2 The Waters Global Machining Center

The Waters Global Machining Center ("Machining Center") is an essential part of Waters' global manufacturing supply chain for its products and services. Before we introduce the Machining Center, a brief overview of Waters' global manufacturing supply chain is introduced in the following section.

2.2.1 Manufacturing Overview

Waters currently assembles a portion of its LC instruments at its facility in Milford, Massachusetts. It outsources manufacturing of certain electronic components, such as computers, monitors and circuit boards, to outside vendors that meet the company's quality requirements. In addition, it outsources the manufacturing of certain LC instrument systems and components to well-established contract manufacturing firms in Singapore. The company primarily manufactures and distributes its LC columns at its facilities in Taunton, Massachusetts and Wexford, Ireland, where it processes, sizes and treats silica and polymeric media that are packed into columns, solid phase extraction cartridges and bulk shipping containers. The company manufactures and distributes its MS products at its facilities in Wilmslow, England and Wexford, Ireland. Consequently, this complex global supply chain requires high manufacturing quality in order to meet the lead time commitment in every stage. In addition, product consistency is the key attribute for the customers in quality control laboratories. As a result, Waters is always pursuing higher manufacturing quality.

2.2.2 The Waters Global Machining Center

Nearly all of the company's LC products have been developed at the company's main research and development center located at Milford, Massachusetts. The Waters Global Machining Center at Milford is the largest supplier to Waters Corporation for machined and fabricated components. It supplies highly complicated components to all of the facilities and contract manufacturers worldwide. It houses a 49,000 sq. ft. Machining Center of Excellence, a 29,000 sq. ft. Advanced Instrument Assembly/Kitting Operation, a 21,000 sq. ft. "Clean" New Product Introduction Operation/Laboratories, a 7,500 sq. ft. Class 10,000 Clean Room for Optics/Micro Valves and a 1,000 sq. ft. Class 10,000 Clean Room for Parts Critical. It operates 24 hours per day, six days per week, 52 weeks per year. It delivers 2.7 million machined parts, more than 4,000 finished goods units and 28,000 SKUs per year.

The Center is divided into four main departments: Valve Cell, Column Cell, NC Turning and NC Milling as shown in Figure 2-1. Box 1 is the Column Area, box 2 is the Valve Area, box 3 is the NC Turning Area and box4 is the NC Milling Area. The Valve Cell and the Column Cell are laid out as production cells, with a variety of different machines arranged next to each other that complete different operations on the same part. Each cell has a dedicated part type that it produces in high volumes, and contains all the machines needed to complete their respective parts. The information about the Machining Center is based on Puszko's summary in 2014 [4].

Figure 2-1. Machining Center layout.

In the Column Cell department, there are seven CNC machines that complete the main operation. Two of them are dedicated to column production, the rest produce end fittings in general. There is a small inspection area where advanced inspection devices provide support for all CNC machines in the Column Area. Convenient hand-held gages are available near every CNC machine for operators to perform quick checks. During their daily production, the operators use the advanced devices in the inspection area to complete an entire inspection for the first part they make at the beginning of their shift. As long as the first part is a good part, they keep the machine running and use simple gages to perform quick checks during the entire production. They only perform an entire inspection before and after their break or shift change.

2.3 Issues in Machining Center

The Machining Center has experienced a significant growth rate over the last few years, and there is a significant issue with the machinists' lack of familiarity with real time inspection techniques and protocols, and ability to apply them to their everyday activities, in this ever increasing environment of high production volumes. As a result, the yield has dropped and the cost associated with quality lost, both from direct scrap costs and associated productivity losses has grown. LC columns, as the major component of the company's total revenue, are the main product of the Machining Center. About 40% of the scrap loss comes from the raw material cost of the column scrap. In our project, we focus on the Column Area to implement a statistical process control system. The Column Area will be used as an example in this thesis to illustrate the implementation of SPC and a gage repeatability and reproducibility study. However, to facilitate the spread of the SPC methodology throughout the Machining Center and achieve a bigger impact in the company in the future, we also deliver a document with further details of our methodology, which can be found in Udayshankar's thesis [2].

Three major problems have been identified as the main causes for yield and quality loss issues: workforce refurbishment, complicated production environment and the lack of standardized operating procedures.

2.3.1 Workforce Refurbishment

As the Machining Center maintains a high growth rate, new workforce keeps being introduced. New hires over the last 18 months make up over 25% of the workforce, with that number growing to 40% over the last three years. In the Column Area, there are operators who have been working for Waters for more than three decades, and there are operators who just joined a couple of months ago. When the old operators run the machines, they have a good control on the machining processes based on their experience. They understand how to react according to different situations. When a new hire comes, he or she seems to have a hard time making a correct decision due to the lack of experience. Managers are concerned that the production quality will decrease once the experienced operators retire.

2.3.2 Complicated Production Environment

The Machining Center delivers a high volume of machined parts every year and machines are always running at a high speed. In the Column Area, a short column takes only 75 seconds to machine and an operator is running two machines at the same time. A column has about ten dimensions at both ends that have to be inspected. More than three measurement devices are necessary to finish one complete inspection. It is hard for new operators to have a good understanding about the processes' real time status with the existing tools in the Machining Center.

2.3.3 Lack of Standardized Operating Procedure

At present, there is not a standardized inspection procedure for the operators to follow during their production. The operators do not have a fixed sampling procedure, and different operators check different dimensions in different frequencies. Also, different operators may choose different measurement devices to inspect the same feature. In addition, there is not a guideline to indicate the correct time to modify a tool offset to compensate for tool wear or to change a tool according to the real-time inspection result. The operators have no record to know when the tools were changed before, and thus they prefer to change tools at the beginning of their shift to avoid producing bad parts. This results in a waste of good tools and a loss in capacity. It takes 30 minutes to 3 hours to change tools; every time they change the tools, they need to make a trial part and perform a complete inspection, which will take 15 minutes to 30 minutes, to set the tool offset correctly. The operators compensate for tool wear in different frequencies with different amounts of offset, which introduces substantial variation into the processes.

2.4 Problem Statement

It is clearly understood that the workforce refurbishment reveals the undesirable consequence of the lack of standardized inspection procedure in the Machining Center. It is necessary and also promising, in terms of cost reduction and quality improvement, to develop and implement a real time quality inspection plan protocol that directs machinists towards a more standardized way of monitoring and controlling their processes. This system, which centers around a data collection process, will include methodology and frequency of measurement and response to data as collected, in a manner that would immediately improve the process yield. In the long term, recommendations can be made based on the analysis of data collected to achieve better processes.

For this purpose, statistical process control is the best tool for the data collection and the quick translation of real time data into useful information for machine operators to have a better understanding about their processes.

To ensure the validity of the data collected, a good measurement system is indispensible, which includes the measurement devices, the operators and their training, techniques and subsequent influence on the data. A common tool to evaluate the capabilities of a measurement system is the gage repeatability and reproducibility study. This thesis focuses on the methodology and the result of the Gage R&R study at the beginning of the implementation of an SPC system. Different measurement devices' capabilities are compared and evaluated. Training is recommended and a standardized operating procedure for ongoing measurement is documented. This thesis will mainly focus on the Gage R&R topic.

After these efforts, a good measurement system will be available for the SPC data collection system. To translate the real time data collected into intuitive information for machine operators, control charts will be used to monitor the processes. Zhu's thesis [3] focuses on this topic and explains the benefits of using control charts.

Given the time constraint of our project, it is impossible for us to construct an SPC systems for every single part in the Machining Center. It has been decided after careful discussion that the Column Area is the best place for us to begin implementing the SPC system. It serves as an experimental area to demonstrate the benefit of the SPC system as well as our methodology. A package of documents illustrating the methodology to implement the SPC system in a high volume machining center are developed and explained in Udayshankar's thesis [2].

2.5 Overall Approach

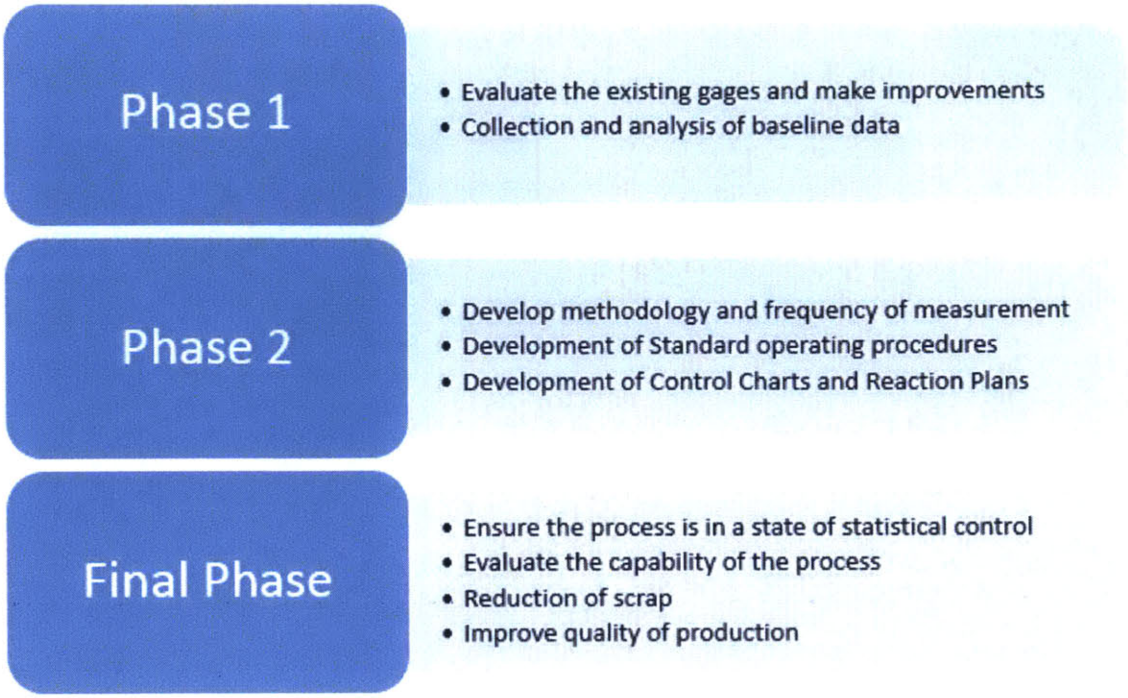
When the problem was described to the team for the first time, it was evident that firstly, there needs to be a methodology set up to solve this issue and secondly, there is a need to ensure that the methodology is portable. The portability of the methodology is critical as the company wants to implement statistical process control not only in the Column Cell but also at the other manufacturing cells.

The team therefore has developed a methodology that is evaluated by implementing it in the Columns Cell. Phase 1 of the project involves carrying out a gage repeatability and reproducibility study to evaluate the measuring systems that are present in the Columns Cell. The next step is to collect baseline data. After collection of baseline data, the team analyzes the data and finds trends that will help in creating sampling plans and also eliminating the variations. Phase 2 of the project involves developing sampling plans that make the life of the operators easier and also the inspection process faster. Assignable causes are eliminated by developing standardized operating procedures that the operator is asked to follow. The final phase of the project is to develop control charts that help the operator to stabilize the process and have it in a state of statistical control. The standard three-sigma rules are incorporated to create the control charts. Also, reaction plans are incorporated in the standard operating procedures that help the operator to bring the process back in control. A process capability study is carried out after the process is in statistical control to quantify the capability of the process to meet its specifications. The operators are trained in the concepts of statistical process control and in the standardized operating procedures that help them in long-term monitoring of the process. By reducing the scrap rate and improving the quality of the production, the team has been successful in validating the adopted methodology.

A booklet has been developed by the team and delivered to Waters Corporation that contains standard operating procedures that could be used to implement statistical process control at a different manufacturing cell.

The entire work that we have done as a team is broken into three parts as summarized in Figure 2-2. The Gage R&R study is covered in this thesis, and the development and value of control charts is discussed by Zhu [3]. Udayshankar's thesis concentrates on the standard operating procedures which are a vital part in bringing the process back into statistical control. It also discusses the scenarios before and after the implementation of standard operating procedures [2].

This chapter was written in conjunction with Udayshankar [2] and Zhu [3], and thus is largely a shared description of the background and problem statement for our joint project.



Phase 1

- Evaluate the existing gages and make improvements
- Collection and analysis of baseline data

Phase 2

- Develop methodology and frequency of measurement
- Development of Standard operating procedures
- Development of Control Charts and Reaction Plans

Final Phase

- Ensure the process is in a state of statistical control
- Evaluate the capability of the process
- Reduction of scrap
- Improve quality of production

Figure 2-2. Three phases of the project.

Chapter 3. Theoretical Review

This chapter will provide the theoretical review for this thesis. A brief review about statistical process control will be summarized in Section 3.1. It mainly focuses on one of the key statistical process control tools: control charts. A detailed review of the underlying theory for the Gage R&R study is discussed in Section 3.2 and related formulas that will be applied for the analysis in the following chapters are presented.

3.1 Statistical Process Control

Statistical process control is a powerful collection of problem solving tools that assist in achieving process stability and improving capability by reducing variability. SPC helps create an environment where all individuals in an organization seek continuous improvements in quality and productivity [5]. Utilizing statistical methods, SPC enables process prediction and emphasizes on early detection and prevention of problems [6].

SPC originated in the United States, developed by Walter A. Shewhart at Bell Laboratories in the early 1920s. Shewhart developed the control chart in 1924 and the concept of a state of statistical control. He was invited to speak at the Graduate School of the U.S. Department of Agriculture by W. Edwards Deming, who was an important architect of the quality control short courses that trained American industry in the new techniques during WWII. Deming became the first president of the American Society for Quality Control, established by the graduates from the wartime courses in 1945. He travelled to Japan to meet with the Union of Japanese

Scientists and Engineers to introduce SPC methods to Japanese industry, where the statistical process control method matured and gained its popularity [6].

Its seven major tools, which are often referred to as the Magnificent Seven, are these: histogram or stem-and-leaf plot, check sheet, Pareto chart, cause-and-effect diagram, defect concentration diagram, scatter diagram and control chart. Among these seven tools, Shewhart control charts are the most technically sophisticated and the most widely used tool.

