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PRECISION METROLOGY

Chapter

20

Measurement Systems Analysis

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20.1 Introduction

Measurement methods analysis is a highly critical step in the overall concurrent engineering process. Today's technology advancements are at a stage where measurement science is being pushed to the limit of technological capabilities. The past has allowed capabilities of measurement equipment to be acceptable if the Six Sigma capability was $\geq$ 1 μm (0.001 mm). Today, submicrometer capability is much more the norm for high technology manufacturing firms, with the percentage of features in this tolerancing regime getting larger and larger.

The primary objective of this chapter is to generate a capability matrix that reflects "Six Sigma capability" for all 14 geometric controls, as well as individual feature controls using an ultra-precision class coordinate measuring machine (CMM). In this particular case, a Brown & Sharpe/Leitz PMM 654 Enhanced Accuracy CMM was used for all testing to generate this matrix.

Analysis included variables that impact optimum measurement strategies in a submicrometer regime such as feature-based sampling strategies, calculations for determining capability of geometrically defined features, the thermal expansion of parts and scales, CMM performance, and submicrometer capabilities in contact-measurement applications.

The methodologies for approaching the characterization of CMMs as a whole is extremely broad, primarily due to a lack of awareness of the broad range of contributing error sources. Measurement system characterization applies to all measurement systems, but due to the diversity of contact CMMs, the 14 geometric controls can be characterized to varying degrees.

Unlike many measurement systems, a contact CMM has the ability to measure one, two, and three-dimensional (1-D, 2-D, and 3-D) features. Based on this unique capability, a CMM is the most appropriate system to consider in the initial spectrum of measurement system characterization. This is not to imply a measurement system such as this can measure the spectrum of geometric shapes in their entirety. It is, however, intended to indicate that a CMM is the most diverse piece of measurement equipment in the world today, in the application of measuring geometric features on mechanical features of components.

20.2 Measurement Methods Analysis

In addition to outlining a methodology for measurement system characterization, this chapter also will define some of the key tests leading to the generation of the capability matrix. In addition, I will identify some significant limitations in currently defined calculations for analyzing measurement system capability, especially in the area of 3-D analysis. The capability matrix, which is the primary deliverable of this chapter, was defined by standard analysis practices.

The following outlines six key phases that are essential to the characterization of measurement systems of this caliber:

- Measurement system definition (phase 1)
- Identification of sources of uncertainty (phase 2)
- Measurement system qualification (phase 3)
- Quantifying the error budget (phase 4)
- Optimizing the measurement system (phase 5), and
- Implementation and control of measurement systems (phase 6)

20.2.1 Measurement System Definition (Phase 1)

As performance specifications grow increasingly tighter, the older gaging rule of a 10:1 ratio has been at times reduced to a lesser ratio of even 4:1. However, even the lower goals are becoming difficult to achieve. This increases rather than decreases the requirement of metrology and quality involvement at the stage of product design.

20.2.1.1 Identification of Variables

The first step of any measurement task is to identify the variables to be measured. While this may appear to be a simple and straightforward task, the criticality of various dimensions is usually nothing more than a hypothesis. If true hypothesis testing is performed, the need for metrology and quality involvement is obvious.

A more common approach is inherited criticality, where the product or part being designed is an enhanced version of an earlier model. This approach is usually valid, because the available empirical data should support the claim of criticality.

Nonetheless, there are times where process variables, rather than properties of the product, require measurement. This method may be preferred because it provides a separate method of ensuring conformance to specifications. An obvious example is injection molding, where tooling certification and control and machine process variables, such as temperature, curing times, etc., are all measured and monitored in addition to the product itself. Such a methodology can graduate to exclude product measurement once a process is deemed “in control” over an extended period of time.

20.2.1.2 Specifications of Conformance

If choosing the proper variables for tracking is not difficult enough, consider the problems with determining valid specifications for acceptance. Again, when considering an enhanced product, empirical data should prove to be the best guide. However, additional testing may be necessary, especially when considering those properties being improved.

Unfortunately, some inherited specifications can be as invalid as any hypothesis. This is particularly true when studies or other data are unavailable to support the requirement. The importance of valid specifications is easily exemplified in the following examples of typical costs.

A contact CMM with ultraprecision (submicrometer) capability requires capital expenditures of approximately $500,000 for the equipment, $100,000 for environmental control, and $100,000 for implementation. Additional costs include adding higher-competency personnel, increased cycle-time for measurement tasks, and increased requirements of measurement system characterization.

A contact CMM with normal (10 µm) capability typically requires less than half the capital expenditure and can perform more timely measurements with less maintenance costs.

The significance is obvious and so should be the ramifications of invalid specifications. Too loose a specification can lead to delivering nonfunctional parts to a customer, which can lead to loss of business, which can lead to diminished market share. Specifications that are too tight add cost to the product and cycle-time to delivery schedules, both without any return and with the same effect on customers and market share.

20.2.1.3 Measurement System Capability Requirements

Once the specifications of conformance are defined, the capability required of the measurement system must be addressed. As stated, if the 10:1 ratio can be achieved the task is more easily accomplished. Regardless, the best approach to defining capability requirements is to develop a matrix. The requirements matrix should address the following concerns:

- Capability for each feature to be measured
- Software (computer system, metrology analysis requirements, etc.)
- Environment (temperature, vibration, air quality, manufacturer’s specifications, etc.)
- Machine performance (dynamics, geometry, probing, correction algorithms, speed, etc.)

Obviously, some of these requirements are interrelated. For example, some environmental concerns must be met to achieve the stated vendor specification machine performance. The final capability matrix should address all concerns relative to the capability desired.

Once the capability and its availability are known, the cost and budget analyses and timelines are required. Such analysis is extremely difficult and must include considerations such as personnel requirements and maintenance costs.

20.2.2 Identification of Sources of Uncertainty (Phase 2)

This step involves identifying the error sources affecting measurement system capabilities. As stated, the system definition phase should have included some consideration of this topic. The following list includes the minimum categories that must be considered in measurement system characterization.

- Machine
- Software
- Environment
- Part
- Fixturing
- Operator

As each source is identified within the given categories, discussion should turn to its projected influence on overall capability and on specific applications. This discussion refers to this influence as being sensitive or nonsensitive.

For example, the ASME B89.1.12 standard for evaluating CMM performance defines methods for testing bidirectional length and point-to-point capabilities. Basically, these tests evaluate the ability of a contact probing system to perform probe compensation. However, this error source is nonsensitive to the CMMs' capability to measure the *position* of circles or spheres.

If labeled as sensitive, efforts should be made to determine its contribution and to assign a priority level of concern. Obviously, these are only projections, but the time is well spent because this establishes a baseline for both qualification and, if necessary, diagnostic testing.

20.2.2.1 Machine Sources of Uncertainty

Identifying error sources associated with the equipment itself sometimes can be easily accomplished. First, many standards and technical papers discuss the defects of various machine components and methods of evaluation. Second, measurement system manufacturers publish specifications of machine performance capabilities. These two sources provide most of the information required.

The most common concerns for CMMs include, but are not limited to, the following:

Dynamic Behavior involves structural deformations, usually resulting from inertial effects when the machine is moving. The sensitivity of this error is highly dependent on the structural design and the speed and approach distances required.

Geometry involves squareness of axes, usually dependent on the number of servos active, temperature, etc. The sensitivity is highly dependent on whether or not the machine includes volumetric error correction, and the environment within which the machine will be operated.

Linear Displacement involves the resolution of the scales, also dependent on the environment within which the machine will be operated. The sensitivity depends on scale temperature correction capabilities.

Probing System involves probe compensation, highly dependent on type of probe, the software algorithms for filtering and mapping stylus deflections, and the frequency response. The sensitivity depends on the material, tip diameter, and length of the probe styli to be used.

20.2.2.2 Software Sources of Uncertainty

The most obvious concern for software performance is its ability to evaluate data per ASME Y14.5M-1994 and ASME Y14.5.1M-1994. However, many attributes to the software should be evaluated. The following list includes, but is not limited to, concerns for software testing:

- Algorithms (simplified calculations to improve response time)
- Robustness (ability to recover from invalid input data)
- Reliability (effects of variations in input data)

- Compliance to ASME Y14.5 and ASME Y14.5.1 (previously mentioned)
- Correction algorithms (volumetric and temperature)

When possible, testing of software should be achieved through the use of data sets. Other methods increase contributions to uncertainty. Some of the software attributes to be tested include its ability to handle those problems. Software uncertainties should not be ignored. Often, the uncertainty involved seems negligible, but that term is relative to the capability required.

20.2.2.3 Environmental Sources of Uncertainty

The most common concern for environment involves temperature, which is often stated as the largest error source affecting precision. Other atmospheric conditions also influence capability.

Humidity, like temperature, can lead to distortion of both the machine and the parts being measured. Efforts to control these atmospheric conditions can lead to the necessity to consider the pressure of the room involved. If lasers are used, barometric pressure may alter performance. The same is true for contamination, which also affects both contact and noncontact data collection.

Nonatmospheric concerns include vibration, air pressure systems, vacuum systems, and power. Note that each and every utility required by the machine can affect its performance.

Consideration of the sensitivity of these sources is dependent on the degree of control and the capability required. For example, the environmental control realized within laboratories is generally much greater than that of production areas. Often, a stable environment can shift the sources of error to the machine’s and the part’s properties within those conditions.

20.2.2.4 Part Sources of Uncertainty

Many aspects of the parts themselves can be a source of measurement uncertainty. The dynamic properties, such as geometric distortion due to probing force or vibration, are obvious examples. Likewise, the coefficient of thermal expansion of the parts’ material should be considered a source of error. This is especially true with longer part features, with areas lacking stable environmental controls, and with machines not supporting part temperature correction.

It is important to note that such correction systems do not alleviate all problems because parts never maintain constant temperature throughout. Also, such systems increase reliance on proper operator procedures, like using gloves or soaking time.

Other concerns regard the quality of the part and its features. For example, the surface finish and form values greatly affect both the ability to collect probing points and the number of points required to calculate accurate substitute geometry. Even the conformance to specifications for any given feature can affect the ability of the measurement system to analyze its attributes.

The sensitivity of these sources depends on the environment, the material of the part, and the capability required.

20.2.2.5 Fixturing Sources of Uncertainty

Part fixturing is listed separately because part distortion within the holding fixture is one of the error sources involved. Other concerns involve the dynamic properties of the fixture’s material, but this depends on the application. For example, given a situation where the temperature is unstable and the part is fixtured for a longer period of time, either prior to machine loading or during the inspection, distortion to the fixture translates into distortion of the part.

Additional environmental concerns involve the fixture’s effect on lighting parameters for noncontact systems and on part distortion during probing for contact systems. Other sources include utility concerns, where air or vacuum pressure fluctuations can distort parts or affect the ability of the fixture to hold the part securely in place. Other concerns are with regard to the fixtures performance in reproducibility, between machines, and between operators.

The sensitivity of fixturing factors is highly dependent on environmental conditions, part and fixturing materials, and the measurement system capability required.

20.2.2.6 Operator Sources of Uncertainty

The user of the system can greatly influence the performance of any measurement system. This is particularly true within the lab environment, where applications-specific measurement is rare. For example, within the lab, operators may have the option to change CMM parameters, such as speed, probing approach, etc. Similarly, within the lab, designated fixturing is less common; therefore, the variability between operators is increased.

Likewise, algorithm selection, sampling strategies, and even the location and orientation of the part can affect the uncertainty of measurements. For this reason, laboratory personnel must be required to maintain a higher level of competency. Formal, documented procedures should be available for reference.

The sensitivity of these concerns is highly dependent on the competency of the personnel involved, the release and control procedures for part programs, the documentation of lab procedures, and, as always, the measurement capability desired.

The goal of this phase was to identify contributing sources of uncertainty. While the next steps involve quantifying the effects, efforts should be made prior to testing to hypothesize the influences. All sources deemed as sensitive to the given capability and/or application should be prioritized. This process will eliminate unnecessary testing and should focus any diagnostic testing that may be required.

20.2.3 Measurement System Qualification (Phase 3)

20.2.3.1 Plan the Capabilities Studies

There are many published standards discussing the evaluation of CMM performance. The same is true for other equipment as well. These standards are particularly effective because they pertain to testing the machine for performing within manufacturers' specifications.