3.1.1 Control Charts

To convey the key ideas of control charts, we begin below with the underlying statistical basis. We then discuss control charts rules, and the benefits of control charts.

3.1.1.1 Statistical Basis

Regardless of how well a process is designed and maintained, it is impossible to obtain identical outputs all the time. A certain amount of inherent variability will always exist, due to the cumulative effect of many small, essentially unavoidable causes, which are identified as chance causes of variation. On the other hand, variation that is relatively large compared to background noise sometimes occurs due to improperly adjusted or controlled machines, operator errors or defective raw materials and so on. These sources are defined as assignable causes of variation. A process that is operating under the effect of chance causes of variation is defined as being in statistical control. The occurrence of assignable causes of variation indicates an out-of-control state of the process [5].

Research has shown that most processes do not operate in a state of statistical process control [5]. The control chart is a tool to detect the occurrence of the assignable causes. The utilization of the control chart is a series of consecutive hypothesis tests. Based on the center line and different control limits, control charts provide different confidence intervals relative to the process mean value. A data point plotted outside certain control limits is equivalent to rejecting the hypothesis of statistical control with a certain significance value. For example, a data point plotted beyond three sigma limits for a normally distributed measurement indicates that we have 99.7% confidence to conclude that the process mean at present is different from the process mean as determined for the process when it was in a state of statistical control. An example of a control chart is presented in Figure 3-1.

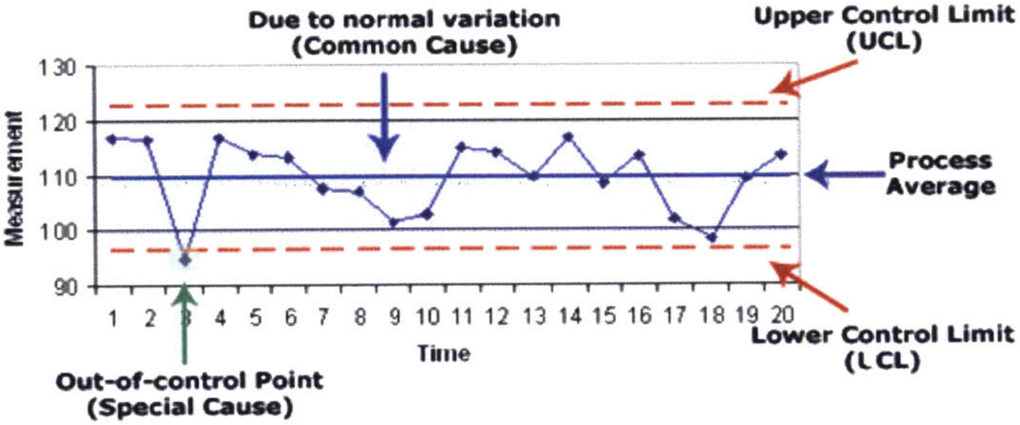


Figure 3-1. Example of a control chart.

3.1.1.2 Rules

There are different rules in the industry to increase the sensitivities of the control charts to enable faster detection of an out-of-control state. The most common set of rules is the Western Electric rules [5]:

1. One or more points outside of the three-sigma control limits;

2. Two of three consecutive points outside the two-sigma warning limits but still inside the control limits;

3. Four of five consecutive points beyond the one-sigma limits;

4. A run of eight consecutive points on one side of the center line;

5. Six points in a row steadily increasing or decreasing;

6. Fifteen points in a row between two-sigma and three-sigma limits (both above and below the center line);

7. Fourteen points in a row alternating up and down;

8. Eight points in a row on both sides of the center line with none between two-sigma and three-sigma limits;

9. An unusual or nonrandom pattern in the data;

10. One or more points near a warning or control limit.

However, the utilization of these rules will increase the false alarm rate at the same time. A careful selection of a set of suitable rules is discussed in Zhu's research [3].

3.1.1.3 Benefits

Control charts are proven techniques for improving productivity. They help reduce scrap and recapture the capacity lost as a result. Control charts are effective in defect prevention, and they also provide reliable information to avoid unnecessary adjustment to the processes. Based on the analysis of the control charts, engineers can have a better understanding about the process and be able to troubleshoot the process more easily. Last but not least, control charts provide an estimate of the true process capability. Ideal process capability without the assignable causes can be calculated and this information can serve as a good reference for a company to decide if more investment to improve the processes is necessary [5]. Successful stories about SPC implementation can be found in the industry easily [7-11].

3.1.2 The Rest of the Magnificent Seven

A histogram is a compact summary of data. Data are divided into bins or intervals which in general have the same width; a histogram is a series of bins with different heights to represent different frequencies of the data within each interval. Histograms offer intuitive information about the distribution of the data, and often serve as a tool to examine the normality of the data.

A check sheet is utilized most at the early stage of the process improvement. It is a tool to help collect historical data and reveal possible assignable causes based on the trend or the pattern of the data, and is the basis for further calculation.

The Pareto chart is simply a frequency distribution of attribute data arranged by category. It enables the engineers to identify the most frequent types of defects [5].

The cause-and-effect diagram is also called the fishbone diagram. It is a powerful tool for root cause analysis and troubleshooting.

A defect concentration diagram is a picture of the unit with various types of defects drawn in different locations as they occurred to examine the tendency of the defect concentration. The analysis of the tendency may lead to the discovery of the assignable cause for the defect.

A scatter diagram is a useful plot to identify the potential relationship between two variables. Designed experiments are needed to verify the causality [5].

3.2 Gage Repeatability and Reproducibility

Gage R&R is a major component of the measurement system analysis (MSA), which will be explained in the next section. P/T ratio, a quick index for gage capability evaluation, is brought into the discussion after that. The mathematical basis of the analysis of variance ("ANOVA") is discussed, followed with an example for typical Gage R&R ANOVA calculation.

3.2.1 Introduction to Measurement System Analysis

Measurement system analysis is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variation [12]. There are five parameters to evaluate in an MSA: bias, linearity, stability, repeatability and reproducibility. Bias reflects the difference between observed measurements and a true value obtained from a master or gold standard, or from a different measurement technique known to produce accurate values. Linearity refers to the difference in observed accuracy and/or precision experienced over the range of measurements made by the system. Stability reveals the difference between the levels of variability in different operating regimes resulting from the variation of outside parameters. Repeatability indicates the difference of the observed values that are measured from the same unit several times under identical conditions. Finally, reproducibility is determined by the difference in observed values when units are measured under different conditions [5].

Gage repeatability and reproducibility, which is usually referred to as Gage R&R, is a fundamental tool to evaluate the gage's capability to distinguish between good and bad units. According to AIAG (2002), a general rule of thumb for measurement system acceptability is: an error under ten percent of the entire process variation indicates this measurement system is acceptable; an error between ten and thirty percent suggests the system is acceptable depending on the importance of the application, cost of the measurement device, cost of repair and other factors; an error above thirty percent is considered unacceptable [12].

3.2.2 P/T Ratio

A common model used for MSA is:

$$y = x + \varepsilon \qquad \text{Equation 3-1}$$

where y is the total observed measurement, x is the true value of the measurement on a unit of product, and ε is the measurement error. We assume x and ε are normally and independently distributed random variables with mean μ and 0 and variances (σ_P^2) and (σ_{Gage}^2), respectively. Then we have

$$\sigma_{Total}^2 = \sigma_P^2 + \sigma_{Gage}^2 \qquad \text{Equation 3-2}$$

where σ_{Total}^2 is the total variance of the measurement system [5].

Then we define precision-to-tolerance (P/T) ratio as

$$\frac{P}{T} = \frac{k\hat{\sigma}_{Gage}}{USL-LSL} \quad \text{Equation 3-3}$$

where k is a constant related to the significance of the hypothesis test, USL refers to the upper specification limit, LSL is the lower specification limit and $\hat{\sigma}_{Gage}$ is the estimated gage standard deviation. For example, the value $k = 5.15$ corresponds to the limiting value of the number of standard deviations between bounds of a 95% tolerance interval that contains at least 99% of a normal population, while $k = 6$ corresponds to the number of standard deviations between the usual natural tolerance limits of a normal population [5]. Lower P/T ratios are desired, indicating that the gage standard deviation is a small fraction of the product tolerance (range in the specification limits). Different companies will set their requirement for P/T ratios accordingly. In general, a P/T ratio lower than 30% is acceptable [12].

3.2.3 ANOVA

A gage's capability can be divided into two parts: gage accuracy and gage precision. Accuracy refers to the ability of the instrument to measure the true value correctly on average, whereas precision is a measure of the inherent variability in the measurement system [5]. To investigate these two components of measurement error, commonly called repeatability and reproducibility, we separate the gage variation into two parts:

$$\sigma^2_{Gage} = \sigma^2_{Repeatability} + \sigma^2_{Reproducibility} \quad \text{Equation 3-4}$$

A Gage R&R Study is the analysis of these two components.

If there are p randomly selected parts and o randomly selected operators, and each operator measures every part n times, then the measurements (i = part, j = operator, k = measurement) can be represented by the model

$$y_{ijk} = \mu + P_i + O_j + (PO)_{ij} + \varepsilon_{ijk}, \begin{cases} i = 1,2,\dots,p \\ j = 1,2,\dots,o \\ k = 1,2,\dots,n \end{cases} \quad \text{Equation 3-5}$$

where the model parameters $P_i, O_j, (PO)_{ij}$ and ε_{ijk} are all independent random variables that represent the effects of parts, operators, the interaction effects of parts and operators, and random error. We assume that these random variables are normally distributed with mean zero and variances given by $V(P_i) = \sigma_P^2, V(O_j) = \sigma_O^2, V[(PO)_{ij}] = \sigma_{PO}^2$ and $V(\varepsilon_{ijk}) = \sigma^2$. Therefore, the variance of any observation is

$$V(y_{ijk}) = \sigma_P^2 + \sigma_O^2 + \sigma_{PO}^2 + \sigma^2 \quad \text{Equation 3-6}$$

We can use analysis of variance methods (ANOVA) to estimate these variance components. We first divide the total sum of squares into different components and divide them by their degrees of freedom to produce the mean squares.

$$SS_{Total} = SS_{Parts} + SS_{Operators} + SS_{PO} + SS_{Error} \quad \text{Equation 3-7}$$

$$MS_P = \frac{SS_{Parts}}{p-1}$$

$$MS_O = \frac{SS_{Operators}}{o-1}$$

$$MS_{PO} = \frac{SS_{PO}}{(p-1)(o-1)}$$

$$MS_E = \frac{SS_{Error}}{po(n-1)}$$

Equation 3-8

The expected values of these mean squares are

$$E(MS_P) = \sigma^2 + n\sigma_{PO}^2 + bn\sigma_P^2$$

$$E(MS_O) = \sigma^2 + n\sigma_{PO}^2 + an\sigma_O^2$$

$$E(MS_{PO}) = \sigma^2 + n\sigma_{PO}^2$$

$$E(MS_E) = \sigma^2$$

Equation 3-9

Therefore, we can use these mean values to estimate each variance component:

$$\hat{\sigma}^2 = MS_E$$

$$\hat{\sigma}_{PO}^2 = \frac{MS_{PO} - MS_E}{n}$$

$$\hat{\sigma}_O^2 = \frac{MS_O - MS_{PO}}{pn}$$

$$\hat{\sigma}_P^2 = \frac{MS_P - MS_{PO}}{on}$$

Equation 3-10

Further analysis can be performed based on the above estimates of the variances. In particular, ANOVA methods generally include F-tests to determine if one or more of the measured variances and effects are statistically meaningful.

In a typical Gage R&R study, we require three operators to measure ten different parts for three times. Montgomery [5] has provided an excellent example to show ANOVA calculation: Table 3-1 is the measurement result on thermal impedance on a power module for an induction motor starter for the Gage R&R study, and Table 3-2 is the summary of the ANOVA result. From Table 3-2, we can see that this measurement system is capable to distinguish the difference between different parts. While the operator variation component and the interaction variation component between the operator and the part are seen to be statistically significant (a p-value less than 0.05), the measurement system is not capable of distinguishing these effects (the variance of these effects is comparable of the pure error of the measurement).

Part Number	Operator 1			Operator 2			Operator 3		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
1	37	38	37	41	41	40	41	42	41
2	42	41	43	42	42	42	43	42	43
3	30	31	31	31	31	31	29	30	28
4	42	43	42	43	43	43	42	42	42
5	28	30	29	29	30	29	31	29	29
6	42	42	43	45	45	45	44	46	45
7	25	26	27	28	28	30	29	27	27
8	40	40	40	43	42	42	43	43	41
9	25	25	25	27	29	28	26	26	26
10	35	34	34	35	35	34	35	34	35

Table 3-1.Measurement result on thermal impedance on a power module for an induction motor starter,

Source	Degree of Freedom	SS	MS	F	P
Part	9	3935.96	437.33	162.27	0.000
Operator	2	39.27	19.64	7.28	0.005
Part*Operator	18	48.51	2.70	5.27	0.000
Error	60	30.67	0.51		
Total	89	4054.4			
Source	Variance Component	Error Term	Expected Mean Square for Each Term (using unrestricted model)		
(1) Part	48.2926	3	(4) +3(3) + 9(1)		
(2) Operator	0.5646	3	(4) +3(3) + 30(2)		
(3) Part*Operator	0.728	4	(4) +3(3)		
(4) Error	0.5111		(4)		

Table 3-2. ANOVA summary [5].

Chapter 4. Column Production

This chapter focuses on the machining processes and the real time inspection protocols of the column production. The background information about the CNC machines and tools we use is provided first and then the machining processes are described in time sequence in Section 4.1. In Section 4.2, available measurement devices are introduced and summarized within different groups divided by different dimensions. A new fixture is required to improve the OASIS system capability, and its design is covered in Section 4.3.

4.1 Column Machining Processes

In this section, we will cover background information about column machining processes. The following section will introduce the machine and tools first, and the machining processes will be described in detail in the subsequent section.

4.1.1 The Citizen A20 CNC Machine

The columns are mainly manufactured by the Citizen A20 CNC machine in the Machining Center. The Citizen A20 model from Japanese Marubeni Citizen-Cincom Inc. is acclaimed as a high-rigidity and low-cost 5-axes ϕ20mm machine. It offers an additional axis on the back spindle which enables front and back simultaneous machining. Combined with its fast 32m/min feed rate, it ensures a short cycle time. The layout of the five axes is shown in Figure 4-1 [13].

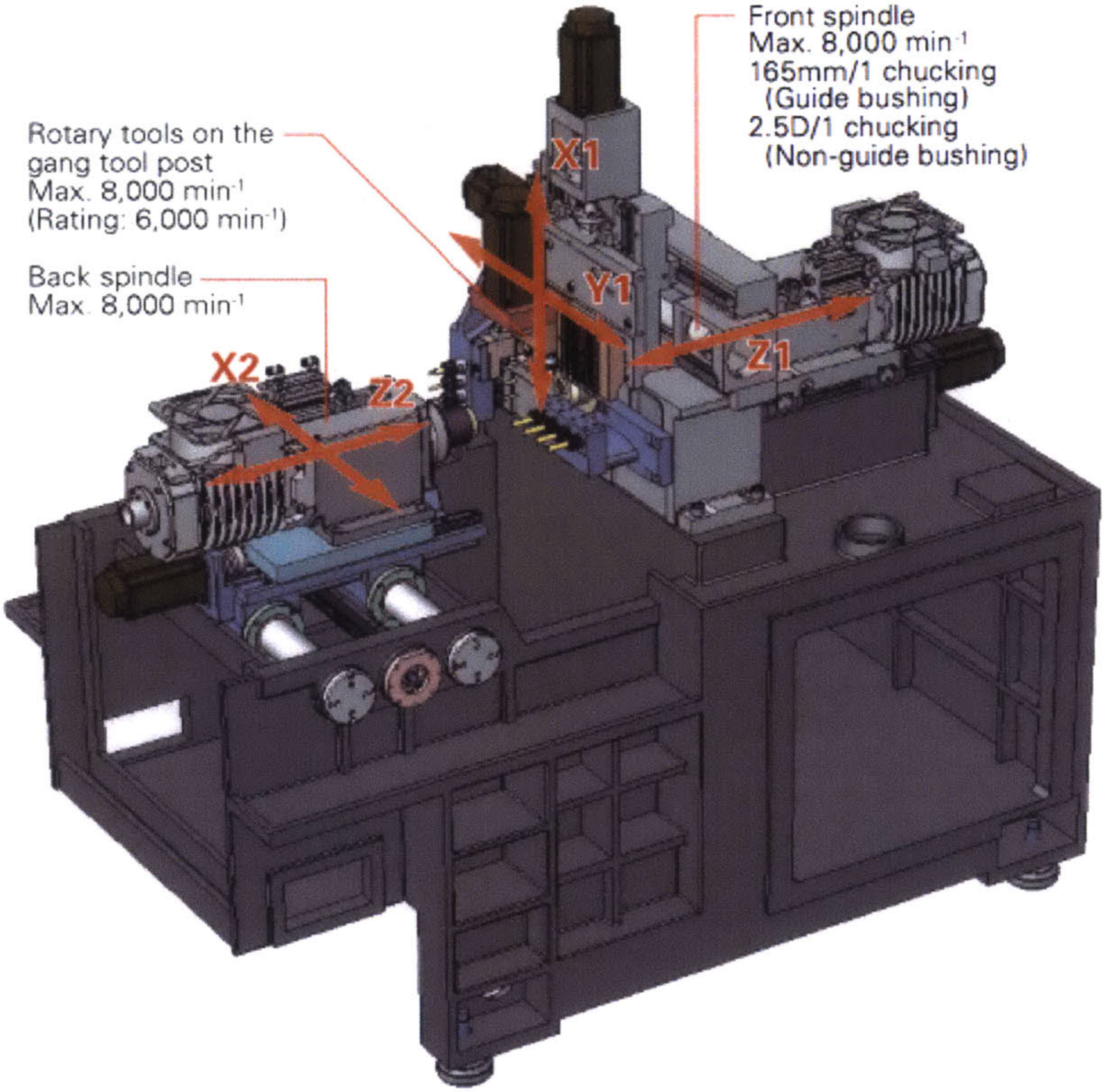


Figure 4-1. 5 Axes layout of the Citizen A20 CNC machine [13].

Cincom is able to provide customized tool layouts for different companies. However, the standard tool layout is adequate for the column production. There are three cross-machining rotary tools in the standard layout, and one cross-milling spindle can be changed to an optional end face drilling spindle. An independent back tool post, which is referred to as the sub side spindle, is available to mount at most of the four ϕ25.4mm drill sleeves, driven by the additional axis in the back spindle to enable simultaneous machining. The standard tool layout of the machine is presented in Figure 4-2 [13].

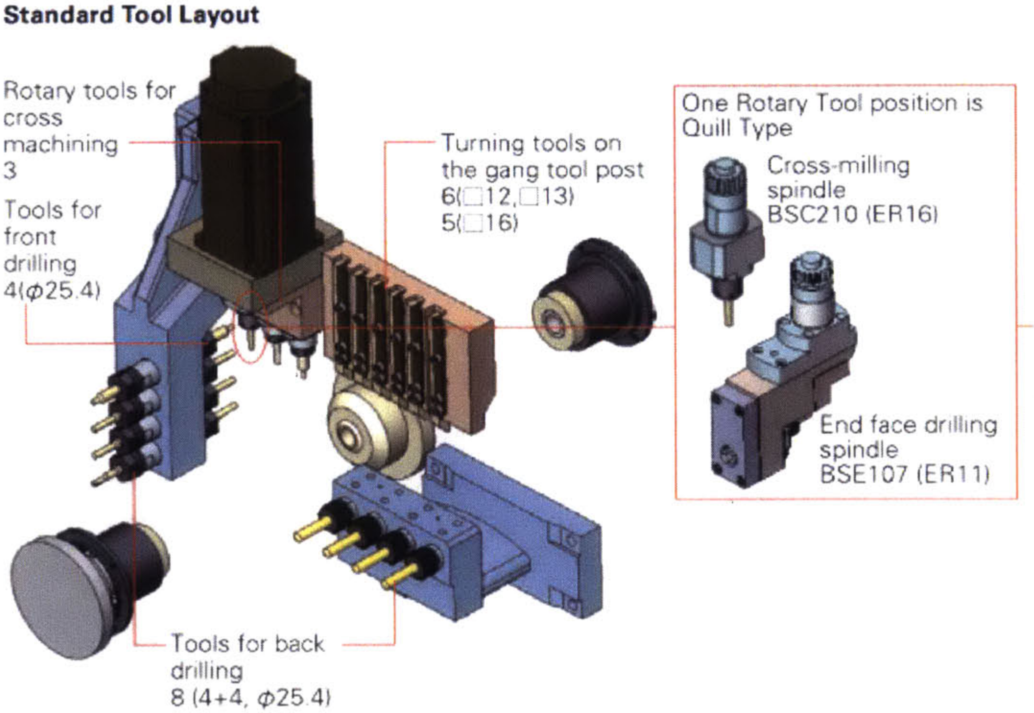


Figure 4-2. Standard tool layout [13].

4.1.2 Tools for Column Production

A variety of tools are utilized based on the unique features of a certain column family. In general, a cut-off tool, a turning tool, a spot drill, a threading insert, an end mill and an engraver are needed to complete the machining tasks at each end of the column. The cut-off tool (Figure 4.3) is used to cut the raw material, which is a long bar in general, into small columns. The turning tool (Figure 4.4) is an insert mounted onto a tool holder, performing the facing and the profiling processes. The spot drill (Figure 4.7) generates the miniature chamfer feature at the edge of the inner diameter. The threading insert (Figure 4.5) finishes the thread and the end mill (Figure 4.6) faces two parallel flat surfaces on the column. The engraver (Figure 4.8) writes the lot number on the column.

Figure 4-3. Cut-off tool.

Figure 4-4. Turning insert.

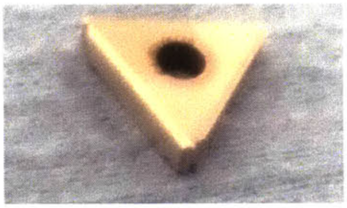


Figure 4-5. Threading insert.

Figure 4-6. End mill.

Figure 4-7. Spot drill.

Figure 4-8. Engraver.

4.1.3 Machining Processes

A simplified image of one end of a common column is shown in Figure 4-9.

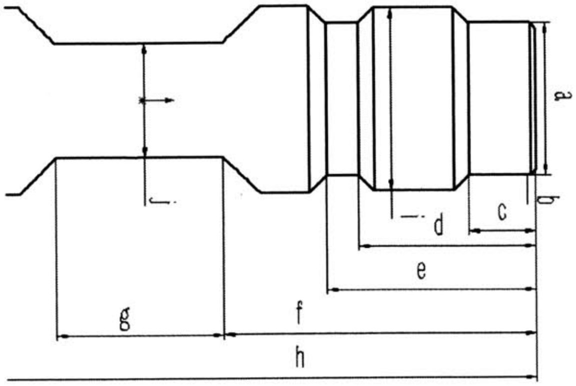


Figure 4-9. One end of a typical column.

There are several critical features on the column: the outer diameter (dimension *a*), the thread (dimension *i*) and the flats (dimension *g* and *j*). The outer diameter and the thread will determine the sealing function of the column while the flats will play an important role during the column packaging and assembly.

To produce these features, first of all, a bar feeder feeds a bar into the main spindle. The turning insert in the main side performs a finish cut on the vertical surface. Then it profiles the chamfer (dimension *b*), turns the outer diameter and profiles the beginning and end position of the thread (dimension *c* and *d*) and the thread relief (dimension *e*). After that, the spot drill comes in and touches the edge of the inner diameter to form the inner chamfer, which can not be seen in the picture. Then the threading insert cuts the thread. The end mill comes and faces one of the flats. The spindle rotates 180 degrees, and the end mill faces the second flat surface. That completes all of the features on one side.

After the machine finishes the main side, the sub spindle, which is Z2 in Figure 4-1, comes and grabs the column. The same end mill comes and faces two flats in the same manner. Then the engraver writes the lot number on the sub side, and the cut-off tool cuts the column close to the main side. The sub side spindle moves to the side with the column and uses the tools mounted on the back tool post to generate the same features as on the main side. Simultaneously, the bar feeder feeds the raw material in and the next cycle begins on the main side. A typical column is shown in Figure 4-10.

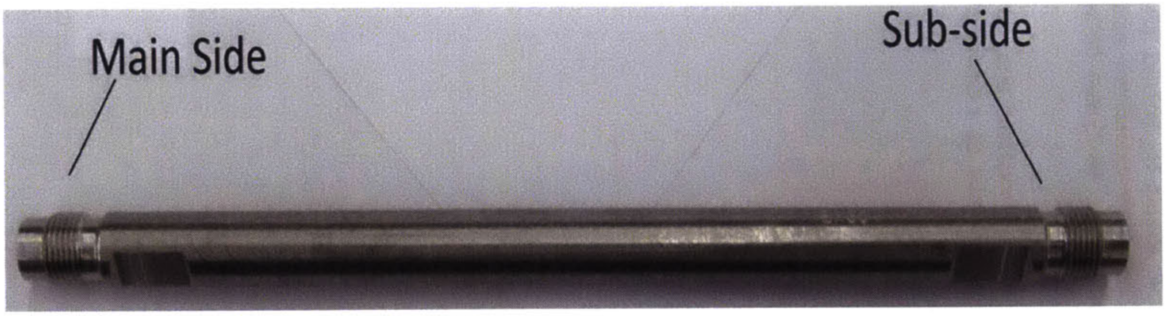


Figure 4-10. Column.

4.2 Introduction to Available Gages

This section will introduce all of the gages available and the related dimensions they can measure. Specific metrics for certain gages are provided as well.

4.2.1 Micrometer

The company uses normal micrometers that are available in the market as shown in Figure 4-11. In general, they have a resolution of 0.00005 inch, and a range from 0 to 1 inch. Some provide a digital reading, and this reading can be sent to data collecting computers. As a result, real time control charts can be plotted based on that. They can be used to measure the outer diameter, the main diameter of the thread, the and thickness of the flats.

Figure 4-11. Micrometer.

4.2.2 Blade Micrometer

The blade micrometer is a similar gage to the micrometer except that it has two narrow blades instead of two flat surfaces to measure the part as shown in Figure 4-12. These two blades enable it to capture the dimension in the specific location. For example, the operator can use the blade micrometer to measure the thickness of the flats in different locations. As a result, the operator can have a better understanding about the tape effect on the flats. The normal micrometer is unable to capture this. However, when measuring a continuous flat surface, the blade micrometer will have a bigger error than the normal micrometer because the normal micrometer provides more contact surface between the gage and the part. So the blade micrometer is used to measure the thickness of the flats only.

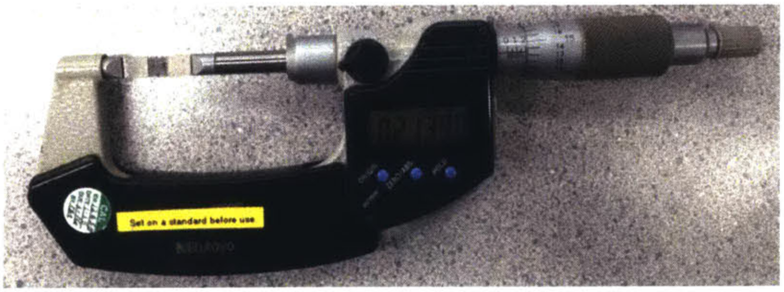


Figure 4-12. Blade micrometer.

4.2.3 OASIS Inspection System

The OASIS Inspection System[1] is an accurate optical measurement device, with an optical transmitter and receiver as shown in Figure 4-13. The transmitter projects lights on the part, and the receiver receives the light that is not blocked by the part. The receiver sends data to the central computing unit, and feeds the digital image into the special program as shown in Figure 4-14 (actual measurement value is blocked for confidentiality reasons). The program will calculate the measurement result for several features as designed. The program is linked to a real time data collection system, which will calculate the control limits and plot the control charts. The OASIS can be used to measure a large range of dimensions.