The three most recognized methods of performance evaluation are known as the comparator method, error synthesis (error budgeting), and the combined method. The comparator method involves statistical evaluation of measurements made on a reference standard. The error synthesis method involves sophisticated software used to model the CMM to evaluate overall performance, given the values of the numerous sources of uncertainty. For laboratory systems, the minimum requirements to consider in the development of a capability matrix include the following:

- Probing Performance
- Linear Displacement
- Geometry (squareness, pitch, roll, yaw, etc.)
- Software
- Feature-dependent capability

Some may notice the inclusion of both measurement capability and performance of specific error sources. Users are free to divide these into two different matrices, yet given the universal nature of laboratory systems, published capabilities must be isolated to facilitate operator evaluations of the uncertainty of various setups and applications.

20.2.3.2 Production Systems

The plan to evaluate the capabilities of a production measurement system may be very similar to past practices in that measurement system analysis tools may be all that is required. The goal is the development of a matrix listing the different capabilities. However, the matrix may be specific to applications, rather than listing feature-dependent capabilities or machine performance levels.

The decision to do more in-depth analysis should depend on the percentage of nonproduction measurements and the level of capability required for those tasks. Regardless, the most common problem becomes deciding on the artifact(s) to provide acceptable reference values (ARVs).

I recommend using traceable artifacts from a nationally recognized laboratory, such as NIST (National Institute of Standards and Technology), when testing machine capabilities. When testing applications, actual parts, or specially produced parts with the same features and attributes of the parts to be measured can be used. The problem with this method involves determination of the acceptable reference values.

In other words, an acceptable reference value without a certification of calibration must be measured by an acceptable reference system. This is similar to the concept of calibrated artifacts; less capable machines rely on values provided by machines of greater capability.

This method addresses the need to include feature imperfections in the testing of capability and the need for evaluations relating to truth. Given the law of the propagation of uncertainty, the true value will never be known. However, this should at least provide an acceptable reference value where the word “acceptable” can be used accurately.

Once the artifacts are selected, the plan is complete, and there is a clearly defined matrix, the remaining steps of this phase are similar to past practices. All test plans must address the following requirements for every attribute evaluated:

- Stability (minimum of two weeks)
- Precision
- Bias
- Reproducibility (minimum of two operators)
- Uncertainty (minimum of length uncertainty)
- Correlation (internal and external)

Many tools exist for testing, and shorter versions of those tests may be useful in evaluating the sensitivity of specific error sources. Such testing is often referred to as “snapshot testing.” While not valid for formal analysis, snapshot testing provides sufficient insight into machine performance, particularly for a new and unknown system.

20.2.3.3 Calibrate the System

The requirements of calibration include, but are not limited to, the following:

- Uncertainty of artifact(s) required to achieve performance
- Selection of artifact(s) to be used
- Selection of calibration services, if needed
- Determination of the calibration interval

The calibration lab should provide support through consulting and services. The services must include automated monitoring of the calibration cycle and maintaining historical records of the calibrations performed.

20.2.3.4 Conduct Studies and Define Capabilities

The requirements of this step involve the data collection and documentation processes. If the studies are well planned, conducting the testing is relatively straightforward.

Testing will consume a great amount of machine time, so extra caution in duplicating output should prevent the need for repeating test procedures. Likewise, extra effort should be made to ensure the validity of the programs used.

As for documentation, all procedures and programs should be documented thoroughly and maintained with the testing data. Other required information for each test conducted includes the time, date, temperature, operator, and system (when more than one). Once a test is complete, a brief synopsis of the test and the results should be included with the documentation.

Once all tests are completed, the results are recorded to define the capability matrix of the system. As stated, these matrices will differ depending on the system’s designated use. In fact, there may be some differences between matrices of like systems.

20.2.4 Quantify the Error Budget (Phase 4)

This phase is an in-depth analysis of the earlier hypothesized influences on uncertainty. In some cases, testing will indicate a need for additional testing; in others, the data may already clearly identify the impact of the error source in question.

As with any testing, the goal is to become knowledgeable about the system being evaluated, not to confirm preconceived hypotheses. The original assumptions serve only as an organized method to approach formal testing where quantitative measurements can be calculated.

Also, if valid priority assignments were established, the focus of the testing should be more apparent. These priorities should prevent delving too deeply into testing of sources with little contribution or with little probability of optimization.

20.2.4.1 Plan Testing (Isolate Error Sources)

While design of experiment techniques provide many methods to analyze multiple variables, tests should be designed in an effort to isolate variables with regard to each specific error source. This facilitates the testing and the analysis.

For example, there are many variables involved in the overall uncertainty of probing performance. While tests could be designed to include length uncertainty, this approach is not recommended. Such a test also would introduce into the test the variables of temperature effects on the machine and the artifact and the performance of those software algorithms. The standards unanimously recommend evaluation of probing performance over a very small volume, using artifacts near 25 mm in size.

Similarly, when evaluating length uncertainty, efforts should be made to remove probing and algorithm performances. Many variables remain, including the temperature considerations of machine and artifact and the correction algorithms available. In this example, ball bars are often used with the length between sphere centers being the focus of the testing.

When compared to qualification tests, a significant difference in this testing is the study of operator influences. Given the numerous applications and the variety of fixturing tools in laboratory systems, the focus on fixturing and the documentation of results serve only as guides to individual users, much like the other information in the capability matrix. Should quantitative testing indicate significant problems, the optimization phase should lead to additional training, etc.

20.2.4.2 Analyze Uncertainty

One of the most difficult concepts involved in error budgeting is analyzing test results to determine overall uncertainty for various applications. Fortunately, there are many guides that recommend various mathematical approaches to expressing the uncertainty of specific measurements. All that is required is quantitative information of the sources considered sensitive to the specific application.

Upon selecting the uncertainty variables that are sensitive to a given capability or application, one needs only to choose the desired combinatory rule and calculate the result.

Correctly identifying the sensitive sources of uncertainty is usually the easier of the two. For example, squareness in the YZ plane will have little to no effect on diametral readings in the XY plane, unless the diameter to be measured is particularly large. Likewise, single-point repeatability may have little effect unless it includes dynamic performance, which affects uncertainty only at specific temperatures, speed, and probe approach distances.

Obviously, there are many sources of uncertainty and not every variable can be tested. However, almost all exist as subsets of other contributing errors. The task may seem daunting, but the reason for statement of relative ease is apparent when selecting combinatory rules. Additional analysis to evaluate relationships and interdependencies may be desired.

Once the testing is completed, the quantitative measures of uncertainties should be known. Analysis is usually as simple as selecting the sensitive variables and the desired combinatory rule.

20.2.5 Optimize Measurement System (Phase 5)

Even if the measurement system performs to the capability required, there is often a need for increased performance. If the system is a production system, where the only studies performed are applications-specific, it may prove necessary to complete Phase 4. Again, this depends on the level of improvement required and the specific use intended. It may be possible simply to qualify the system for the new application.

Otherwise, the optimization phase consists of conceiving possible improvements in various areas of uncertainty. Revisiting the original testing provides a means of determining success. Once realized, requalification should indicate a more capable system.

20.2.5.1 Identify Opportunities

Opportunities to improve capability are dependent upon the variables contributing to uncertainty. In such cases, the next steps are obvious.

Problems manifest themselves when no apparent prospects exist. For example, even when exhausting tests have been completed, the uncertainty values sensitive to the capability in question may seem infinitesimal. The obvious question arises as to whether anything can be done to reduce uncertainties even further, or whether an unknown error source remains that was unaccounted for in the original testing.

Other problems may be specific to the application in question. A common example would involve measurement of extremely small part features or the tooling required. One of the largest sources of error for contact CMMs is probing uncertainty. This is particularly true for probes smaller than 1 mm. The effects of probing uncertainty on the capability to measure feature size are well known.

20.2.5.2 Attempt Improvements and Revisit Testing

The most obvious recommendation when attempting optimization is the need to exercise caution. Efforts should not include multiple variables. “Snapshot testing” is the best tool for informal evaluations.

Improvements are not always machine specific. They can involve revamping the HVAC system, training operators, and attempting new probing strategies. In fact, optimization can be realized simply through implementation of formal procedures.

Once "snapshot testing" results indicate the possible result desired, formal testing must be revisited to support formal analysis of the optimization efforts. While the same documentation requirements exist for retesting, an additional synopsis should describe the optimization process, the desired results, and the success or failure of the effort.

If optimization is successful and uncertainty values are reduced, the process is repeated for all attributes where increased performance is desired and deemed probable. Once uncertainty contributions are considered acceptable, the system must be requalified for any and all capabilities that may be affected.

20.2.5.3 Revisit Qualification

Determining the qualification tests that require repeating is dependent upon the enhancements realized. For example, improving fixturing reproducibility for a laboratory system should not affect any other qualification tests, unless those tests were poorly conceptualized.

Once completed, the capability matrix should be updated, even if the results are not as expected or desired. Additional efforts of optimization should repeat the process, and all documentation should reflect all efforts, even unsuccessful ones. This information could prove beneficial at a later date or to other measurement system characterization projects.

Optimization requires identifying opportunities, "snapshot testing" of enhancements, repeating the formal testing of uncertainty contributions, and reproducing the capability matrix. Both successful and failed attempts should be well documented for future reference.

20.2.6 Implement and Control Measurement System (Phase 6)

The last phase of measurement system characterization is implementation and control. This is not to say optimization efforts are complete, but once initial efforts are completed, the system is activated. Control is achieved through periodic calibrations, maintenance, and performance tracking.

True characterization takes place over time. Some systems will maintain initial levels of capability with ease, while others will require additional efforts to improve performance and long-term stability.

20.2.6.1 Plan Performance Criteria

Prior to implementation, performance monitoring criteria must be identified. The variables tracked can include specific capability studies and critical sources of uncertainty. Keep in mind, performance tracking generally should not consume more than 30 minutes a week.

Once the variables are ascertained, the artifact(s) for interim testing should be selected. This can be a calibration artifact used during testing, or a part or group of parts used during testing. As stated previously, only traceable reference standards should be used for laboratory systems.

The final criteria involves the interval of testing and when requalification should be required. Interim testing is usually performed between once a week and once a month. The interval can be changed for many reasons. For example, shorter intervals could be used to assess the effects of increased system utilization.

The question of requalification is dependent upon those factors that may be expected to dramatically affect the system. Some may consider the periodic calibration of the system to be of significant impact. Others may include system crashes, major repairs, or changes in utilization.

The same documentation rules apply to interim testing that apply to other testing. This is particularly true with regard to temperature and other environmental factors. The charting of performance is recommended. Charts provide constant reminders of performance, allowing operators to easily recognize any problems with the system.

20.2.6.2 Plan Calibration and Maintenance Requirements

The calibration cycle is similar to that of interim testing in that the interval is not required to be constant. In fact, performance tracking may indicate the need for shorter or longer periods between calibrations. The same may be true for preventive maintenance schedules.

The manufacturer’s recommendations are the logical place to start, with system performance dictating any changes. The necessary artifact(s) should already be available from the original calibration, unless, of course, outside services are supporting the requirements.

20.2.6.3 Implement System and Initiate Control

Performance tracking should establish a baseline, but it is dependent on the statistical tools being used. Once completed, everything should now be in place for implementation. As with any new system, caution should be exercised, with full utilization being achieved in phases. However, this is also dependent upon the amount of testing done earlier.

Once activated, users should benefit by having a qualified measurement system. The interim testing provides a means of control, and the data can be utilized to address other concerns, such as:

- Cases of “slow drift” should be more apparent.
- Data exists for diagnostic analysis.
- Data is available for evaluating effects of calibration.

The process of measurement system characterization process should ensure only qualified and controlled systems are used. The process also provides methods to address both internal and external correlation issues. While the above comments do not include specific details for every system and every approach, it should serve as a sound outline to comprehensive characterization efforts.

20.2.6.4 CMM Operator Competencies

One of the most important aspects of a high precision inspection system is the background of the operator. It would be wonderful to believe that anyone could run an ultraprecision CMM. Realistically, if a company expects to work within the submicrometer regime, the operator’s skills as a dimensional metrologist (as well as the skills of engineering and manufacturing support personnel) must be highly refined. For example, the error budget for a part that has a manufacturing tolerance of 2 μm might be pages long. Procedures that are normally not used (like torquing clamps or fixtures, calibrating probe tip sphericity or roundness, and calculating “Uncertainty of Nominal Deferential Expansion” for known materials) must now be accentuated to work within this tolerance band.

Almost as important as the operator’s skills is a support team that helps minimize both the random and systematic error sources in the measuring process. At the submicrometer level, there is simply no room for either. Both error sources are difficult to minimize. For example, different operators will get different results. Like materials will have different coefficients of thermal expansion (of course the way to avoid/minimize problems here is to perform all inspections at 20 °C). The same part can show two different form errors depending on which section of the probe was used for the inspection.

Now that the six phases for measurement system characterization have been outlined, the next step is to define actual testing. This testing leads to the necessary confidence for developing the capability matrix. Tests are done to the degree necessary to achieve optimum submicrometer capability, which is the primary objective in the area of operating interest.

20.2.6.5 Business Issue

Before discussing the actual testing results, an unexpected situation that came up during the testing should be mentioned at this time.

Proving the environment is stable should always be a priority issue. An unstable environment can have a large detrimental effect on the confidence of a CMM's results. Unfortunately, the temperature flow of the room was not taken seriously enough in the initial stages of room development, which led to significant delays in testing and system integration.

Based on this situation, I composed the following memo and presented it to corporate executives to justify additional dollars to enhance room temperature controls.

Internal Memo: Need for Tightened Temperature Control

Concerns and possibly doubts have been raised regarding the true need to control the high-accuracy CMM room to tighter-than-specified temperature controls. My objective for this document is to address some of the high-level issues applicable to the CMM so as to aid individuals in their level of understanding of this technology. I hope in turn, they not only will support the current need for this level of control, but also entertain it as a minimum standard for future controls.

My challenge in this justification effort, while preparing this memo, was in figuring out the audience that would possibly review it. Due to the wide range of technical expertise, within the potential audience, particularly concerning the understanding of thermal effects, I chose to stay generic with the content and to offer to make myself available to elaborate on key points and respond to specific questions any individual might have.

The following outlines the content of this memo:

1) Issues related to the justification of the CMM
    - Assumptions
    - Intangibles
2) Basis for the manufacturer's recommended temperature specification
3) Five blocks for building an understanding of temperature effects
    - Differential expansion
    - Expansion uncertainty
    - Source of temperature errors
    - Bi-material effects
    - Gradients
4) Temperature control of the current CMM room
5) Testing results applicable to the CMM in its current environment
    - Thermal drift test
    - Tolerances on tooling components and assemblies
    - Miscellaneous "feature-based measurement tests"
6) Miscellaneous variables aid in decreased confidence of measured results
7) Summary

(1) Issues Related to the Justification of the CMM

The original CMM focus was an extension of the tooling and product qualification procedure developed over one year ago. Our inability to measure tooling features within their stated tolerances and our ongoing struggle to make sound engineering decisions on less-than-accurate and repeatable measurement results were the principle justifications for spending well over one half million dollars to procure a ultra-precision class CMM. Some of the key issues that were made visible at that time were as follows:

Assumptions

1) < 1 µm is accurate enough to tell us what effects the tool shapes have on the forming process.
2) Environmentally controlled room is available (20 °C +/- 0.14 °C).
3) Trained operators/programmers are available to run the CMM.
4) All tools are mapped for “critical” characteristics and tracked over time to observe performance capability to longevity of tool life.

Intangibles

1) The trend is toward finer and finer forming capabilities. We continue to allow for (insist on) less variation in the tooling.
2) Data can be used to tell us the tool shape to understand the interaction between tool, press, and material.
3) Should provide better future tool designs “out of the shoot.” As we understand what dimensions worked in the past, we can incorporate those into future tool designs.
4) Improved process capability.
5) We currently end up with no permanent solutions to many tooling issues.
6) Customer satisfaction.
7) The target is moving. If we do not improve, the current situation could get worse with more difficult products “coming on board.”
8) Benefits of reduced lead times on new products (1-4 week improvement due to tool qualification).

(2) Basis for the Manufacturer’s Recommended Temperature Specification

I believe most of the doubt or confusion regarding the true need for tighter temperature control in the CMM room stems from individuals’ awareness of what the Brown & Sharpe/Leitz environmental requirements are for their enhanced-accuracy CMM (which is the machine we have).

Their environmental requirements allow for a vertical range of 0.75 ^{o}C/meter, a horizontal range of 0.7 ^{o}C/meter, and a maximum variation per day not to exceed 0.5 ^{o}C/day on any individual thermistor. Keep in mind that both the vertical and horizontal variations are targeted around 20 ^{o}C. To clarify, this would be 20 ^{o}C +/- 0.35 ^{o}C in the horizontal axis. What is essential to understand about this specification is that it is also based on a “total volumetric inaccuracy” of the system, not to exceed +/- 2 µm.

All CMM manufacturers are sensitive to the fact that the tighter the temperature specification, the more the room is going to cost to build and to maintain. Anytime you get beyond the mechanical, electrical, and software aspects of their system, and still want higher accuracy and repeatability, they will always tighten the environmental requirements of their specification. In most industries, companies would be extremely content with +/- 2 µm capability within the machine cube. In our case, it is not adequate.

Based on prior knowledge of the influencing variables, we decided to purchase the enhanced-accuracy system with standard environmental requirements and to tighten up the internal controls ourselves.

(3) Five Blocks for Building an Understanding of Temperature Effects

For the best accuracy, you should make all measurements at 20 °C. Both the measuring machine and workpiece should be at that temperature. At other temperatures, thermal expansions will cause errors. These errors cannot be corrected fully, even by the best temperature compensation methods. This is not to say that all measurements must be taken at 20 °C, but one must go through the following analysis to make a positive determination.

1) What are the workpiece tolerances?
2) How much measurement error can I reasonably accept?
3) How much of this error can I allow for in temperature effects?
4) How much temperature control do I need to keep temperature effects at an acceptable level?

The answer to question 1 is easily determined, questions 2 and 3 are business decisions, and question 4 is the difficult one to answer. I'm going to stay away from listing the formulas necessary for calculating each of the theoretical values for the influencing variables to question 4, but I want to touch briefly on five key blocks for building an understanding of temperature effects, which are differential expansion, expansion uncertainty, source of temperature errors, bi-material effects, and gradients.

Differential Expansion

Most materials expand as temperatures increase, but the amount of expansion varies by material. Expansion of a measuring machine is considered 0 at 20 °C. This is a matter of politics, not physics. A measuring machine compares a length on a workpiece with a corresponding length on a machine scale. Generally though, the workpiece and scale expand by different amounts. This is termed "differential expansion." With no other problem, error equals workpiece expansion minus scale expansion over the length of the measurement.

Expansion Uncertainty

Coefficients of expansion are given in shop, engineering, or scientific handbooks. Different handbooks will in some cases state different coefficients for the same type of material. This occurs because not all test specimens of a particular material are exactly alike.

NIST estimates expansion of a gage block to vary +/- 5% if heat and mechanical treatment of the blocks is defined, +/- 10% if undefined. Samples cut from a single large steel part vary +/- 2 %. Hot or cold rolling causes changes +/-5%. Grain structures cause different expansions in different directions.

Sources of Temperature Errors

It might seem that you cannot have large temperature errors with small workpieces because short lengths mean small expansions. But measurements that take a long time can be influenced by slight changes in temperatures of the workpiece and machine.

Influence from lighting on large machines in small rooms can have an impact. If the lighting is uniform, the machine will settle down to a stable shape that can be error mapped, but normally it is not uniform. The most common problem is the horizontal bending of the bridge (like on our machine). Air conditioning systems that alternately blow hot and cold air on a part of the machine can cause bending as well. Computers and controllers near the machine, as well as bodies (programmers and operators) will cause local heat sources that have the potential of causing a problem if the heat is not dissipated.

The principle problem with all of these potential heat sources is that they cause stratification problems within the envelope of the system. This causes different areas of the machine and workpiece to be at different temperatures.

Bi-material Effects

Bending of bi-metallic thermostat elements caused by temperature is fairly well understood. The same effect occurs in the measuring machines and workpieces. The effect is caused by slightly different coefficients of expansion of different parts of the machine or workpiece. Bi-material bending effects are “usually” very small.

Gradients

If temperature rises, heat flows through the machine surfaces and into the machine structure. The same happens with a workpiece. For heat to flow from the surface into the structure, there must be a temperature difference or gradient. You can think of this flow somewhat like a flow of water caused by a difference in pressure.

Gradients cause different expansions in different parts of the machine or workpiece. The results are similar to the bi-material effect and come in three situations:

1) If air temperature cycles rapidly (as with air conditioning) there is not much time for heat to flow into the machine or workpiece before it has to flow out again. Gradients are close to the surface, and the machine bending is small.
2) Where temperature changes slowly, the effect is as discussed under differential expansion.
3) The worst case is where temperature changes rapidly in the same direction for a long period of time. It causes that part of the machine or workpiece structure to change temperature more quickly than thicker parts, causing bending.

(4) Temperature Control of the Current CMM Room

The critical issue to keep in mind when reviewing the following is that our target has always been 20 °C +/- 0.14 °C.

Recent “repeatability” tests on our CMM for diameters and lengths (lengths less than 100 mm) had outcomes that were considered extremely high (0.6 µm at Six Sigma). Attempts at optimizing programs yielded only a slight gain (0.5 µm at Six Sigma). These results do not include accuracy.

Poor temperature stratification was suspected to be the main problem, which led to installing eight thermistors around the machine at various heights and the results were monitored. The range of temperature within the envelope of the system was greater than 0.83 °C, with an average of close to 20 °C. Since that time, air flow has been adjusted coming into the room to aid in dissipating local heat sources, which in this case is principally the computers and bodies. Based on these adjustments, the range has improved but is still greater than 0.56 °C.

(5) Testing Results Applicable to the CMM in its Current Environment

Thermal Drift Test

In 1985, ANSI/ASME published a standard (B89.1.12M) which covered “Methods for Performance Evaluation of Coordinate Measuring Machines.” This standard covers generic test procedures for determining both linear and volumetric inaccuracies of CMMs, as well as procedures for determining the stability of the environment. This test is called a thermal drift test.

To run this test, the machine is required to sit stable for a specified length of time, then with a calibration sphere located as close to the machine work surface as possible (to ensure stability), the probe is to be calibrated using a defined number of points. Once calibrated, you establish the coordinate system to -0- (all three axes). Then you place the CMM in a continuous loop to re-measure the sphere, one time every minute. This is continued for 48 hours, storing the x, y, and z axis displacement values from its original -0-, as well as storing the size and profile displacements from its original size and shape. Note: There are temperature sensors built into the x, y, and z axes slides that are monitored during the test period.

The test ran for 56 hours. The results clearly explained why we could get no better than 0.5 µm repeatability at Six Sigma on prior tests. The range of drift over the length of the test in our case was not the critical variable we were concerned with, but rather the amount of drift recognized over a length of time equivalent to the longest program used to measure a component or assembly. In this case, we were interested in a time segment of two hours.

Once the machine stabilized (about 2 hours), the largest drift within any two hour segment in a single axis was approximately 0.4 µm, with individual spikes of 0.3 µm over a 30-minute time frame. Two additional 24-hour versions of this test were run with the same level of results. It is critical to note that the charts clearly display a direct correlation between temperature change and displacement, very close to a linear relationship.

Tolerances on Tooling Components and Assemblies

What needs to be kept in mind on this issue is that the “enhanced-accuracy” CMM was justified principally to measure critical features on tooling components and assemblies. In addition, we were clearly aware (up front) that this CMM (or any CMM) was not capable of measuring every feature we considered critical to process or function. For example, one of the restrictions on a contact CMM is probe diameter. The smallest “standard” probe tip available is 0.3 mm, which restricts measurements on an inside radii or diameter.

A large percentage of the features of size have tolerances of 1.25 µm to 2.5 µm with feature location tolerances of 5 µm. I believe I would be conservative in saying that greater than 50% of the features that are measured on this CMM are ≤ 5 µm. These are “current” tolerances defined on tooling drawings at this time.

If we look back at one of the original “assumptions” (#1. 0.5 µm is accurate enough to tell us what effects the tool shapes have on the forming process), this was a “worst-case” statement which included accuracy and repeatability of the measurement system. What has been discussed so far has been only “repeatability.”

Miscellaneous Feature-Based Measurement Tests

It is essential that the results from the thermal drift test are understood to be based on a simple measurement within a small known envelope of 25 mm, so accuracy and repeatability are at their best. Where it starts becoming more difficult is in measuring other types of geometric features within a larger envelope, such as perpendicularity, cylindricity and profile, to name a few. It takes a significant number of points on a given feature to get an accurate representation of its geometry. A general rule to note is that as you increase the number of points, the better the accuracy and repeatability. There are exceptions, but in general this holds true.