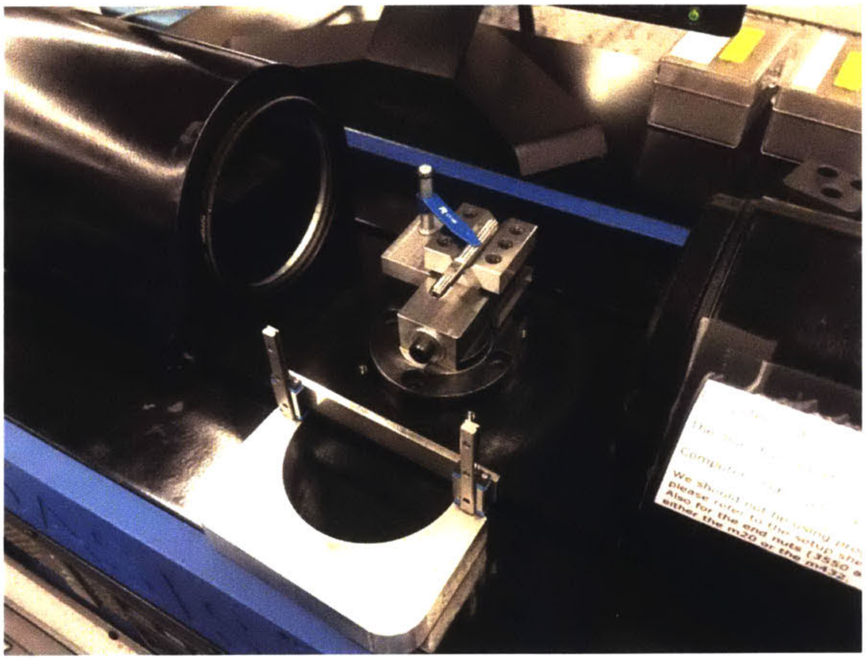


Figure 4-13. OASIS Inspection System: the optical transmitter and receiver, the column and fixture.

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[1] Manufactured by George Products Company, Inc. at 110 Sleepy Hollow, Middletown, DE 19709.

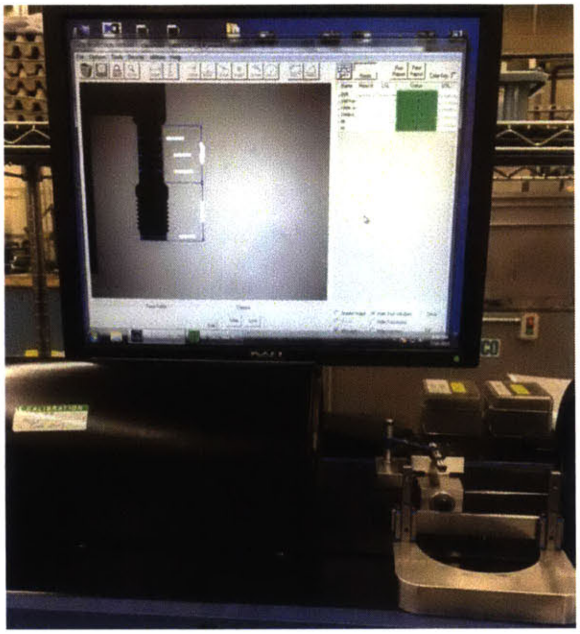

Figure 4-14. OASIS Inspection System: the automatic measurement program.

4.2.4 Profilometer

The profilometer uses a sensitive probe costing $800 each to profile the surface of the part. The operator brings the probe to touch the target surface of the part manually and then the probe will move in the preset direction horizontally. Figure 4-15 shows that as the probe moves, the bumps and cavities on the target surface of the part will force the probe to move up and down. This movement data is sent to a computer and a surface profile is constructed as shown in Figure 4-16. Miniature features on the surface, like chamfers and grooves, can be measured and the surface finish can be calculated as well.

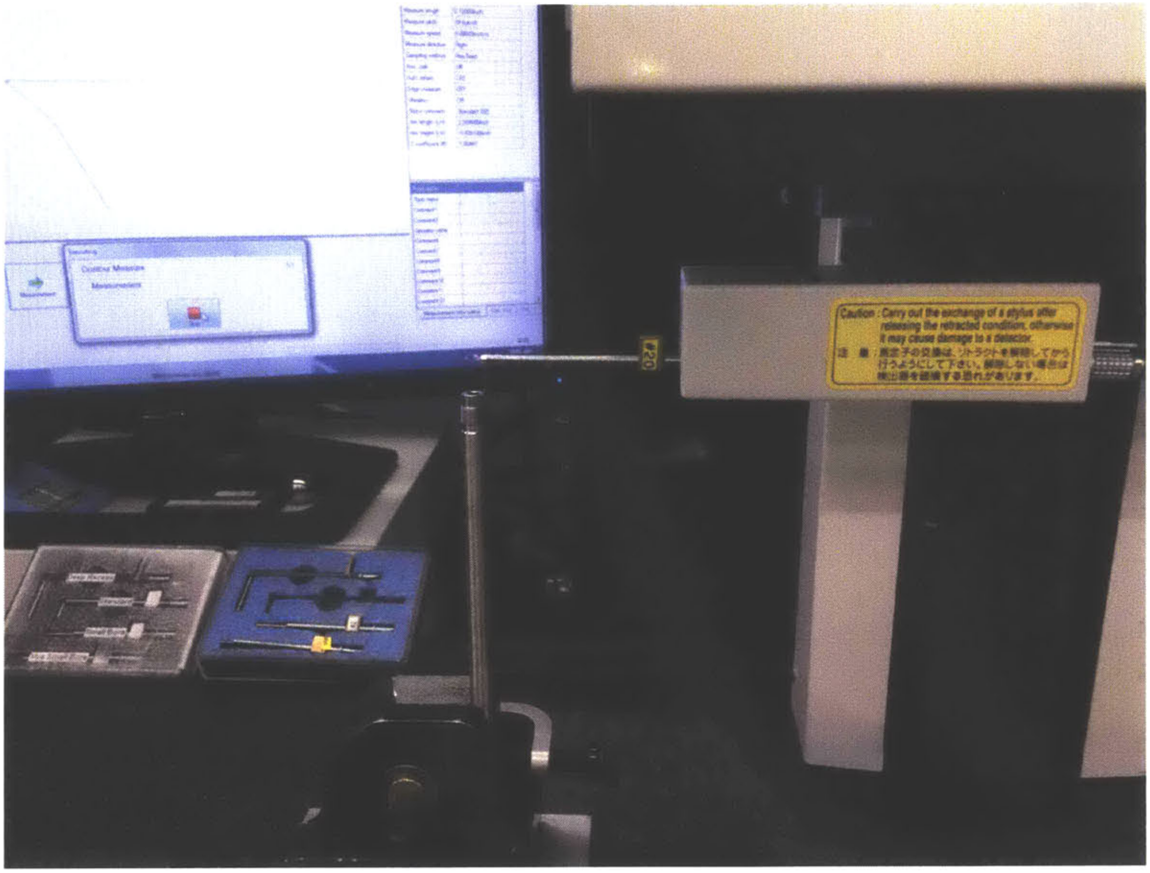

Figure 4-15. Profilometer.

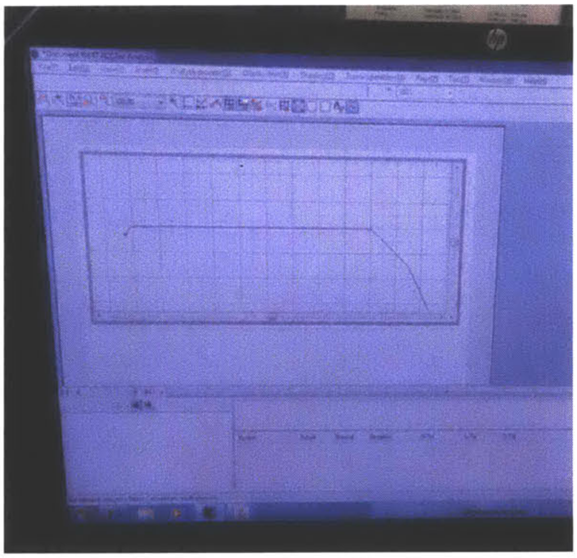

Figure 4-16. Surface profile constructed by profilometer.

4.2.5 Comparator

The comparator is an optical measurement device similar to the OASIS system except that it does not offer an automatic measurement function. It has a projector and a screen as shown in Figure 4-17. Figure 4-18 shows the projector as it shines light on the part, and Figure 4-19 shows the shadow of the part that will be projected on the screen. The part can be moved relative to the coordinates on the screen, and the difference between different coordinate values can be calculated; in this way, the dimension of certain features can be measured. The comparator is used to measure the position of the thread, the chamfer size, the location of the flat, the width of the flat and the shape of the flat.

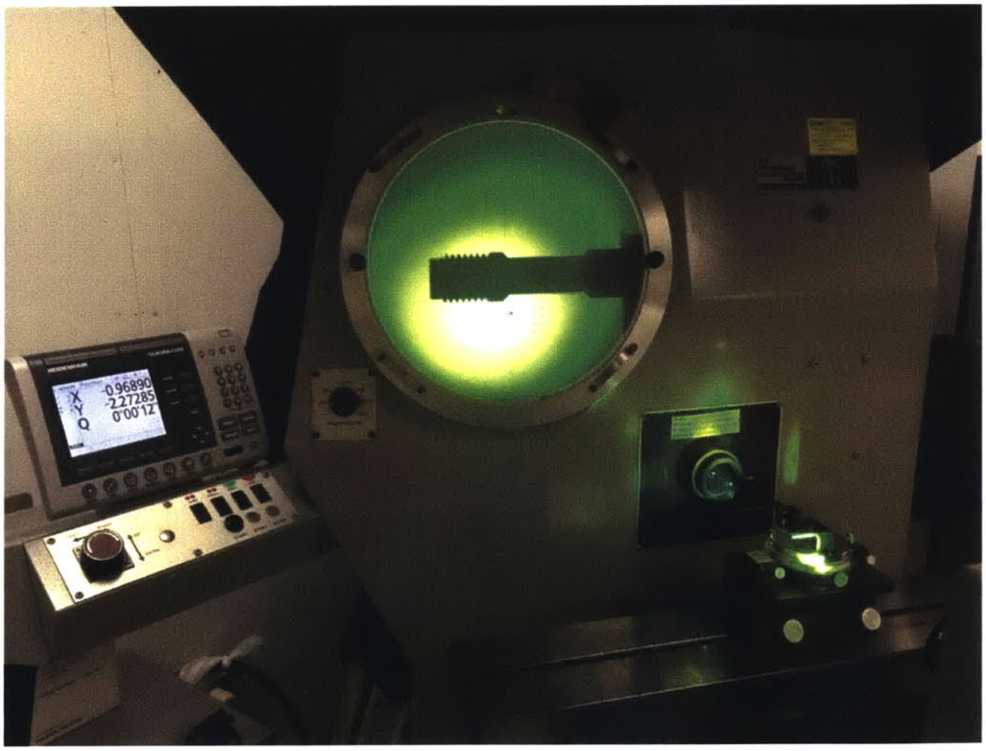

Figure 4-17. Comparator.

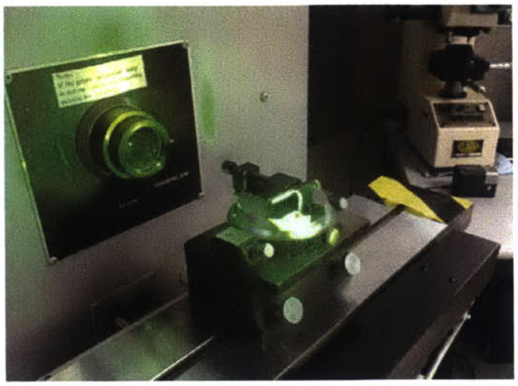

Figure 4-18. Light receiver of the comparator.

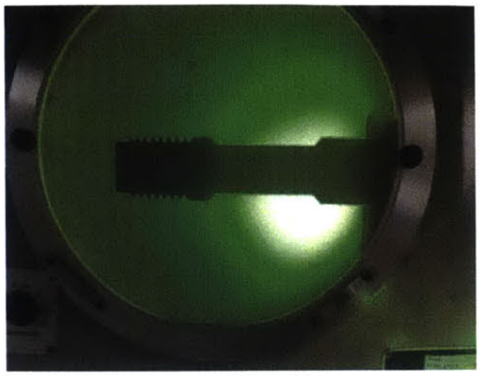

Figure 4-19. The screen of the comparator.

4.2.6 Johnson Gage

The Johnson gage[2] is a specific measurement device designed and manufactured for the measurement of the thread dimension as shown in Figure 4-20. Depending on which mode it is set up with, it can measure the pitch diameter or the form of the thread. It provides a digital reading and is connected to the computer for real time monitoring. Its resolution is 0.0001 inch and its range depends on the mode. In general, the range is adequate for the standard thread measurement.

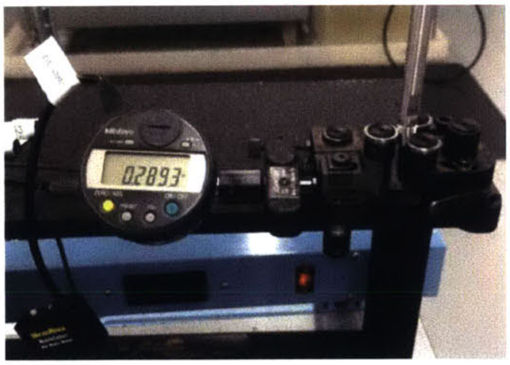

Figure 4-20. Johnson gage.

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[2] Manufactured by Johnson Gage Company at 534 Cottage Grove Rd. Bloomfield, CT 06002.

4.2.7 Height Gage

The height gage is placed on a flat marble surface as shown in Figure 4-21. Its resolution is 0.0001 inch. Its range is 0 to 18 inches. It is used to measure the total length of the column.

Figure 4-21. Height gage.

4.2.8 Microscope

The microscope (Figure 4-22) can amplify the image 100 times and the operator uses it to check the surface finish of the part. As mentioned in Chapter 2, a column as a final product is sold at a high price, and a tiny scratch on the surface is unacceptable for the customers even though it does not affect the function. And a scratch on the sealing surface will be fatal to its function and thus is also unacceptable.

The microscope can also be used to check the tools. When the operator is suspicious about the current tool condition or a new tool, he can check it under the microscope. It is an important gage in the Inspection Area but there is not a standard way to utilize it.

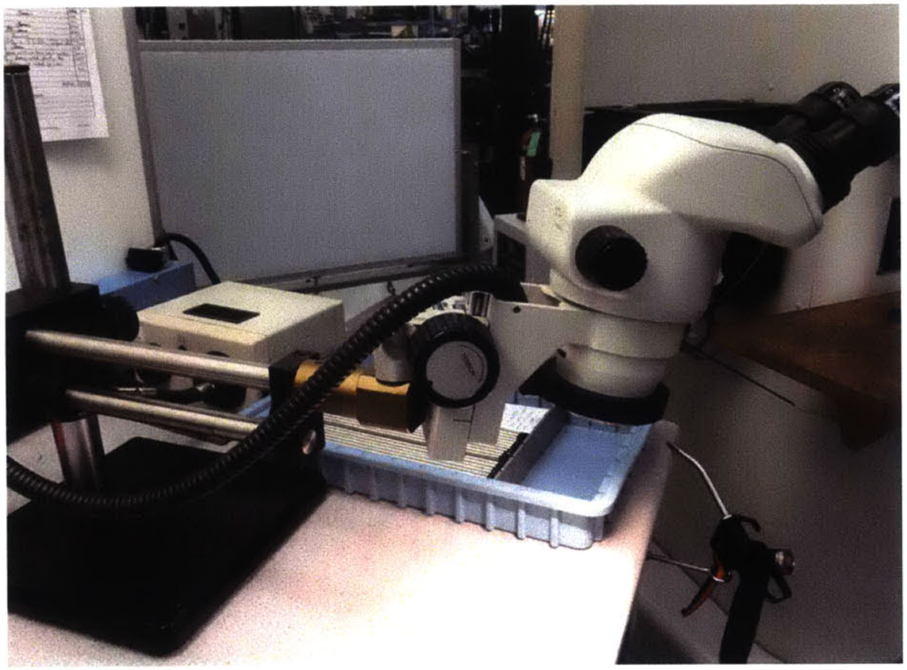


Figure 4-22. Microscope.

4.2.9 Table of Dimensions and Respective Measurement Devices

Table 4-1 summarizes the gages that can be used for measurement of different dimensions of the column, as previously illustrated in Figure 4-9.

	Dimension	Measurement Devices
a	Outer diameter	Micrometer, Blade micrometer, OASIS
b	Chamfer	OASIS, Comparator, Profilometer
c	The begin of the thread	Comparator
d	The end of the thread	Comparator
e	The location of the thread relief	OASIS, Comparator
f	The location of the flat	OASIS, Comparator
g	The width of the flat	OASIS, Comparator
h	Total length	Height gage
i	Pitch diameter	OASIS, Johnson Gage
j	The thickness of the flat	Micrometer, Blade micrometer, OASIS

Table 4-1. Dimensions and respective measurement devices.

4.3 Fixture Design for OASIS Inspection System

Before we conducted the Gage R&R study, we noticed that the OASIS system was not capable of locating the part correctly for measurement. The operator needed to manually adjust the location of the column to achieve a good measurement result. As a result, this measurement procedure included too many variations. Therefore, we decided to design a new fixture for the OASIS system before we began our Gage R&R study.

4.3.1 Design Requirement

A new fixture for the OASIS Inspection System was deemed to be necessary, in order to utilize the OASIS system to enable quick real time inspection, the column needs to be located and fixed properly relative to the inspection coordinate.

For the OASIS Inspection System, we assume that the direction in which the light is transmitted is the x direction. The z direction is the vertically upward direction. And the y direction can be determined by right-hand rule. The x, y and z directions are shown in Figure 4-23.

There are two ways to locate the column properly: horizontally or vertically. Located horizontally as shown in Figure 4-23, the column is supposed to be placed in a way that its axis is parallel to the y-axis, and its flats are vertical to the z-axis. If it is located vertically, its axis should be parallel to the z-axis and its flats should be vertical to the y-axis. In this way, all the dimensions will be either parallel or vertical to the digital coordinates in the program, and the thickness of the flats can be measured properly. Thus the fixture should be able to constrain three rotational degrees of freedom.

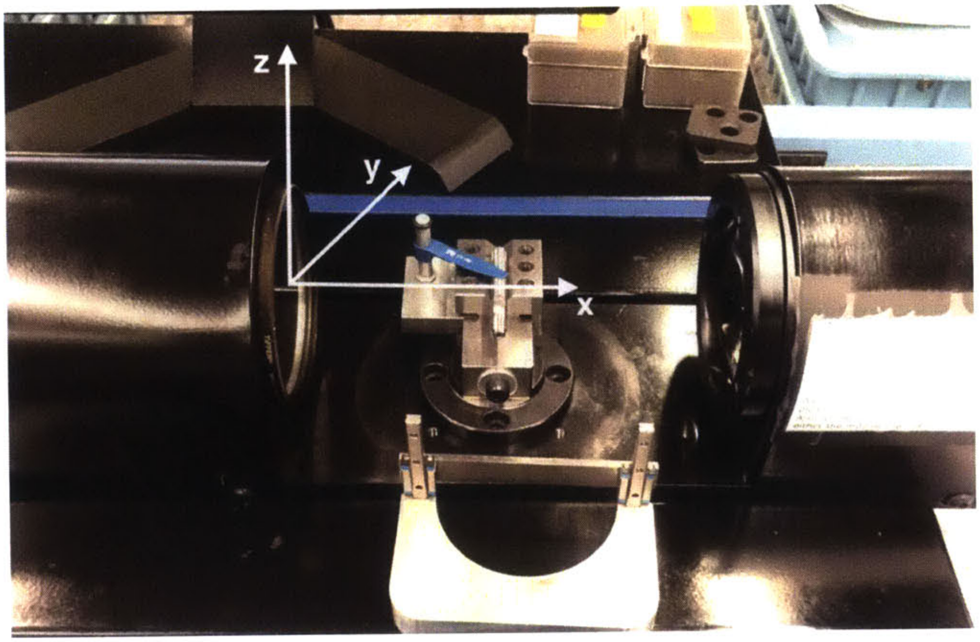


Figure 4-23. OASIS system coordinate.

As for the translational degrees of freedom, the column is required to be located in the middle of the transmitter and the receiver in order to achieve good image quality. Therefore, the fixture should be able to constrain one translational degree of freedom.

Besides its functional requirements, the fixture also needs to be easy to manufacture, assemble and operate. In addition, the column size varies from less than half inch to more than 4 inches in length, less than quarter inch to more than 1.5 inches in diameter. The fixture should be able to accommodate this variation.

4.3.2 Actual Design

Figure 4-24 shows the rectangular base previously in use. It has a flat surface to place the part. There are two locating pins at the bottom of the base as shown in Figure 4-25, and there are three respective locating holes on the surface of the OASIS system between the transmitter and the receiver as shown in Figure 4-26.

These locating pins and holes, with the mating feature between the bottom surface of the base and the surface of OASIS system, ensure the flat surface on the base is vertical to the z-axis of the OASIS system. This base can be used to measure the end fittings on the OASIS system, but it does not meet the requirements needed to measure the columns.

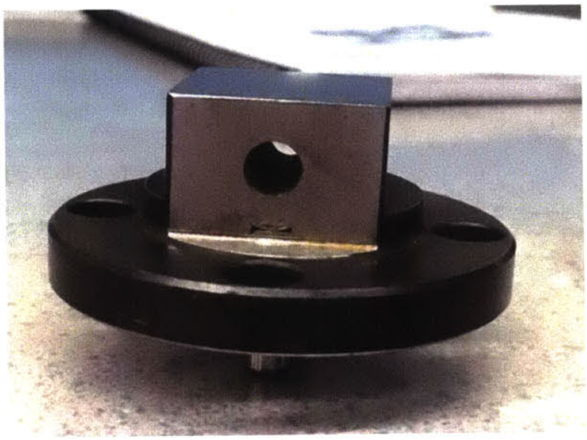


Figure 4-24. The rectangular base for OASIS system.

Figure 4-25. Location pins.

Figure 4-26. Location Holes.

First of all, a V-block was designed. Its two mating surfaces were machined carefully so that they are perpendicular to each other. The bottom surface, which is surface B in Figure 4-27, is perpendicular to the center line of the V-groove perpendicular to the symmetric plane of the V-groove. The front surface A is perpendicular to the center line of the V-groove. Surface A is mounted onto the existing base by a screw through the through hole perpendicular to it so that it is perpendicular to the y-axis. Surface B mates with the base surface to make sure that it is perpendicular to the z-axis. There are several threaded holes on surface C and D to integrate the fastening mechanism into the V-block. Figure 4-28 shows the actual V-block we obtained from the distributor and Figure 4-29 shows the final V-block mounted onto the base with a fast loading mechanism (the blue clip).

When a column is placed on the V-block, its two rotational and two translational degrees of freedom are constrained. Its axis is parallel to the y-axis and its translational degree of freedom in x direction is constrained. The only degree of freedom that still needs to be constrained is the rotational degree of freedom about the y-axis.

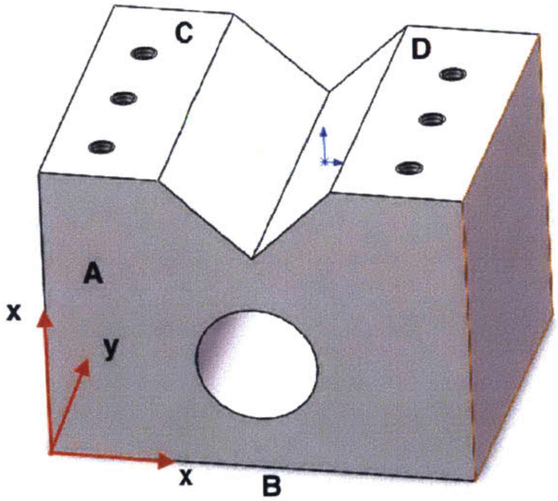


Figure 4-27. V-block CAD model.

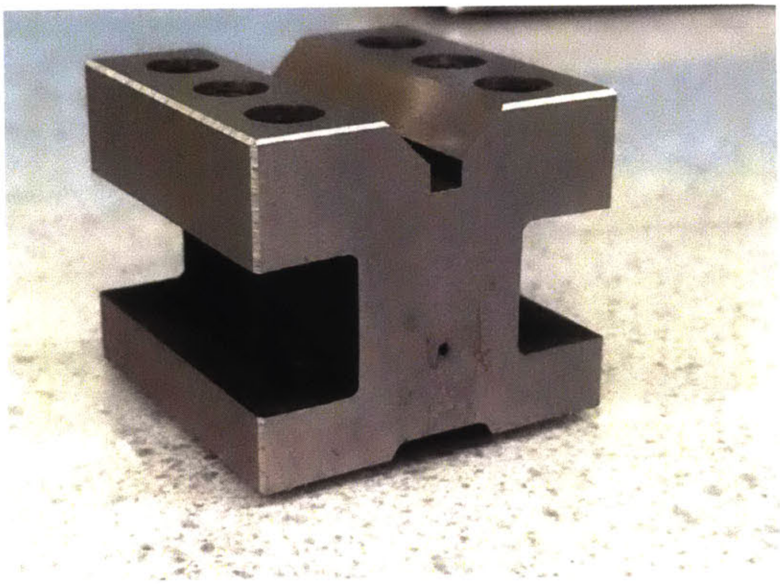


Figure 4-28. V-block before drilling the through hole.

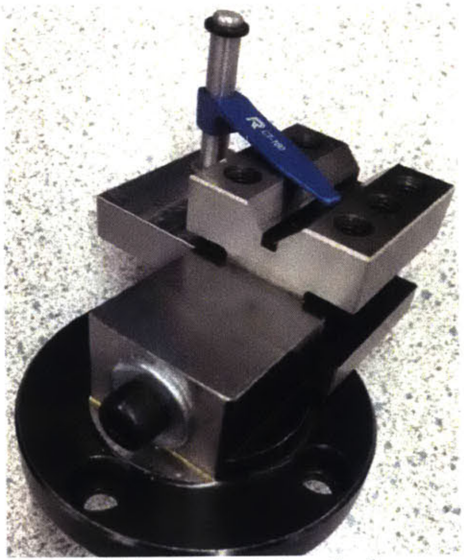


Figure 4-29. V-block mounted on the base.

A second component of the fixture was designed to accomplish the constraint of the last rotational degree of freedom. In addition, the fixture should not block the transmitter or the receiver. So, a parallel guiding rail subsystem was designed. The key idea is to use the machined flats on the column to achieve a repeatable and fixed angle of rotation. A cross parallel can slide up and down on the rail to constrain the rotational degree of freedom for columns of different sizes, making contact with and facing the machined flat to be parallel with the fixture cross parallel. The subsystem consists of a base, two pairs of guiding rails and carriages and a cross parallel. Figure 4-30 shows its CAD model. There are two grooves on the front surface of the base. They are designed to be machined perpendicular to the bottom surface, so that the guide rails can mate with them and remain vertical. There is a carriage on each guiding rail, such that each carriage can move up and down independently on the rail. Finally, a cross parallel is mounted on the carriages.

It is obvious that the guiding rails and the carriages are quite complicated to manufacture while the base and the cross parallel are much easier to machine. In order to shorten the lead time for fabricating, we chose the guiding rails and the carriages from a mechanical component distributor, and then designed the geometric tolerance on the base and the cross parallel. As a result, the whole subsystem took less than four hours to machine and assemble. Figure 4-31 shows the actual fixture we machined and assembled. Figure 4-32 shows the entire fixture used on the OASIS system.