(6) Miscellaneous Variables Aid in Decreased Confidence of Measured Results

In addition to temperature, there are many other variables that influence accuracy and repeatability. Some of these variables are humidity, contamination, types of probes due to stability (stiffness) such as the difference between steel shafts versus ceramic and carbide, probe speed, and fixturing. The list goes on and on. The key item at this time that is restricting our leap into the sub-micrometer capability we need (and have been striving for) is “temperature.”

(7) Summary

The “great” part about our CMM is that it is exceeding the specifications committed to by Brown & Sharpe/Leitz. They were aware from the beginning that our expectations of their system was to push it well beyond their stated capability. They also mentioned that tight temperature control would be necessary to accomplish this task.

I sincerely feel the level of temperature control I’m stating here is also needed in many other measurement applications at our site to reduce current inaccuracies. I hope I have convinced the readers of this memo on the need for tight temperature controls to achieve sub-micrometer measurement capability on this type of measurement system. I will need approval for additional expenses of $35K to achieve the defined controls for the CMM room.

If there are any questions, I would be happy to address them as best I can.

END of MEMO.

All funds were approved based on this presentation.

20.3 CMM Performance Test Overview

The testing was done on a Brown & Sharpe/Leitz PMM 654 Enhanced Accuracy CMM to determine the machine's capability and the confidence with which various features could be measured.

There are a variety of parameters affecting the repeatability of measuring a geometric element on a CMM. These parameters can be separated roughly into three categories: environmental, machine, and feature-dependent parameters. These include, but are not limited to, the following:

1) Environmental

- Room (and part) temperature stability
- Room humidity
- Vibration
- Dirt and dust in room
- Airline temperature stability

2) Machine

- Settling time (probing speed, probing offset, and machine speed)
- Probing force (upper and lower force, trigger force, and divider speed)
- Flexibility of probe setup (probe deflection)
- Multiple probe tips (star probe setups and magazine changes)

3) Feature Dependent

- Size (surface area) of feature
- Number of points per feature
- Surface roughness (form) of the part
- Scanning speed

The following three sections will add detail to the above three categories with insight to the testing completed. This should be considered summarized information that leads to the final development of the capability matrix — the final goal of "measurement methods analysis in a submicrometer regime." The scope of these tests is intended to do whatever is necessary to have Six Sigma measurement capabilities for all geometric controls of interest, less than 1 µm.

Many of the machine (Section 2) and feature-dependent (Section 3) tests have graphs showing a visual representation of the data. For convenience, these will not be referred to by graph number and will be located within the test section to allow better use of space.

20.3.1 Environmental Tests (Section 1)

20.3.1.1 Temperature Parameters

To understand the relationship between the room environment and the CMM's results a "thermal drift test" that tests for thermal variation error (TVE) was completed. This test is outlined in the ANSI/ASME Standard B89.1.12M and is called "Methods for Performance Evaluation of Coordinate Measuring Machines."

To run this test, the CMM was parked in its home (upper, left, back corner) position for a period of six hours. This allows the machine enough time to stabilize if necessary. Then using five points, a 25-mm sphere was measured three times, reporting the average x, y, and z center position, diameter, and form. This measurement sequence was repeated for a minimum of 12 hours, and the results graphed opposite the temperature of the three axes scales. Temperature compensation was enabled at the beginning of every sequence. The range of the drift over the full length of the test was not the critical variable. Rather, it is the amount of drift that occurs over the length of time equivalent to the longest program used to measure a component or assembly. In this case, the interest was in the maximum time segment of two hours.

TVE Test # 1:

	X	**Y**	**Z**
Coordinate range (mm)	0.00417	0.00080	0.00068
Temperature range (°C)	0.10040	0.08752	0.12872

This TVE test was run for a period of 56 hours in the new lab with temperature centered on 20 °C. The y and z axes showed an amazing linear response to the temperature of their respective axis. These test results prove that controlling the temperature of the machine axes is essential to the performance of the CMM. However, the results were not as good as expected and raised some new questions.

First, why does the x-axis not respond to its temperature in a linear manner? Was there another parameter creating a greater effect on the x-axis than temperature? If so, what was that parameter? Also, why was the x-range so much larger than the y and z ranges? Finally, why do all three axes show a large decrease in temperature at the beginning of the measurement cycle? Was it the fact that the machine is running? (You would logically expect the machine to heat up, not to cool down when running.) Or was it the position of the machine when resetting in the home position versus its position when measuring the sphere? If so, what was causing the temperature drop?

TVE Test # 2:

	X	**Y**	**Z**
Coordinate range (mm)	0.00068	0.00053	0.00081
Temperature range (°C)	0.04247	0.06178	0.10812

The next step was to run a shortened version (24 hours) of the same test to ensure the results of the first test were repeatable. When duplicating results, it is essential each step of the original test is followed exactly.

The results were very similar to those from the first test. The y and z axes continued to have a strong linear relationship with their axes temperatures, while x was definitely nonlinear in nature. The initial decrease in all three axes temperatures was again evident in the first two hours of the test. In this test all three axes' temperatures were also plotted against one another, showing that all three axes were following the same pattern. It was evident that whatever was creating the fluctuations in one axis was also affecting the other axes. When looking at the magnitude of the temperature drop, the z-axis had the largest temperature range followed by the y and then the x axis.

In addition, the three axes temperature plot revealed a great deal of stratification in the room (over a 0.3 °C difference) between the y and z axes and the x-axis. It is highly possible such a large amount of stratification could cause problems when attempting to hold the room environment constant. Finally, the y-axis temperature was displaying a cyclical pattern about 40-45 minutes in length. A closer inspection of the first test showed a similar pattern as well. This test left four questions to be answered:

1) What machine or environmental parameter was causing all three axes to decrease in temperature at the beginning of every run?
2) Why was the x-axis displaying a nonlinear relationship to its axis temperature? Is there some other outside parameter affecting its performance?
3) Would the stratification of the room create any performance or room stability problems? If so, what was creating this stratification?
4) What was causing the cyclical effect observed in the y-axis?

TVE Test # 3:

	X	Y	Z
Coordinate range (mm)	0.00167	0.00072	0.00135
Temperature range (°C)	0.04762	0.06693	0.11585

The next TVE test was designed to test whether the decrease in temperature occurred directly after the machine began to run. The temperatures of all three axes were recorded while the machine was resetting in its home position for six hours before measuring the sphere for 24 hours.

The results of this test clearly indicated the machine reached a higher temperature plateau when placed in the home position. Either the movement of the machine or the machine placement was causing this change in temperature. Based on this, the decrease was being caused either by the room environment or the temperature of the air exiting the air bearings.

At this point, a sensor was placed directly within the air line entering the room to monitor the temperature going into the air bearings. The results showed the temperature going into the air bearings was indeed higher than the room temperature. Could the air bearings be closer to the axes scales at certain positions of the machine? Or in the case of the z-axis, was the ram being warmed up due to the higher temperature air exiting from the air bearings?

Questions arose regarding whether temperature compensation would create problems in the resulting data if it were activated. An additional test was run without temperature compensation. Additionally, there was at least one rest period of six hours where the machine was left directly above the sphere. This data would tell us if the position of the machine was causing the temperature drop.

Finally, these test results displayed the y and z axes were again linear to temperature while the x-axis was not. The temperature of the three axes continued to follow one another, and the same amount of stratification was evident. However, the cyclical pattern of the y-axis was not displayed in this test.

TVE Test # 4:

	X	Y	Z
Coordinate range (mm), (temp comp on)	0.00092	0.00051	0.00133
Coordinate range (mm), (temp comp off)	0.00092	0.00048	0.00113
Temperature range (°C)	0.08336	0.09782	0.16476

In this test, the machine was placed in the home position for six hours, run for 12 hours, placed in the home position for six hours, run for 12 hours, placed directly above the sphere for six hours, and run for twelve hours. The sphere was measured with and without temperature compensation to see if any difference did exist in the results.

The results indicated the position of the machine was causing the change in temperature to occur. In all three axes, there was a definite rise in temperature when the machine was in the home position. When the machine was left to rest above the sphere, however, no similar rise in temperature was evident. Additionally, the test showed only a simple bias between the data taken with and without temperature compensation. The data collected up to this point was indeed valid. Finally, the cyclical effect that had disappeared in the previous test had resurfaced not only in the y-axis but also in the z-axis.

Based on this data, a new approach was taken to control the room environment (based on the memo shown at the beginning of section 1). A new air-flow system was added to ensure a uniform air flow moving over and away from the CMM. This would prevent warm pockets of air from being trapped around the machine. Test # 4 was replicated.

TVE Test # 5:

	X	Y	Z
Coordinate range (mm), (temp comp on)	0.00047	0.00042	0.00052
Coordinate range (mm), (temp comp off)	0.00052	0.00047	0.00051
Temperature range (°C)	0.03928	0.04332	0.04111

Based on these results, test #5 was replicated two more times to ensure a high degree of confidence in the measured results.

TVE Test # 6:

	X	Y	Z
Coordinate range (mm), (temp comp on)	0.00042	0.00038	0.00049
Coordinate range (mm), (temp comp off)	0.00048	0.00046	0.00050
Temperature range (°C)	0.04211	0.04182	0.04132

TVE Test # 7:

	X	Y	Z
Coordinate range (mm), (temp comp on)	0.00045	0.00040	0.00050
Coordinate range (mm), (temp comp off)	0.00050	0.00042	0.00054
Temperature range (°C)	0.03723	0.04123	0.03998

It is interesting to note that the cyclical effects stayed present in the last three tests, but to a lesser degree. Further temperature optimization was not pursued due to current satisfaction in the noted results.

20.3.1.2 Other Environmental Parameters

There are obviously more environmental parameters than simply temperature. Humidity, vibration, dirt and compressed air quality are generally considered less important, but were determined to be well within specifications.

The pressure and temperature of the compressed air was also within specifications before the machine was installed. However, due to concerns arising from the TVE tests, the compressed air was examined again. Sufficient pressure was being supplied to the machine and the temperature (although higher than room temperature) was within specification. Finally, the dust content of the room was lowered slightly by adding floor mats in the buffer room and by sealing off miscellaneous areas.

Based on the Six Sigma capabilities being driven for in the submicrometer regime, it is essential the room environment be as stable as possible. Uniform air flow and temperature over the CMM must be constant, as any change will be recognized.

20.3.2 Machine Tests (Section 2)

20.3.2.1 Probe Settling Time

The Leitz PMM 654 machine was installed so the factory default machine parameters were active. These default settings have been optimized for maximum accuracy and throughput when using the machine for a majority of the applications. However, these settings can be changed to improve accuracy or throughput on out of the ordinary applications. For example, the force applied by the probe head must be lowered in order to measure a thin, flexible part. The machine settings marked as important to test are the probe settling time and probe force.

Machine Test #1: Z-Axis single-point measurement versus probe settling time (see Fig. 20-1)

The probe settling time is a function of two probe settings: the probing speed (mm/sec) and the probing offset (mm). By decreasing the probing speed and increasing the probing offset (thereby increasing settling time), we should see an increase in the performance of the machine.

To test this theory, a single point in the z-axis was measured 25 times and its Six Sigma repeatability was calculated. This sequence was repeated using various combinations of the two settings. The results displayed unique changes in the repeatability of single-point measurement as the settling time increased from 0.125 to 1 second. These results were contradictory to the original hypothesis that increasing the settling time would increase machine performance.