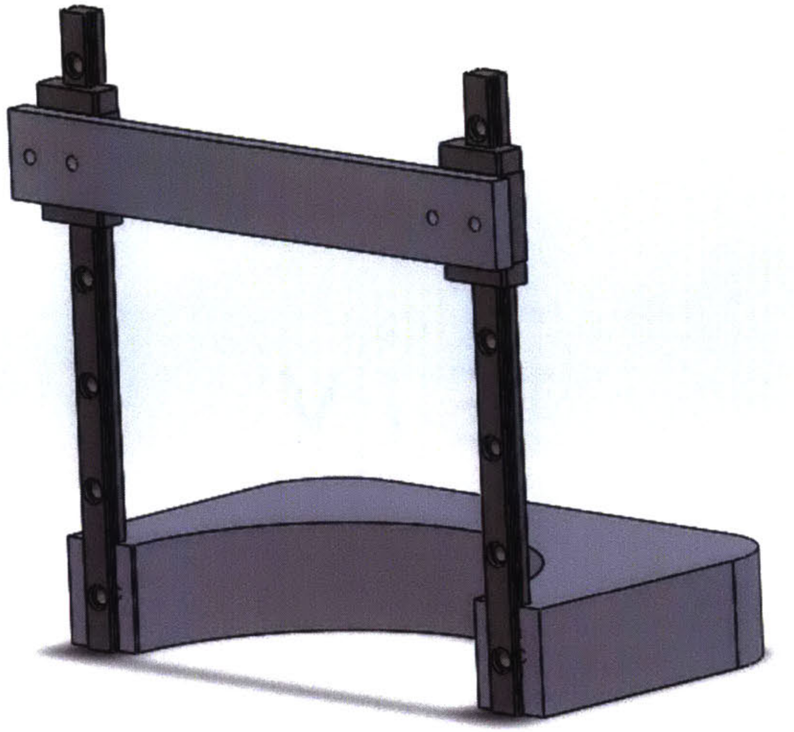


Figure 4-30. Guiding rail subsystem CAD model.

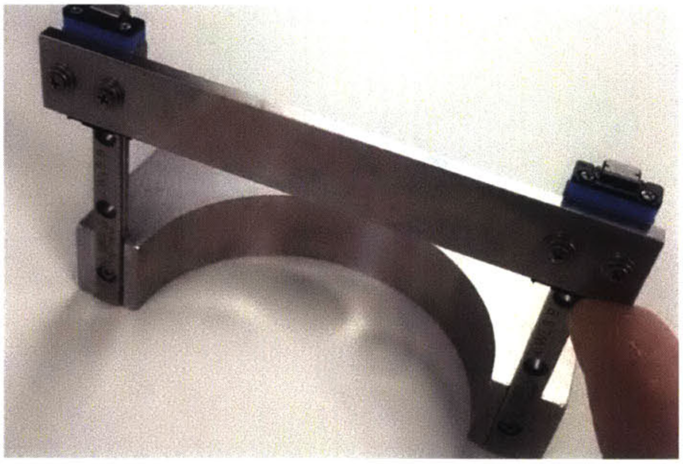


Figure 4-31. Actual guiding rail subsystem.

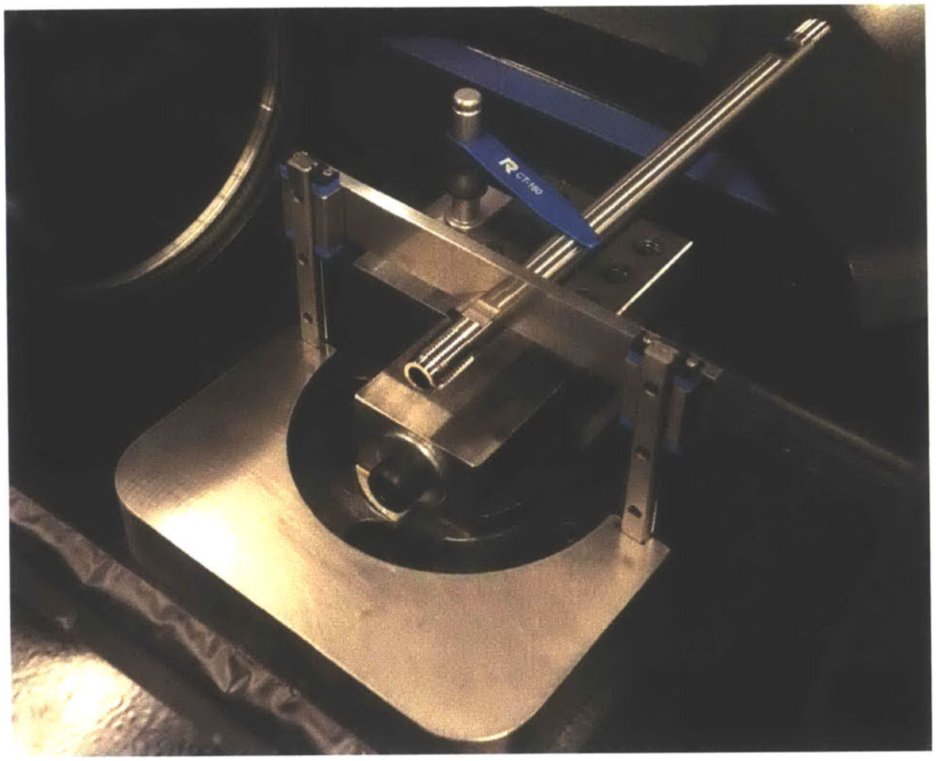


Figure 4-32. Entire fixture for OASIS system.

Chapter 5. Gage Repeatability and Reproducibility

This chapter is the main body of this thesis, focusing on gage capability analysis. The purpose, methodology to deal with different part types, capability analysis, approach to improve capabilities and final results are discussed in each section below.

5.1 Purpose

This Gage R&R study is to evaluate the gage capabilities to perform inspection and serve as a part of the SPC real time inspection system. The analysis of the variation will also reveal potential opportunities to eliminate assignable causes of the variation during the inspection.

5.2 Methodology

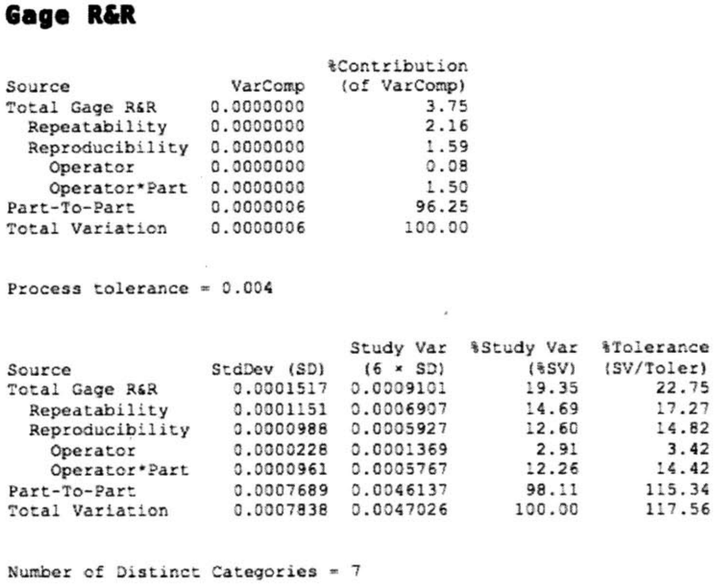
The company supplies more than 90 different types of columns to the market. They share similar features with different sizes. It is impossible for us to evaluate the gage capabilities to measure the dimensions from all the different types of parts given the time constraint. Since the features are similar and the same gages are used to measure the same features across different types, our methodology is to focus on the inspection of one type of columns and evaluate the gage capabilities first, and then show that the methodology can also be applied to different types of columns.

We conducted the Gage R&R study, identified the sources of variation and developed methods to eliminate the dominant variation. Then we conducted the Gage R&R study again and verified the effectiveness of the variation reduction methods. After we demonstrated the gage's capabilities to inspect this type of column, we created three different column configurations to represent different column families. By conducting the Gage R&R study on these three configurations and demonstrating the gages' capabilities, we validate that the gages are capable to inspect different types of columns during the real time inspection.

5.3 Initial Gage R&R ANOVA Result

The 10 column dimensions in Figure 4-9 can be measured by different devices. In order to reduce the amount of time to conduct the study, we only conducted Gage R&R study on practical options based on theoretical analysis and engineering experience. For example, the outer diameter (dimension *a* in Figure xxx) can be measured by the OASIS system, the micrometer or the comparator. However, the operators never use the comparator to measure the outer diameter because it takes much more time and does not provide a more accurate result than the other two options. So in our study, we do not evaluate the comparator's capability to measure the outer diameter. Another example is the begining position of the thread (dimension *c*). Both the OASIS system and the comparator can be used to measure it. However, based on our knowledge about how the OASIS performs the measurement, we know it cannot capture the exact position of the thread due to physical limitations. So we only conducted the study on the comparator's capability for this dimension. The total length (dimension *h*) can be measured by the height gage only, and the column specification limits are wide. So this total length measurement is not included in our Gage R&R study.

In our Gage R&R study, we measured 10 different columns of the same type. We had three operators to measure them, each for three times in a random order. Then we used $Minitab^{TM}$[3] to conduct ANOVA. Minitab provided detailed ANOVA report for further analysis, including tables and graphs. Figure 5-1 and Figure 5-2 are screen shots from Minitab exported reports. We can obtain information about the different sources of the variation, their percentage contribution in the table report. In Figure 5-2, the graph report provides column graph to present variance components more intuitively. And the measurement result distribution, R chart, X-bar chart and boxplot by different operators help evaluate the variation from operators and the interaction between the operator and the part.



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Gage R&R

                                     %Contribution
Source                    VarComp     (of VarComp)
Total Gage R&R          0.0000000             3.75
  Repeatability         0.0000000             2.16
  Reproducibility       0.0000000             1.59
    Operator            0.0000000             0.08
    Operator*Part       0.0000000             1.50
Part-To-Part            0.0000006            96.25
Total Variation         0.0000006           100.00


Process tolerance = 0.004


                                    Study Var  %Study Var  %Tolerance
Source                  StdDev (SD)  (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R            0.0001517  0.0009101      19.35       22.75
  Repeatability           0.0001151  0.0006907      14.69       17.27
  Reproducibility         0.0000988  0.0005927      12.60       14.82
    Operator              0.0000228  0.0001369       2.91        3.42
    Operator*Part         0.0000961  0.0005767      12.26       14.42
Part-To-Part              0.0007689  0.0046137      98.11      115.34
Total Variation           0.0007838  0.0047026     100.00      117.56


Number of Distinct Categories = 7
```

Figure 5-1. Screen shot of the ANOVA table from Minitab.

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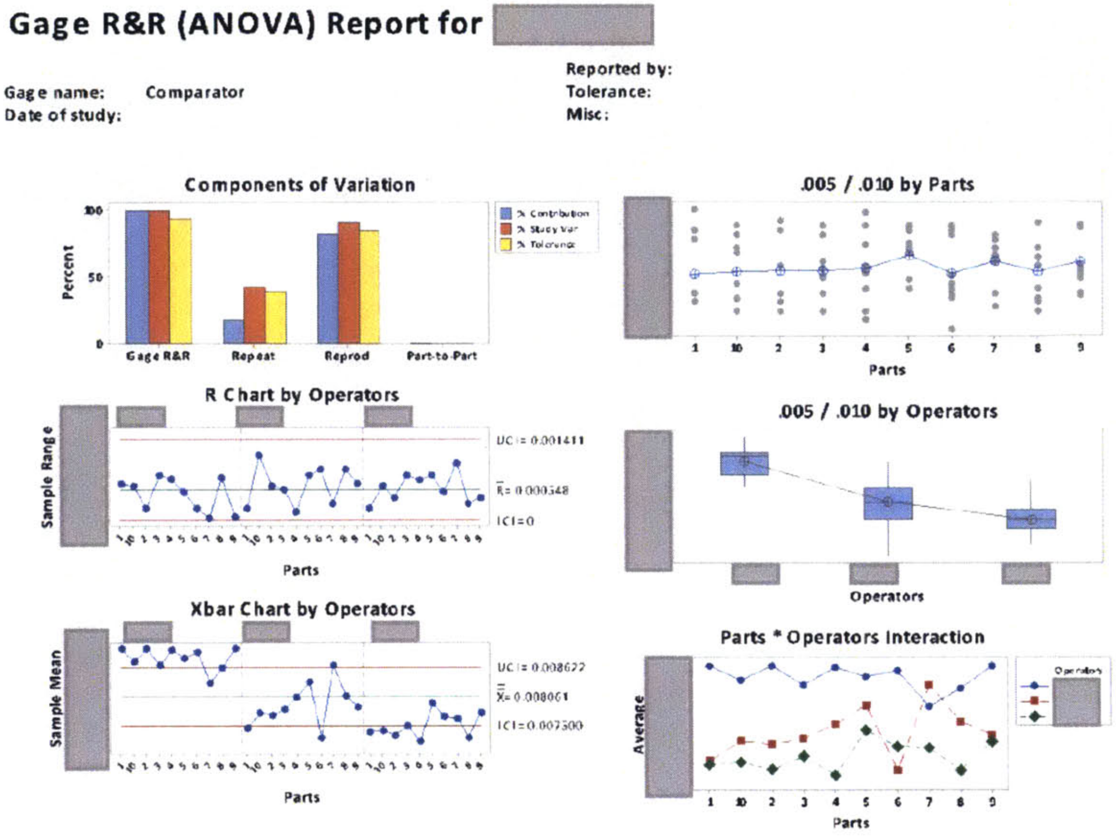
[3] Developed by Minitab Inc. at Quality Plaza, 1829 Pine Hall Road, State College, PA 16801



Gage R&R (ANOVA) Report for [redacted]

Gage name: Comparator
Date of study:

Reported by:
Tolerance:
Misc:

Figure 5-2. Screen shot of the ANOVA graphs from Minitab.

In order to have an overall review of the study, we use P/T ratio, which is a common parameter to evaluate a gage's overall capability as introduced in Chapter 3. Recall that P/T ratio given by Equation 3-3 expresses the fraction (or percentage) of the part tolerance (lower to upper specification limits) that is consumed by some multiple k times the gage standard deviation. Here we use $k = 6$ to indicate our desire for a good precision gage. Table 5-1 is the summary of the P/T ratios expressed in percentage for different dimensions in our study. For the outer diameter, we measured it in two different locations using the OASIS system to compare the measurement difference. They are noted as *a1* and *a2*. For the thickness of the flats, we measured it on the OASIS system in three different locations: close to the edge, middle and farther to the edge, noted as *j1*, *j2* and *j3* in the table. The difference in the measurement result assists in further analysis of the bending effect during machining.

Dimension	Gage	P/T Ratio (%)	
		Main side	Sub side
a1	OASIS	46.81	18.21
a2	OASIS	31.3	10.61
a	Micrometer	61.52	84.95
b	Comparator	1013.38	93.35
	OASIS	156.45	339.55
c	Comparator	49.97	23.42
d	Comparator	3634.65	41.77
e	Comparator	89.04	63.58
	OASIS	18.04	15.19
f	Comparator	34.09	45.3
	OASIS	55.42	8.61
g	Comparator	39.34	32.24
	OASIS	131.05	159.82
i	Johnson Gage	179.66	47.12
j1	OASIS	22.75	41.4
j2	OASIS	34.24	60.16
j3	OASIS	20.25	39.67
j	Micrometer	62.58	64.36

Table 5-1. Initial Gage R&R Result Summary.

5.3.1 Gage selection

From Table 5-1, it is obvious to conclude that the OASIS system is more capable to measure dimension *a* and *j* than the micrometer, and the comparator is more capable to measure dimension *b* and *g* than the OASIS system, while the OASIS system is better at measuring dimension *e* and *f* than the comparator.

Based on this comparison, we can select suitable gages for each dimension. However, in most cases these gages are not capable to meet the 30% P/T Ratio requirement. Further investigation is needed.

5.3.2 Root Cause Analysis for Incapable Gages

First of all, it is not quite reasonable for a gage to be capable to measure a certain dimension on one side of the column but incapable on the other side: the column that is machined with the same processes and it is measured in the same way by the same gage. Also, based on the operators' and the engineers' experience, these gages are very capable and they have been using them for a long time. We were suspicious that we identified the gages as incapable due to certain mistakes in the calculation. After we looked into the graph report provided by Minitab, we identified the existence of an outlier or extreme data point as the cause of mistakes in the calculation.

For example, Table 5-1 indicates that the OASIS system is capable to measure *a1* and *a2* on the sub side of the column, but that it is incapable to measure these dimensions on the main side. If we look at the R Charts in Figure 5-3 and Figure 5-4, we can see that there is an extreme data point on each graph. When Minitab took this extreme data point into calculation, it exaggerated the gage variation and as a result, the gage was deemed incapable.

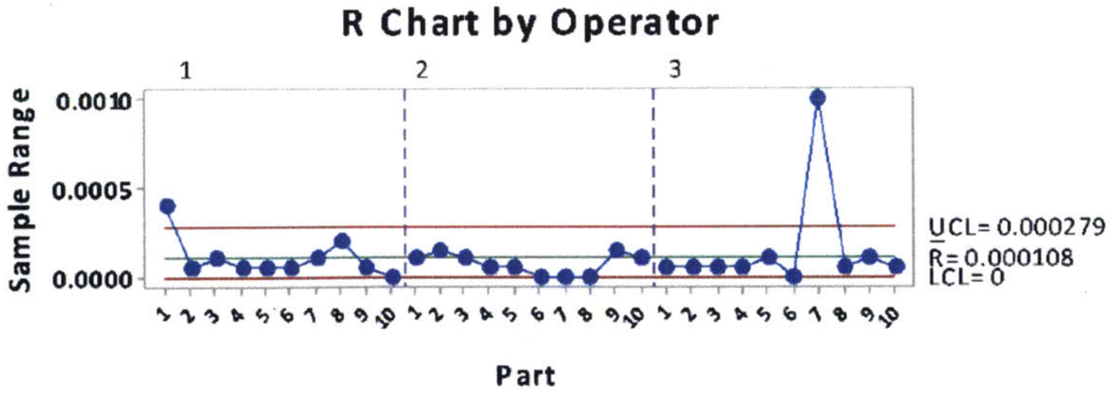


Figure 5-3. R Chart for dimension a1 on the main side.

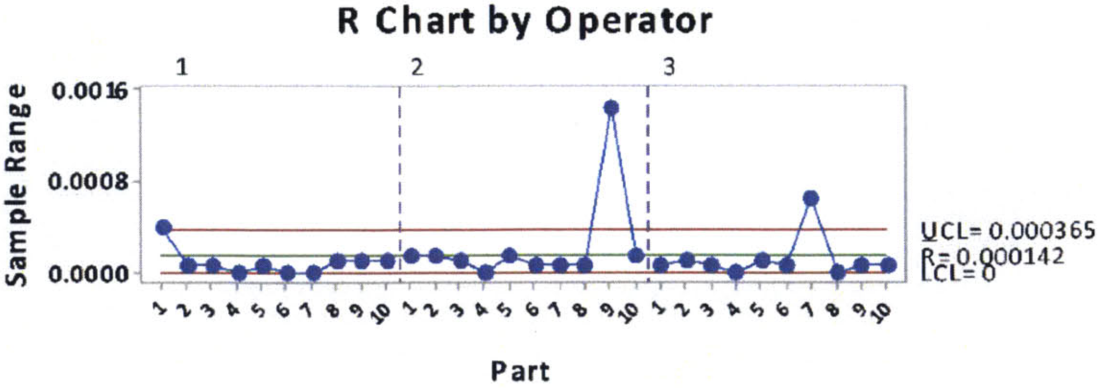


Figure 5-4. R Chart for dimension a2 on the main side.

The reasons for the occurrence of these outliers are various. If there is burr on the column surface, the program will take it into calculation. If the column is not located properly on the V-block, it will tilt and the measurement result will not be accurate. This really indicates that this measurement system may trigger false alarms frequently which we did experience during our implementation phase. As a result, we recommend the operator clean the surface of the part and the fixture and measure the part again to reduce false alarms when they see a point plotted outside control limits.

The same conclusion can be drawn for dimension *f* and *j*. Due to the measurement error during the inspection, the existence of extreme data points led to the wrong conclusion that the gage was incapable.

For dimension *b*, *c*, *d* and *i*, the gages did introduce a significant amount of variation into the process. The assignable causes for the variation needed to be identified and eliminated as much as we could. From the Minitab reports, we can see that the main variation comes from the inconsistency of the measurement procedure by different operators. For example, Figure 5-5 is the graph report for dimension *b* (actual measurement value is blocked for confidentiality reasons). From the box plot, it shows that three operators had different measurement results for the same part though the measurements made by the same operator seemed to be more consistent. Figure 5-6 shows the graph report for dimension *c* (actual measurement value is blocked for confidentiality reasons). From the R chart and the box plot, we can see that the second operator had a bigger variation than the others. And if we look at the Parts*Operators interaction plot, it also shows a large effect on the result.

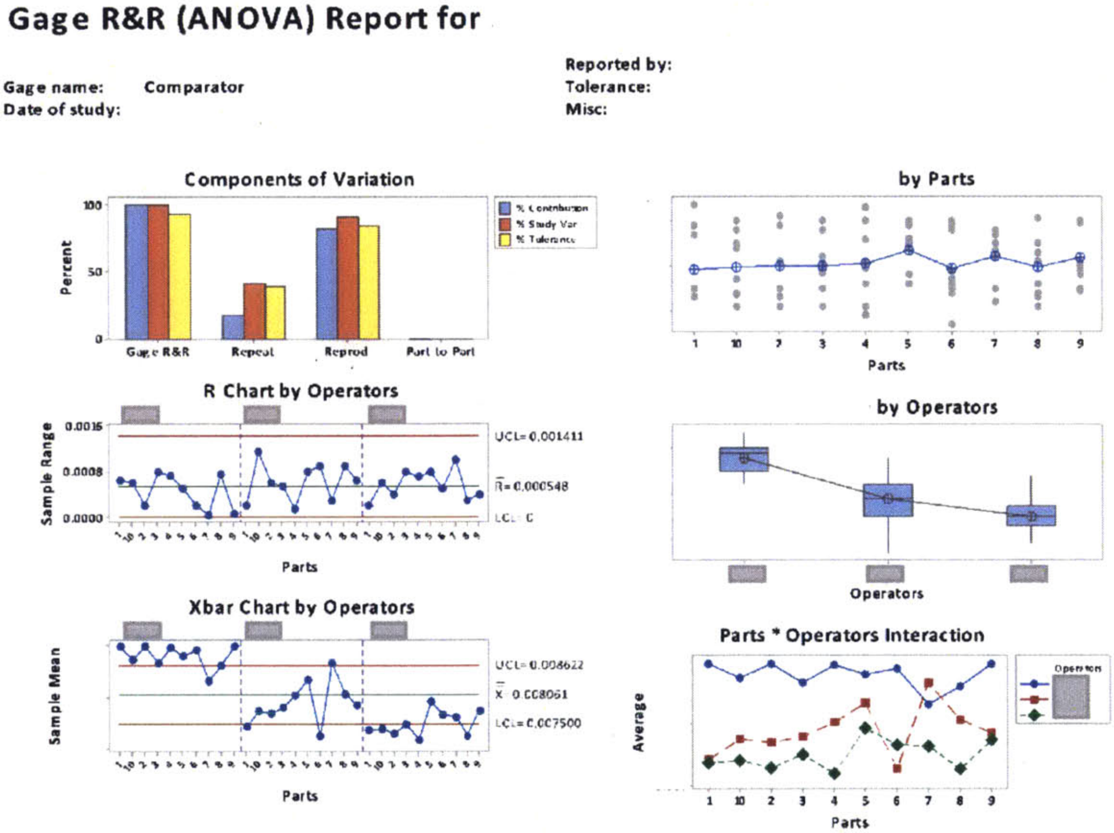


Figure 5-5. Graph report for dimension *b*.

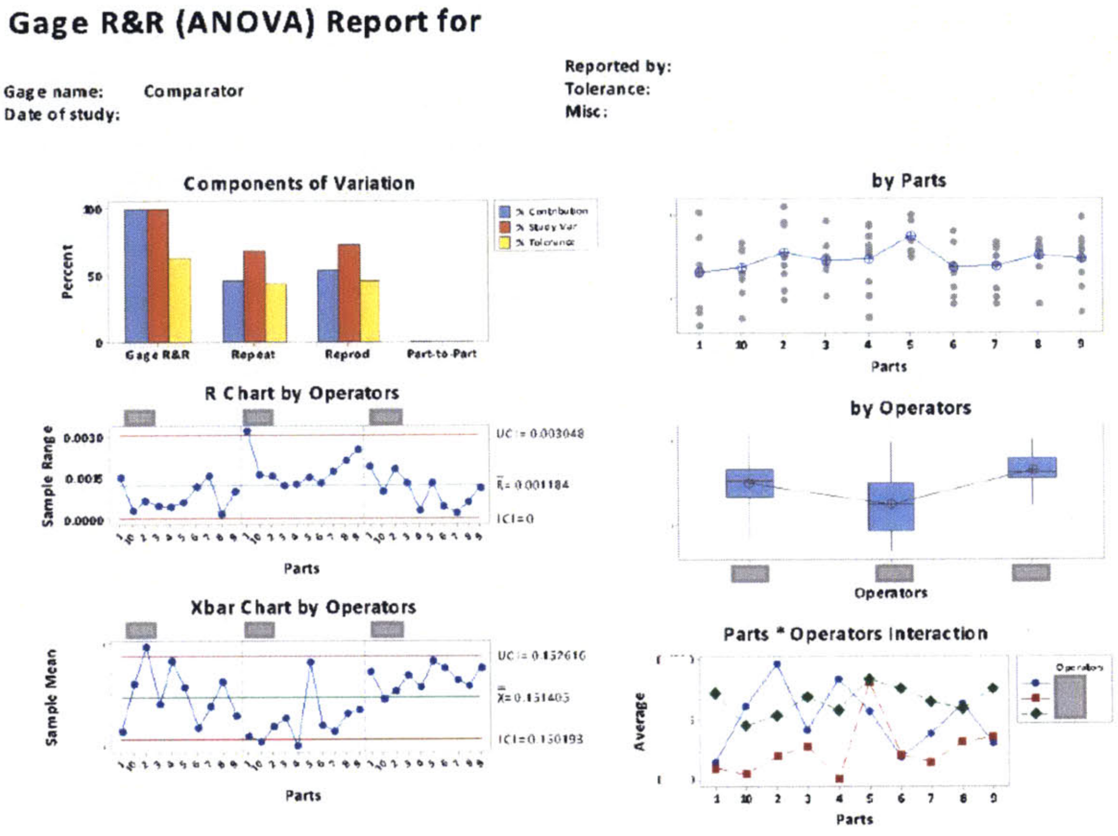


Figure 5-6. Graph report for dimension *c*.

It is reasonable that the operators have a large effect on the measurement using the comparator than the OASIS system. The OASIS system is an automatic measurement machine, while the comparator is not. The comparator measurement result depends on how the operator determines the edges of the dimension, and on the way that the operator visually aligns the part up with the coordinate axis. If different operators inspect parts differently, they will have different measurement result. If the operator does not measure the part in a consistent way, he will have different measurement results within his or her own measurements. Thus a consistent procedure is critical to achieve both operator-to-operator accuracy, and good consistency by any one operator.

5.4 Standardized Operating Procedure for Inspection

This section discusses the implementation of a standard operating procedure for inspection and the improvement it brings to the gage capabilities.

5.4.1 The Purpose of SOP

After we identified operator variation as the main source of variation, the necessity of standardized operating procedure is clear. With the SOP defined and proper training after its development, we can reduce the operator variation, improve gage capabilities and ensure the data validity for future SPC implementation.

5.4.2 The Implementation of the SOP

We collaborated with a quality engineer to develop a standard way to use the comparator to inspect parts. We also noticed that the way the operator places the column onto the Johnson Gage will affect the result significantly. Considering the fact that the thread is a critical feature on the part, we developed a standard way to use the Johnson Gage as well. We then trained the operators and conducted the Gage R&R study again. For more details about the implementation of the SOP, refer to Udayshankar's thesis [2].

5.5 Gage R&R Result after Implementing the SOP

After implementing the SOP, the P/T Ratios for these dimensions reduce as we can see from Table 5-2 because the operator variation is minimized. In addition, if the operator follows the standard procedure, they will avoid the major measurement errors during their inspection, and therefore the extreme data points previously observed will not occur any more. We can see that the gage is equally capable of measuring the same feature on both main side and sub side. The gage capabilities are improved after the SOP implementation and we are more confident about the validity of the data we will collect.

	P/T ratio (%)			
	Before		After	
Dimension	Main side	Sub side	Main side	Sub side
b	1013.38	93.35	31.57	38.94
c	49.97	23.42	26.3	27.97
d	3634.65	41.77	13.44	19.11
i	179.66	47.12	10.51	8.21

Table 5-2. Comparison of gage capabilities before and after the implementation of the SOP.

5.6 Gage R&R Study across Different Parts

This section presents our methodology to demonstrate that the existing measurement system is capable for different column types.

5.6.1 Production of Three Special Configurations

The company's column products can be split into different families. Within the same column family, different types of columns will have identical features but different total lengths. Except the total length, the gage capabilities to inspect the same features on different types of columns should be the same. So, we summarize all the different features we have across different families, and separated them into three configurations. After we standardized the inspection procedure as described in previous sections, we were confident that the gage capabilities to inspect main side and sub side should be the same. For the evaluation of gage capabilities across different part types, we therefore considered features on only one side of the column.

In order to evaluate the gage capabilities to distinguish between good parts and bad parts, three different configurations were machined in a way to span the entire specification range. We machined ten parts for each configuration. If the outer diameter (dimension *a*) on Configuration 1 is 10±5 inches, we would machine three parts whose outer diameter targets on 5 inches, three parts targeting on 10 inches, three parts targeting on 15 inches and one part with a random target within the specification limits. By increasing the part-to-part range, a better Gage R&R study result can be achieved [14]. In this way, ten parts with Configuration 1 were machined and three operators measured them for three times to complete a Gage R&R study for this configuration. Ten parts with Configuration 2 and ten with Configuration 3 were produced in the same way. Three additional Gage R&R studies were performed to complete the entire Gage R&R study.

5.6.2 Gage R&R ANOVA Result Summary

Dimension	P/T Ratio (%)		
	Configuration 1	Configuration 2	Configuration 3
a	7.98	41.76	9.9
b	32.7	26.64	18.42
c	15.54	52.02	27.6
d	61.26	32.4	24.66
e	23.76	12.84	59.16
f	89.46	54.42	50.64
g	87.9	167.34	88.2
j	15.12	39.6	15.12

Table 5-3. Comparison of Gage R&R result from OASIS system between three configurations.

The results of our multi-configuration Gage R&R study are shown in Table 5-3. From Table 5-3, we conclude that the OASIS system can be used to measure dimension *a, b, c, e* and *j* across a wide range of column configurations. Based on our previous gage studies, we know that dimension *d*, *f* and *g* need to be measured on the comparator. However, the OASIS system will measure these dimensions simultaneously, and it takes less than one minute to complete the inspection. If we use the comparator to measure these dimensions, it will take more than 15 minutes to measure, which is not practical for the SPC real time inspection. Furthermore, it would be too expensive to invest in new gages to measure these dimensions. Last, these dimensions are critical to function but are not critical to manufacturing processes. The flats are machined by the end mill and this dimension depends on the size of the end mill only. This process is so stable that it always remains in control for more than a month.