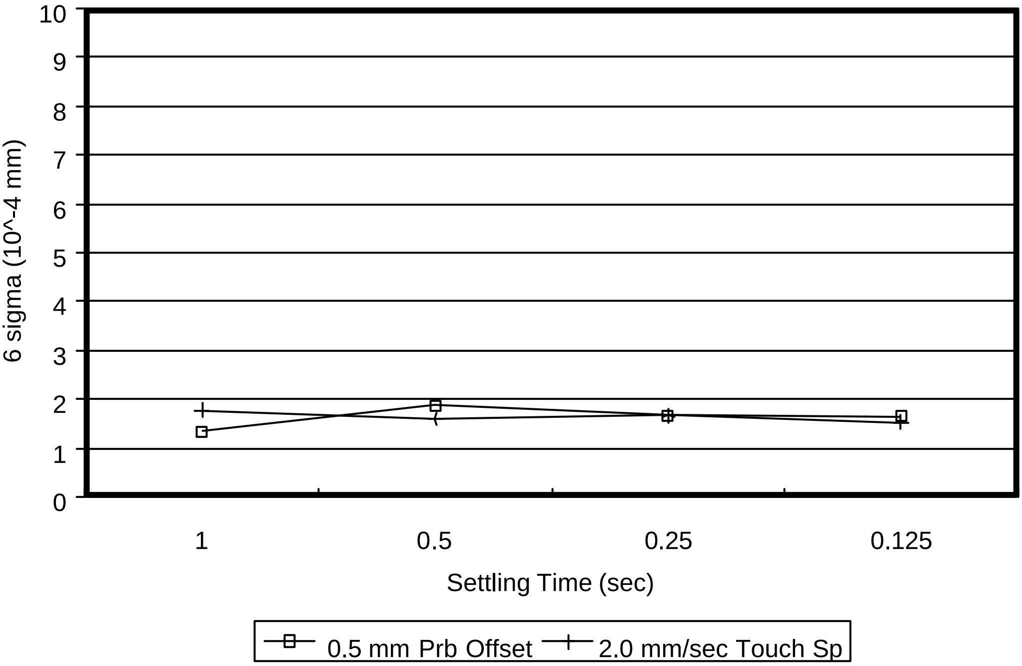


Figure 20-1 Z-Axis single-point repeatability

Machine Test #2: Sphere form versus probe settling time (see Figs. 20-2a and 20-2b)

In this test, three different probes were calibrated on a 10-mm sphere. This same sphere was then remeasured 25 times using a 29-point pattern, reporting the sphere's mean form and Six Sigma value. The

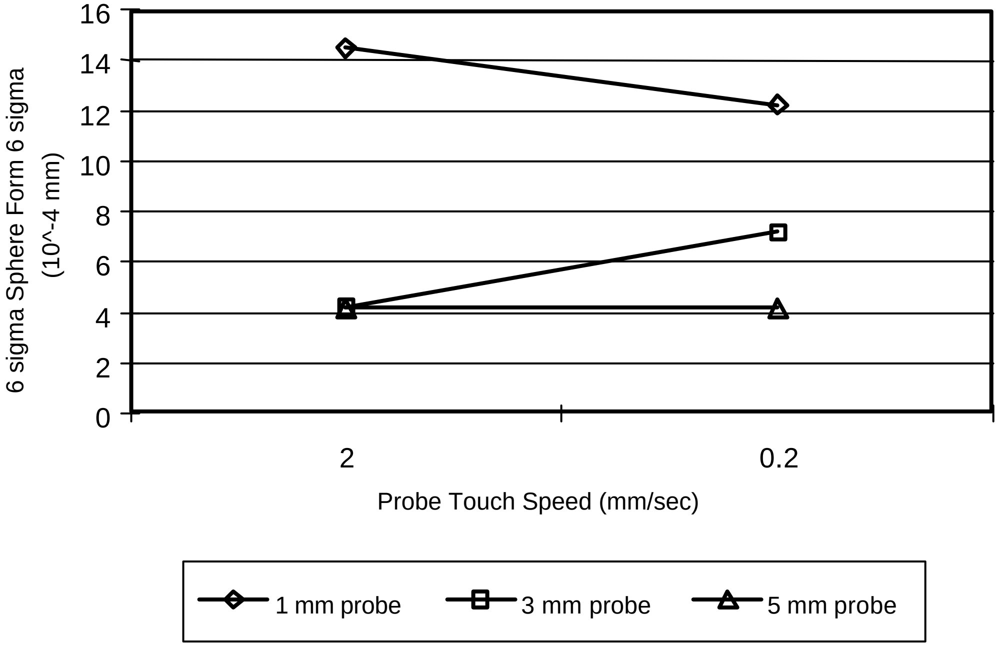


Figure 20-2a Form Six Sigma versus probe settling time (10-mm sphere)

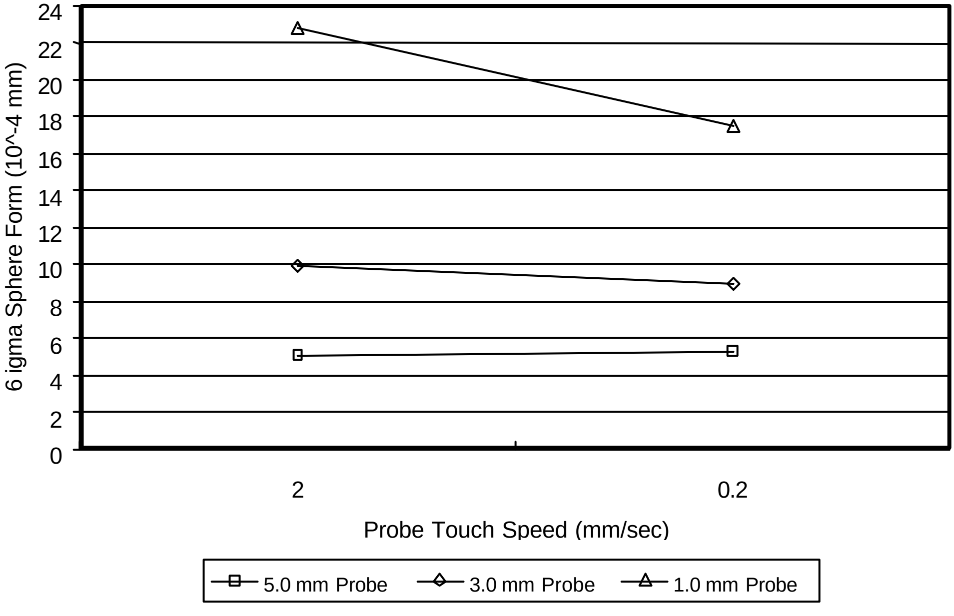


Figure 20-2b Sphere form versus probe settling time (25-mm sphere)

first series of measurements were taken using the default probe speed of 2 mm/sec. A second series of measurements were taken at 0.2 mm/sec (the probe was recalibrated at the lower speed before measurement). This entire procedure was then repeated with a 10-mm sphere.

The results show a slight improvement in the mean form when lowering the probe speed. These results were similar to those from the single-point repeatability. This is more than likely due to the design of the Leitz probe head, where the actual probe point is registered as the head is pulling away from the part. Therefore, the small range of this test had a limited effect on the machine's performance, which is adequate based on the speculated range of operation.

Machine Test #3: Probe speed versus sphere form (see Fig. 20-3)

This test was run to get a better idea of the machine's response over a greater range of settling times. Using the default probe offset of 0.5 mm, the following probe speeds (mm/sec) were tested: 4, 2, 1, 0.5, 0.25, 0.125, and 0.0625

At each probe speed, two different probes were calibrated on the 25-mm sphere. This sphere was then remeasured using a 29-point pattern, with the form, diameter, and probe deflection being reported. The results again showed limited decrease in the sphere form as the probe speed decreased, regardless of which probe was tested.

At this time, there is no evidence to support the idea that decreasing the probe settling time will increase the performance of the machine. Within the range of values tested, there was no evidence of relationship between settling time and machine performance.

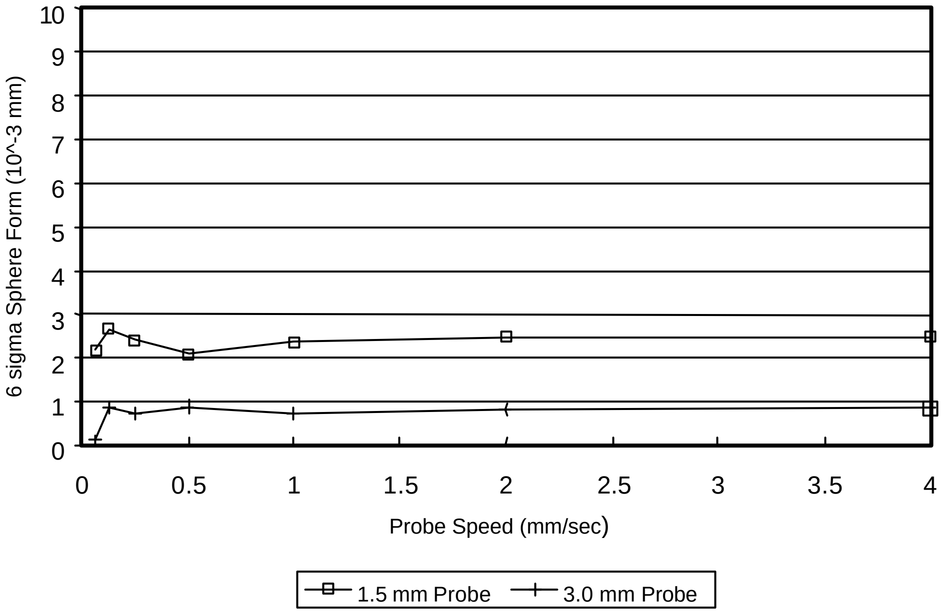


Figure 20-3 Probe speed versus sphere form

Machine Test #4: Sphere form versus probe trigger force (see Fig. 20-4)

Another assumption made before testing began was that lowering the probe head "trigger force" would improve the machine's performance. By varying the probe force, it should be possible to decrease the deflection to which the probe shaft is subjected. This theory was put to the test using three different probe tips calibrated on the 25-mm sphere. This sphere was then remeasured 10 times using a 29-point pattern, reporting the mean form and Six Sigma value.

The first series of measurements were taken using the default trigger force of 0.5 N. A second series of measurements were taken using 0.05 N trigger force (the probe was recalibrated at the lower trigger force before measurement). This entire procedure was then repeated using the 10-mm sphere. The results show an inconsistent relationship between the probe force and sphere form. It was determined that probe force is really a function of several machine settings; upper and lower force, trigger force, and divider speed. Further testing showed that it was possible to influence the form and diameter of the measured sphere by changing these parameters.

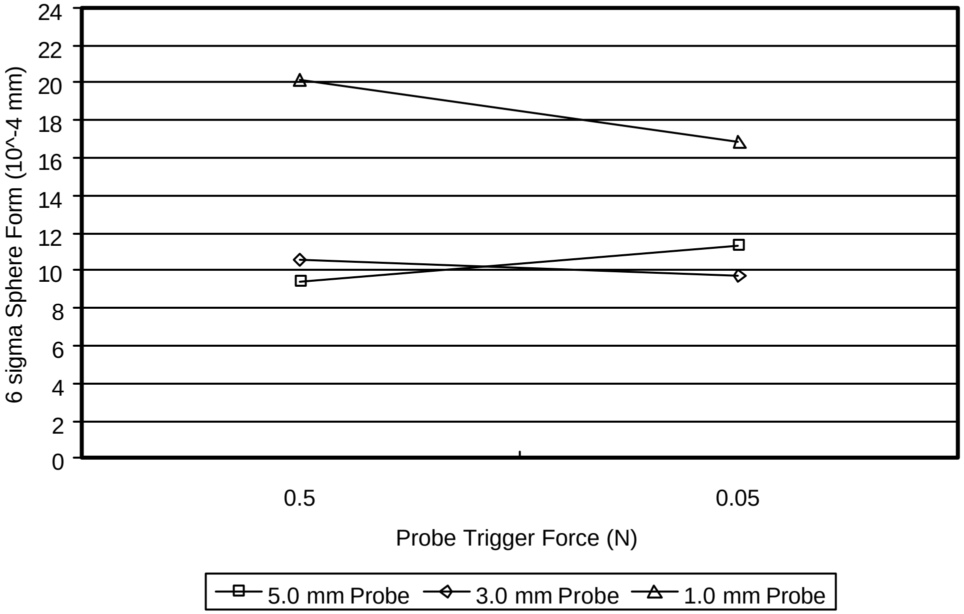


Figure 20-4 Sphere form versus probe trigger force (10-mm sphere)

20.3.2.2 Probe Deflection

The more flexible the probe shaft becomes, the more difficult it becomes to measure in an accurate and repeatable manner. To compensate for this problem, the Leitz probe head creates a deflection matrix, which attempts to map out the amount and direction the probe shaft will deflect. The following is a layout of this matrix:

$$\begin{array}{ccc} xx & xy & xz \\ yz & yy & yz \\ zx & zy & zz \end{array}$$

For example, the xx position in the matrix defines how much deflection occurs in the x-axis when probing solely in the x-axis. This deflection matrix should dampen the deterioration that occurs in accuracy and repeatability as a probe becomes more flexible.

Machine Test #5: Diameter (circle), form, x and y versus probe deflection (see Fig. 20-5)

This test was conducted using four different diameter tips with varying deflection values ranging from 0.295 µm to 1.982 µm. A diameter was measured 25 times and its x, y, diameter, and roundness values were recorded. There was a definite deterioration in repeatability that occurred as the deflection values increased. It must be noted that all probes used were placed straight down in the z-axis using a 25-mm extension. When measuring a diameter with this type of probe, all points were taken with a direction vector that is a combination of the x and y axes. This direction is one in which the probe will deflect the greatest amount. It would then seem very logical that such deterioration would exist as the probe deflection values increased.

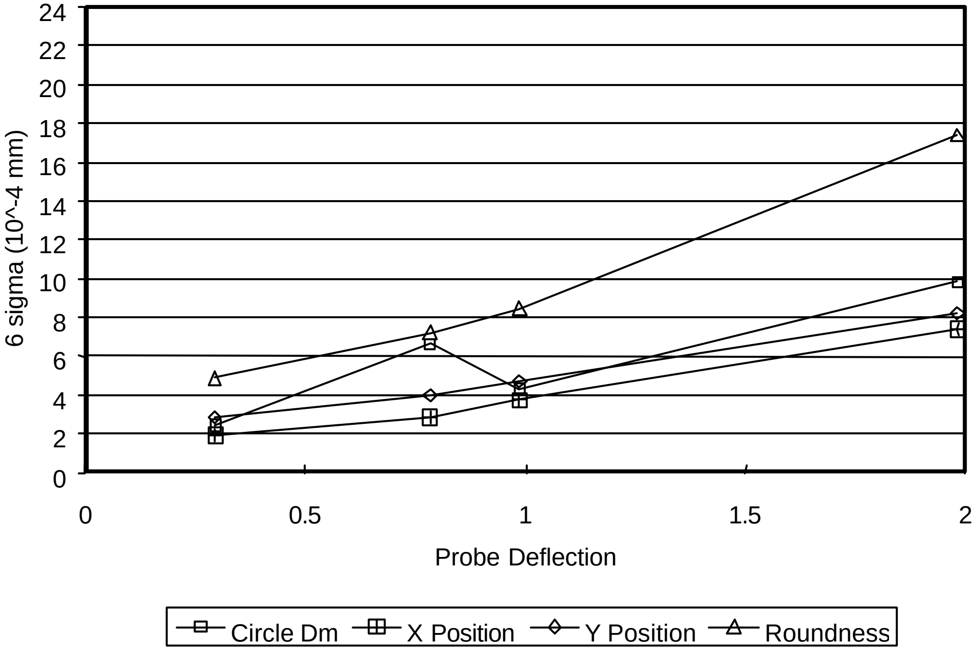


Figure 20-5 Circle features versus probe deflection

In addition, this test also displayed the average diameter in relation to the probe's deflection value. No pattern seemed to exist within the graph, although this may be due to the limited number of probes that were run in the test.

Machine Test #6: Diameter (cylinder), form, x and y versus probe deflection (see Fig. 20-6)

Another test was run using three different probe tips with deflection values ranging from 0.298 μm to 2.278 μm. A cylinder was measured 25 times at three heights, reporting its form, diameter, position, perpendicularity, and straightness values. Again, the results display a deterioration in the repeatability of these features as the deflection values increase.

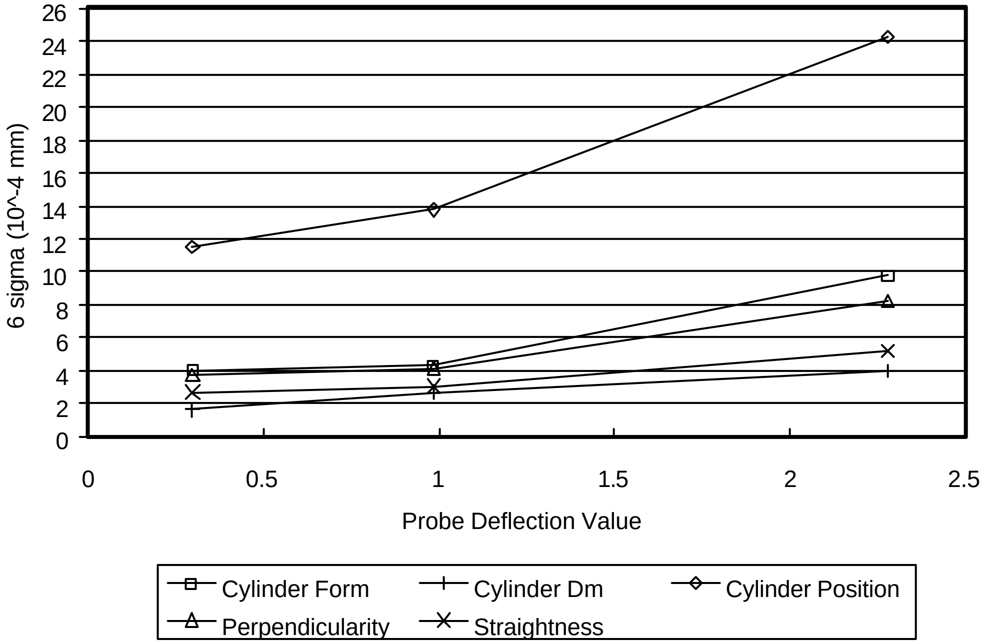


Figure 20-6 Cylinder features versus probe deflection

From these tests, it would seem that the Leitz probe deflection matrix is effective when ensuring the accuracy of the machine does not deteriorate as the probe deflection increases. However, the repeatability of the more flexible probes remains worse than that of the stiffer probes. Mentioned earlier was the possibility that by manipulating those parameters which contribute to the probing force, the deflection that a probe shaft undergoes could possibly be lowered. If this can be accomplished, improvement on performance of all probes should be possible.

Machine Test #7: Probe deflection versus sphere form (see Fig. 20-7)

It has been proven that the machine performance decreases as the probe flexibility increases. It is important that operators of this machine have a very good understanding of how each probe in the probe kit will perform when used. This begins by creating a matrix which contains the deflection of every single probe. When the operator is attempting to maximize the performance of the CMM, they will then be able to choose the probe with the least amount of deflection that will accomplish the job at hand.

Each probe was calibrated 10 times in the xy plane with a 25-mm extension using the three-axis deflection calculation. The calibration sphere was then remeasured using a 29-point pattern, reporting the form, diameter, and probe deflection. In this manner, a matrix containing the probe deflection of every probe was constructed for the operators. In addition, a graph was developed showing the relationship between probe deflection and the sphere form over a large variety of probes. The results again support the theory that the performance does decrease with increased probe deflection.

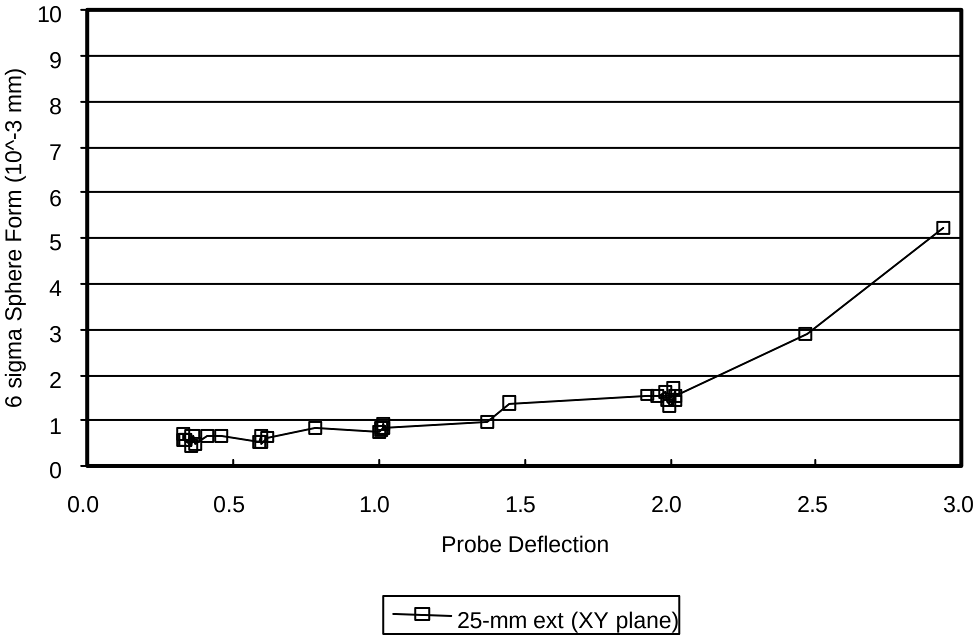


Figure 20-7 Probe deflection versus sphere form

20.3.2.3 Other Machine Parameters

Machine Test #8: Ring gage test (roundness)

The Leitz probe head interprets an electromagnetic signal (differential transformers with a moving core) to determine the amount of deflection that is taking place when probing a part. Each axis has its own spring parallelogram that independently determines the amount of deflection in that one axis. If two axes are interpreting their signals differently, then the results from measuring a circle will appear oval in shape. This is a good way to test the balance of the probe head.

In this test, a XXX ring gage was measured with 360 points in the three planes and the results plotted. If the circle appears to be pinched in the x or y axis, then it is a good possibility that the probe head is out of balance. If the circle is distinctly oval in shape, rotate the ring gage 90 degrees and remeasure the gage. If the oval shape does not rotate with the gage, then the error is either occurring in the probe head or the machine. The results of this test did not indicate a problem.

Machine Test #9: Single-axis repeatability

When the service personnel calibrated the machine on site, they measured a Moore bar in all three axes. It was assumed that if there was a mechanical problem with one axis, it would appear at this time. We conducted a simple single-point repeatability test on each axis. We chose an axis, took a single-point probing in that axis, then moved away from that point using three axes movement. We repeated this measurement using 50 runs, and ran this procedure in the remaining two axes. The results showed that all three axes performed equally well.

20.3.2.4 Multiple Probes

It is often necessary to use more than a single probe when measuring a part. On this particular Leitz machine, there are two types of multiple probe setups; two or more probes located within the same probe configuration (e.g., star probes) and two or more probe configurations established using the magazine probe changer. At this time, it is believed that changing between two or more probes within the same setup will not decrease the repeatability of the measured feature. However, there is the possibility of a bias being incorporated into the offset established between the probe being used and the reference probe. For the sake of these tests, it is not considered a factor that has significance due to certified artifacts being used in all cases for the development of the capability matrix.

20.3.3 Feature Based Measurement Tests (Section 3)

Feature-dependent parameters affect a machine's performance to varying degrees depending upon the type of geometric tolerance being measured and calculated. These parameters include the size or surface area, the number of points taken, and the surface roughness of that feature.

How many points does a programmer take when measuring a small diameter? How many points on a large diameter? Does this remain true for other features such as flatness of a plane? What effect will the surface roughness have upon these numbers?

The repeatability of the machine does indeed vary from one feature to another. For instance, the repeatability obtained from calculating the diameter of a hole measured with 16 points is better than that received when calculating the roundness using the same points. This is simply because the diameter is a least squares best-fit average of those 16 points. The roundness of the hole on the other hand is a range of those 16 points. It is understood that all performance values are a function of the repeatability of a single probing point. However, the question remains as to how the various parameters contribute to that function.

It was important to answer these questions in order to obtain the necessary level of confidence in the machine. Simply stating that the machine's linear accuracy is 0.5 +L/600 micrometers (where L = length in meters) and its single-point repeatability at Six Sigma is 0.1 µm is not enough. This information does not help an operator determine if he/she can measure a runout tolerance of 2.5 µm or a diameter tolerance of 1.25 µm. This is not to imply that it was necessary to test every tolerance that may be called out on all features. Many tolerance repeatability values can be extrapolated from data obtained from other tested tolerances. Therefore, the attempt here was to optimize testing to those types and sizes of features most commonly required by engineering drawings at a given organization.

Feature Based Test #1: Circle features versus hole diameter (see Fig. 20-8)

This first test was run to determine what effect, if any, the size of the hole would have upon the machine's performance. The results indicate limited relationship between the diameter of the hole and the repeatability of any of the circle elements. The graph also displays the fact that the repeatability is indeed feature-dependent. The repeatability of the hole's roundness value is much worse than the hole diameter value.

Feature Based Test #2: Cylinder features versus hole diameter (see Fig. 20-9)

As in test #1, the objective was to determine if the size of the cylinder would have any effect on the measured results. Six ring gages ranging from 12.5 mm to 54 mm were measured 25 times at two heights using 32 points per height. Their diameter and cylindricity repeatability values were plotted versus size. The graph again shows limited relationship between the hole's size and the repeatability of its diameter or form. Possibly, the length of the cylinder may affect the repeatability of such features as position, perpendicularity, and straightness.