For these reasons, we still use the OASIS to measure dimension *f* and *g* during the real time inspection, even though in many cases the OASIS system struggles to achieve the desired gage capability of 30%. At the beginning of the production, we use the comparator to inspect these dimensions. As long as these dimensions on the first part are in specifications, we can use the OASIS system to monitor the process. When the control chart shows an out of control state, the operator is directed to measure this part again on the comparator to confirm the measurement result, so that any possible false alarm resulting from the OASIS measurement error can be reduced.

Chapter 6. Results and Discussion

This chapter summarizes the final Gage R&R results in Section 6.1. Section 6.2 then discusses about our tolerance redesign resulting from the gage capability analysis.

6.1 Gage Capability Analysis

Table 6-1 shows the final result of gage capabilities after our root cause analysis and the SOP implementation.

Dimension	Gage	P/T Ratio (%)	
		Main side	Sub side
a1	OASIS	46.81	18.21
a2	OASIS	31.3	10.61
b	Comparator	31.57	38.94
c	Comparator	26.3	27.97
d	Comparator	13.44	19.11
e	OASIS	18.04	15.19
f	Comparator	34.09	45.3
	OASIS	55.42	8.61
g	Comparator	39.34	32.24
	OASIS	131.05	159.82
i	Johnson Gage	10.51	8.21
j1	OASIS	22.75	41.4
j2	OASIS	34.24	60.16
j3	OASIS	20.25	39.67

Table 6-1. Gage capabilities summary.

From our Gage R&R study, we select the suitable gages to measure different dimensions. The OASIS system can be used to measure dimensions *a, e, f, g* and *j*; the Johnson Gage can be used to measure the pitch diameter (dimension *i*). These two gages are automatic devices and they can be used for real time inspection. The comparator is capable to measure dimension *c, d, f* and *g*. None of them is capable to measure the beginning position of the thread (dimension *b*). The comparator is a slow device without automatic data collection system. It takes so much time to measure one part that it cannot meet the requirement for real time inspection. To solve this problem, the easiest way is to invest in new measurement devices and replace the comparator. However, given the time constraint of our project, we prefer to look for alternative options to solve this measurement concern with less capital expense.

6.2 Tolerance Redesign

To avoid large capital investment for further SPC implementation, we investigated the option of adjustments to the design specifications in the manufacturing area. This section will discuss the theory behind this approach, and the final result.

6.2.1 Purpose and Feasibility

As described in Chapter 5, we proposed to use the comparator to measure the first part to set up the machine, but not to use the comparator for process monitoring, and instead use the OASIS for ongoing monitoring. In order to qualify the OASIS for monitoring of some dimensions, we consider again the definition of P/T ratio as the ratio of gage precision to part tolerance. Our benchmark of 30% P/T ratio might be achievable with the OASIS if the true product tolerance is wider than currently stated. We discussed with design engineers and manufacturing engineers the possibility to redesign the tolerance for certain dimensions so that we could approve this proposal.

Dimensions *a, b, c, d* and *e* are machined by the same tool in a continuous manner. As introduced in Chapter 4, the turning insert faces the surface, profiles the chamfer, turns the outer diameter, profiles the begin and end positions of the thread and then profiles the thread relief. These features are created in the same process. If the process is in control, all of these features should be in control. Since the OASIS system is very capable in measuring dimension *a* and *e*, we can use the OASIS system to monitor the process. If dimension *a* is in control, we can assume that all the dimensions that are vertical to the column axis are in control. For those dimensions that are parallel to the column axis, we can have the same assumption when dimension *e* is in control. However, the tolerances for dimensions *b* and *c* are tighter than dimension *e*'s tolerance according to the drawing at present, which challenges our assumption.

After we analyzed these dimensions with design engineers and manufacturing engineers, we were suspicious about this tolerance design. Dimension *b* and *c* are the position of the thread and from the design aspect, the position of the thread should not need such a tight tolerance. The length of the thread matters more than its position. The reason why the positions were designed to be so tight was because of tolerance stack-up concerns and the worse case scenario was adapted to design the tolerance. But based on our knowledge about the machining process, we argue that these dimensions, created by the same process, will not have the worse case scenario in the same part. Thus we can relax the tolerance to some degree. Meanwhile, based on our knowledge about the machining capability, we are confident that we can achieve a tighter tolerance for the dimension of the thread relief. So we put a tighter tolerance on this dimension. In this way, we can monitor the process by measuring dimension *e* only. However, it takes a relatively long period of time to change the drawings across the entire company and the customer base. Considering the time span of our project, we keep the design tolerance to be the same as previously, but use the redesigned tolerance for manufacturing monitoring and process control.

6.2.2 Result

After the tolerance redesign, we can eliminate the usage of the comparator during the SPC real time inspection. By using the OASIS system and the Johnson Gage only, it will not take the operator too much time to perform process monitoring. Therefore, the operator can still work on two machines simultaneously and the company does not have to hire additional workforce in order to implement the SPC system. In addition, the Column Area will have a smaller risk to reject good parts after the adjustment to the tolerance. As a result, a reduction in the manufacturing cost can be expected.

Chapter 7. Conclusion and Recommendations

This chapter will give a final conclusion for the entire project as well as for this thesis. Recommendations to the company are provided in the second section.

7.1 Conclusion

After our Gage R&R study, we have selected the proper gages to measure different dimensions. We have evaluated the gage capabilities and conducted root cause analysis for incapable gages. We have designed and machined a new fixture for the OASIS system to reduce setup time and minimize operator variation. We have developed a standardized procedure to perform the inspection and improved the gage capabilities. We have also redesigned the tolerance for certain dimensions to ensure the validity of the SPC monitoring system without using the comparator. After we completed an entire study for a specific type of column, we have produced three different configurations to evaluate the capability of this measurement system to inspect different types of column. In conclusion, with our inspection protocols, the measurement system in the Column Are is adequate and also practical for the SPC implementation.

As for the entire project, we have demonstrated the SPC methodology by experimenting in the Column Area. Our result indicates the achievement of scrap reduction by half for a specific type of column.

As discussed in Udayshankar's thesis [2], 80% of the failure modes can be addressed by SPC with 60% reduction in the scrap rate from these failure modes in the columns cell. Using the same analysis for the entire machining center, a similar percentage of failure modes that now appear such as tool change, tool wear, threads and initial setup throughout the machining center can be reduced by implementing SPC. Therefore, a substantial annual savings can be achieved for the entire machining center.

7.2 Recommendations

Given the time constraint, the SPC system was implemented for only several types of column tubes. A number of opportunities have been identified to improve the process further. This section describes recommendations for the company to consider in the future.

Firstly, a new database system should be established for better data management in the future. At present, the method of storing data is inefficient. Data is collected and stored in a file named with the part number of the column tube. Irrespective of which CNC machine performs the machining processes, no matter if the dimension is on the main side or the sub side of the column tube, the measurement results are stored in the same file in the same way, which means that data cannot be separated into different sets for further analysis. This is a major issue because different CNC machines have different inherent characteristics while producing the same column tubes. And in the CNC machine, the main side of the column tube is machined by different tools in different machining conditions compared to the sub side of the column tube. A new data structure will help manage the data better and deliver more valuable information in the future for process diagnosis and improvement.

A possible database structure is developed and shown in Figure 7-1. QCC is the central database for the whole SPC system. SAP is the internal system the company uses to share data. All of the automatic gages feed their data into the central database and the data is integrated. Below the gage is the part structure. A gage can be used to measure column tubes, end fittings and other parts. First, the parts are divided on the basis of family. Parts in the same family share similar features and similar inspection protocols. Then there are different part numbers ("P/N"), and different sides machined by different CNC machines. In this way, all of the data can be separated in the future and then data management becomes an easier task.

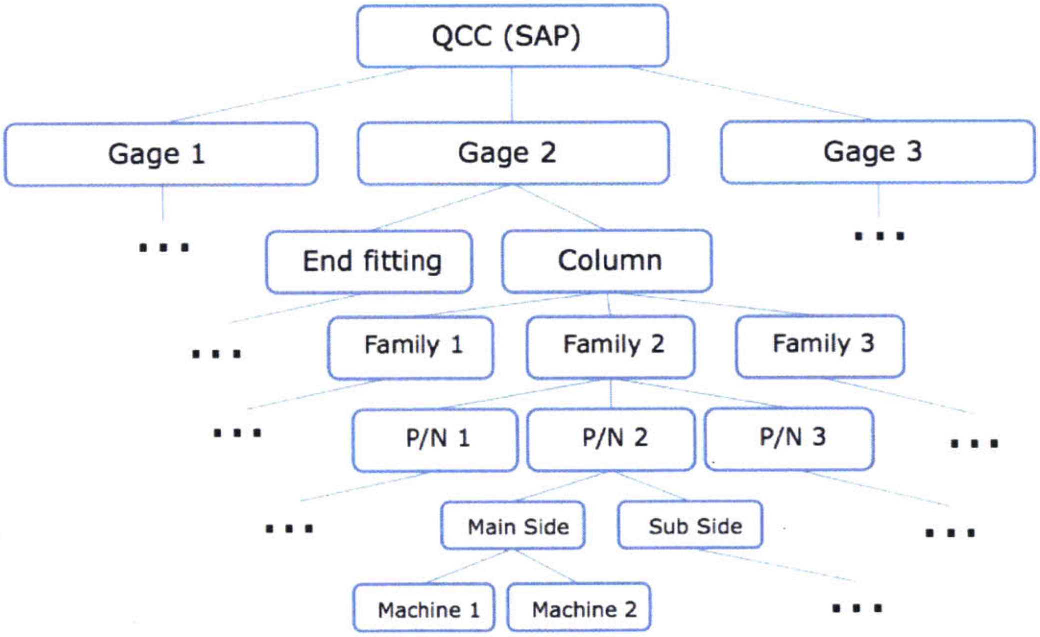


Figure 7-1. Recommended database structure.

Secondly, it is recommended to implement the SPC system across the entire machining center. As discussed in Section 7.1, there is a large potential for cost savings in the machining center. It is practical to implement SPC throughout the entire machining center with the help of the SPC methodology booklet that has been delivered to the company. With this portable SOP documentation, quality engineers will find it easier to incorporate the SPC culture in the different sections of the machining center.

Thirdly, a training program is recommended to help the operators understand the concept of SPC and be able to utilize it as a powerful tool to assist their daily production. A training program for the management level is helpful to foster a culture of better quality control.

Fourthly, data mining can provide potential opportunities for continuous process improvement. Once the system is set up, a number of data points can be collected every day. Beyond real time monitoring, this database can be used to identify failure modes and its frequencies. This will lead to a continuous improvement of the process. An example that illustrates this point is our analysis of data to identify that tool breakage was the main assignable cause for producing defective threads. Future analysis might include a tool life study in particular to provide valuable insights to help indicate the proper time to change tools before they break.

Finally, regular maintenance is a vital part of the entire process. The SPC software needs to be maintained and updated regularly to provide real time control charts that will help the operators and the engineers. Data collected has to be regularly checked to ensure that data is not lost by other factors. If a new part or process is introduced, an updated inspection protocol should be developed for the continuous improvement of the manufacturing process.

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