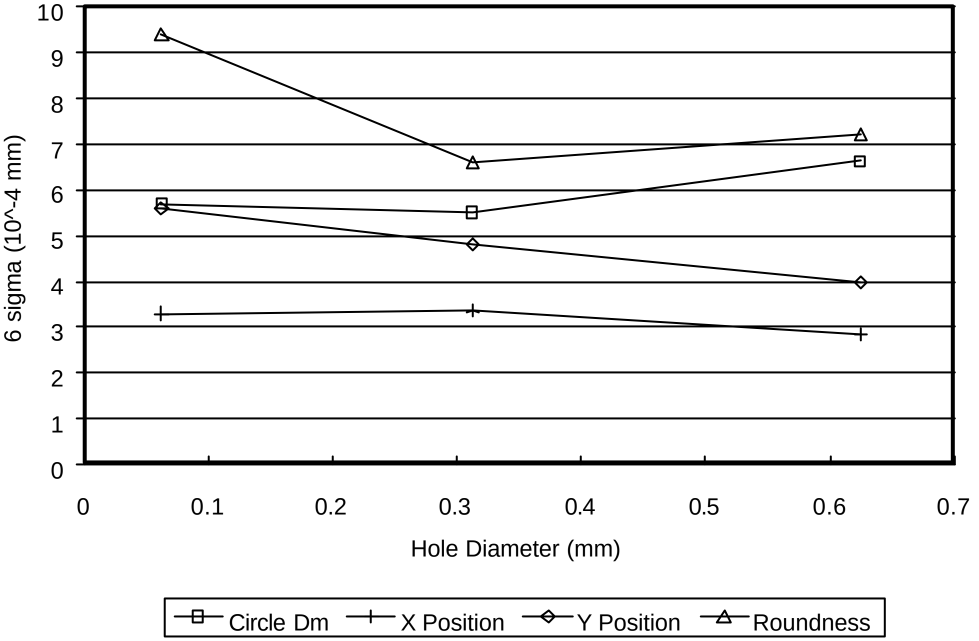


Figure 20-8 Circle features versus hole diameter

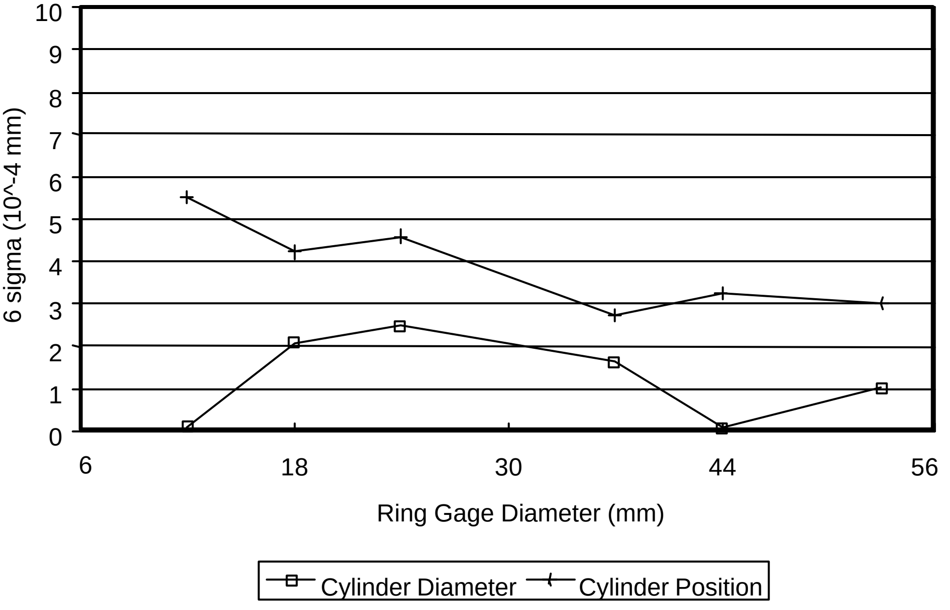


Figure 20-9 Cylinder features versus hole diameter

Feature Based Test #3: Bidirectional probing versus varying lengths (x and y axis) (see Figs. 20-10a and 20-10b)

Six gage bars of lengths 25, 50, 100, 200, 250, and 400 mm were placed in the x- and y-axes. The two end planes were measured using 32 points each, recording the minimum and maximum length of the bars. In addition, a single point was taken on each end, and the bidirectional probing repeatability was calculated. These results again showed a discernible pattern between length of the gage and repeatability of the features. Additionally, neither the x or y axis seemed to perform better than the other. These tests have been limited to the 25 mm × 25 mm area on the ends of the gage blocks.

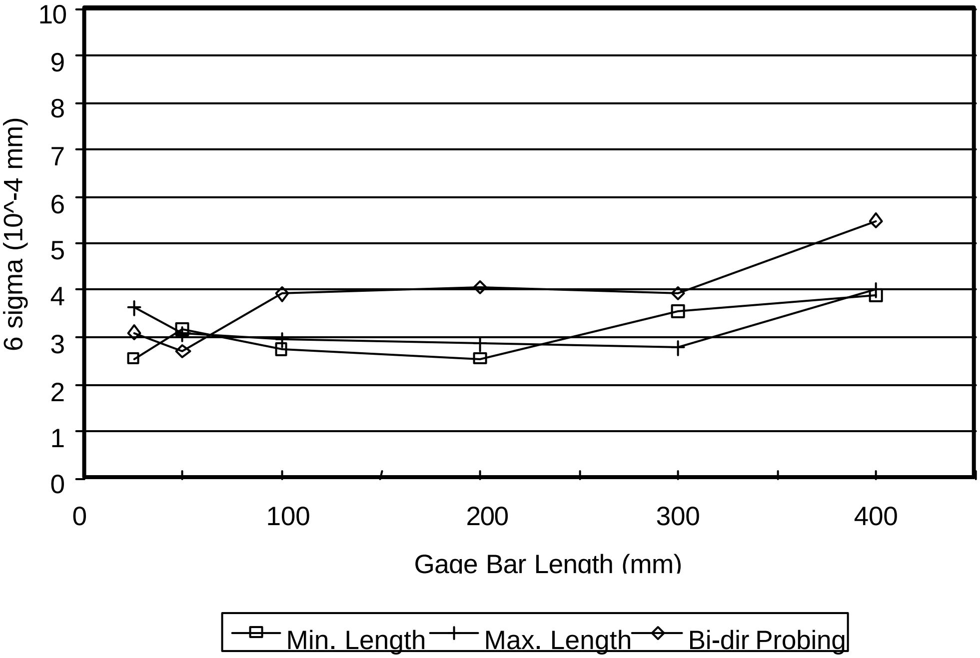


Figure 20-10a Bidirectional probing versus varying lengths (x-axis)

20.3.3.1 Number of Points Per Feature

Feature Based Test #4: Circle features versus number of points per circle (see Fig. 20-11)

This test was run using a very stiff 5-mm probe (0.295 deflection) that measured a circle 20 times and reported the diameter, roundness, and position. There is a strong indication that the diameter and the x and y position have a better repeatability as the number of points taken increases. This makes sense, because these three geometric elements are averages of the points taken. The roundness of the hole, on the other hand, is a range of values; therefore, its repeatability deteriorates as the number of points increase.

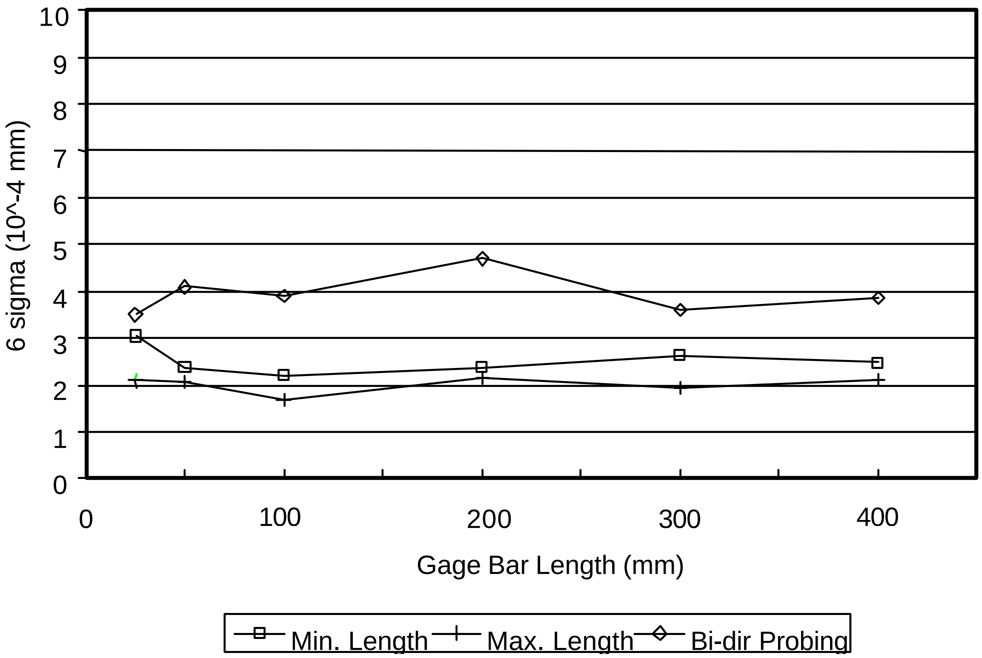


Figure 20-10b Bidirectional probing versus varying lengths (y-axis)

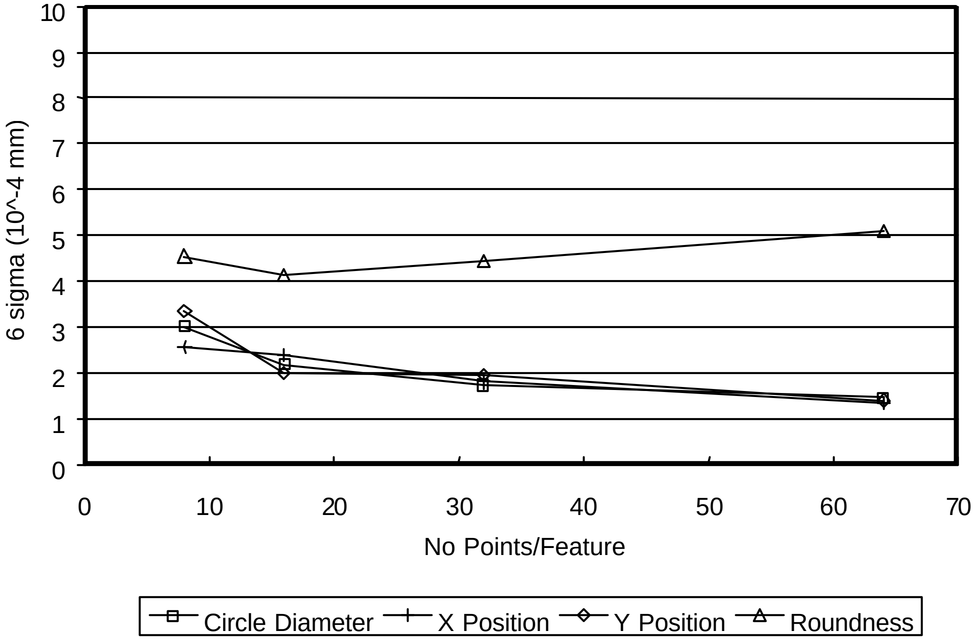


Figure 20-11 Circle features versus number of points per section

Feature Based Test #5: Cylinder features versus number of points per section (see Fig. 20-12)

Varying the number of points per feature was expanded to the measurement of cylinders. Four 16-mm diameter cylinders 18 mm in length were measured at three sections, increasing the number of points per section from 16 to 32. Each individual point density measurement was repeated 25 times before moving on to the next density.

At first glance, these results followed the pattern expected. Cylinder position, perpendicularity, and straightness repeatability improved as the number of points per section increased, while cylindricity displayed the opposite effect. It appeared that the 16 and 32 point tests were very similar, possibly due to the law of diminishing returns. However, this is with only three different point densities used, so an additional test was designed ranging from 4 to 16 points.

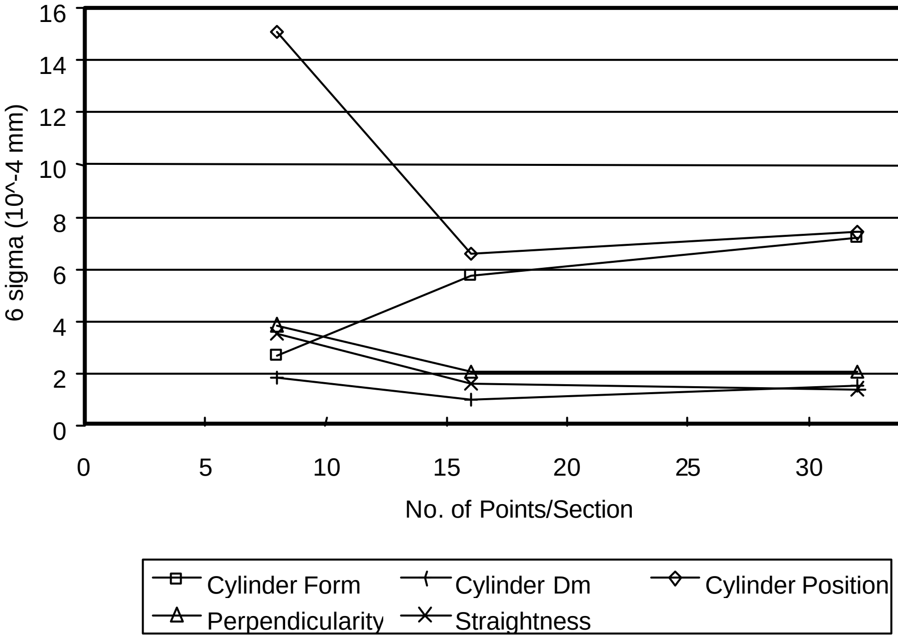


Figure 20-12 Cylinder features versus number of points/section

Feature Based Test #6: Cylinder features versus number of points per section (see Fig. 20-13)

Again, four 16-mm diameter cylinders 18 mm in length were measured at three sections. The first series of measurements were conducted using four points per section and were repeated 25 times. Runs using 8 and 16 points followed in the same manner. Unfortunately, these results were not what was expected. No pattern displayed in these results indicated that the number of points per feature affected the repeatability of the cylinder measurement.

After much consideration, testers decided that more information needed to be collected. Therefore, a more extensive test was outlined using the following range of points per section: 4, 6, 8, 10, 12, 14, 16, 18, 20, 24, 28, and 32. Also, the manner in which each point density run potentially allowed temperature to affect one run more than the other was a concern.

Feature Based Test #7: Cylinder features versus number of points per section (see Fig. 20-14)

In this test, two 16-mm diameter cylinders 18 mm in length were measured with each of the above-mentioned point densities, working from four points per section to 32 points per section. This entire procedure was then repeated 25 times. If there were any temperature stability problems, their effects would be the same for all point density runs.

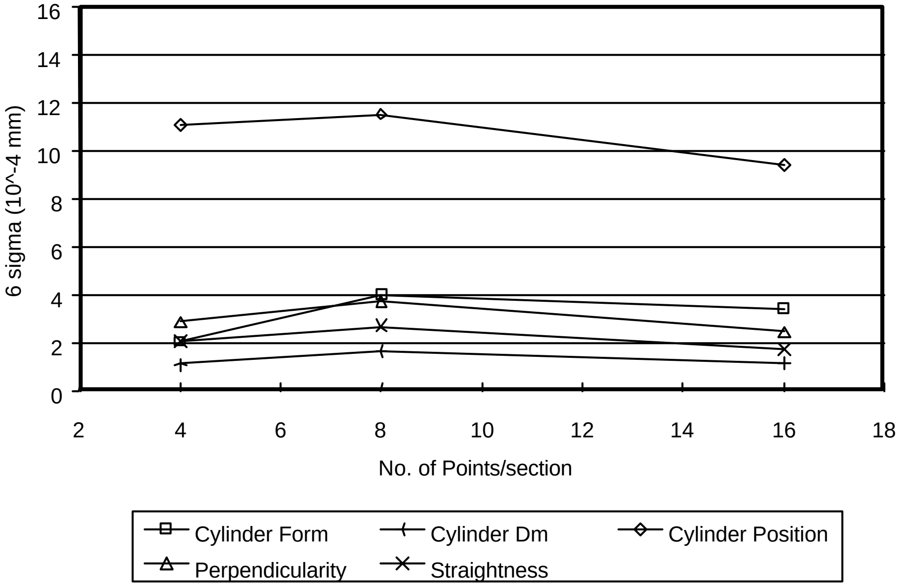


Figure 20-13 Cylinder features versus number points/section

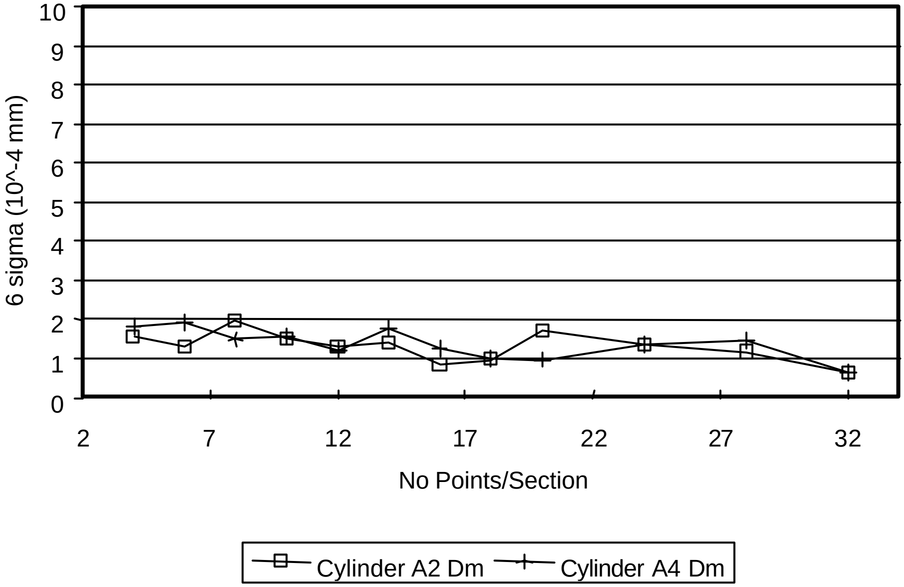


Figure 20-14 Cylinder features versus number of points/section

The results proved to be extremely confusing. Although all the graphs exhibited the trends expected, there was a great deal more variation around the regression straight (at the lower point densities) than anticipated. This created more questions than answers. What secondary effects may be causing this variation? Is this a random fluctuation around the regression straight, or is this a point-dependent pattern? A point-dependent pattern would indicate problems with the algorithms being employed. Because the primary objective of this effort was to achieve the best possible results for a capability matrix, these questions were deferred.

20.3.3.2 Other Geometric Features

Feature Based Test #8: 25-mm cube test (planar features) (see Fig. 20-15)

A 25-mm square quartz cube was measured 25 times on its five open sides using 32 points per surface. Two different probe setups were utilized; a five-point star probe setup and a single probe setup. When using the star probe setup, the Six Sigma repeatability values were better than when the single probe setup was used. This was because each planar surface measured with the star probe was perpendicular to the shaft of the probe. Very little deflection takes place up the shaft of the probe. All planes measured with the single probe (except the top plane) were parallel to the probe shaft, creating much more deflection.

It is interesting to note that on every evaluation (except squareness) using the star probe, the x-axis planes seemed to repeat slightly better than the y-axis planes. This was not the case for the single probe setup, although this does not rule out the possibility that one axis may be more repeatable than the other. With the single probe tip, the deflection of the probe tip could be the dominating parameter overshadowing any effect the axis may have had on the results.

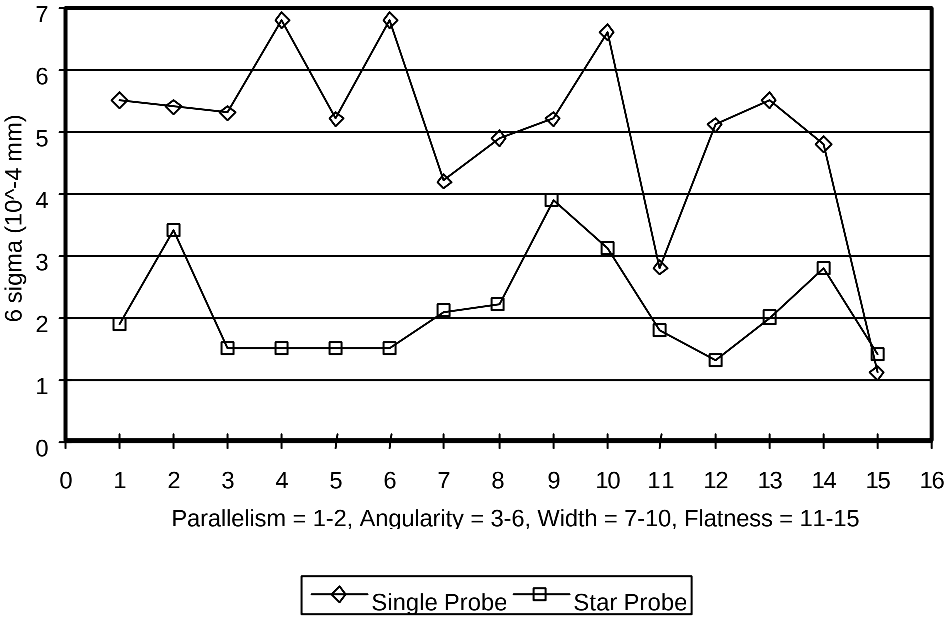


Figure 20-15 25-mm cube test—single versus star probe setup

20.3.3.3 Contact Scanning

Due to its unique probe head, the Leitz PMM can carry out constant contact scanning. This helps the user to obtain a large amount of points on a feature in a very short time. It is also very useful when measuring 2-D and 3-D curves in space. Unfortunately, there is some loss in repeatability when moving from point-to-point measurement to scanning.

Feature Based Test #9: Circle features versus scanning speed (see Fig. 20-16)

To determine how scanning speed affects the repeatability of the measurements, a test was run measuring four diameters using several different scanning speeds. The scanning speed was altered from 2 mm/sec to 0.2 mm/sec. The results showed the repeatability of the measurements do indeed become worse as the scanning speed increases. As expected, this deterioration was most evident in the roundness of a circle, while less on the other parameters. Based on the primary objective being optimum results, which can best be achieved using single-point measurements, no further testing on scanning was done at this time.

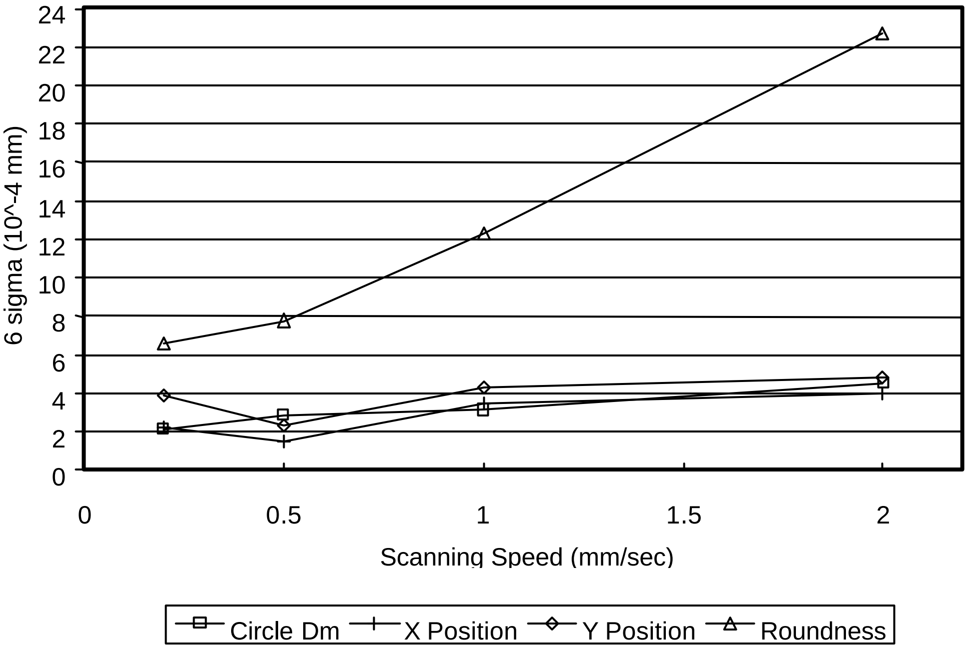


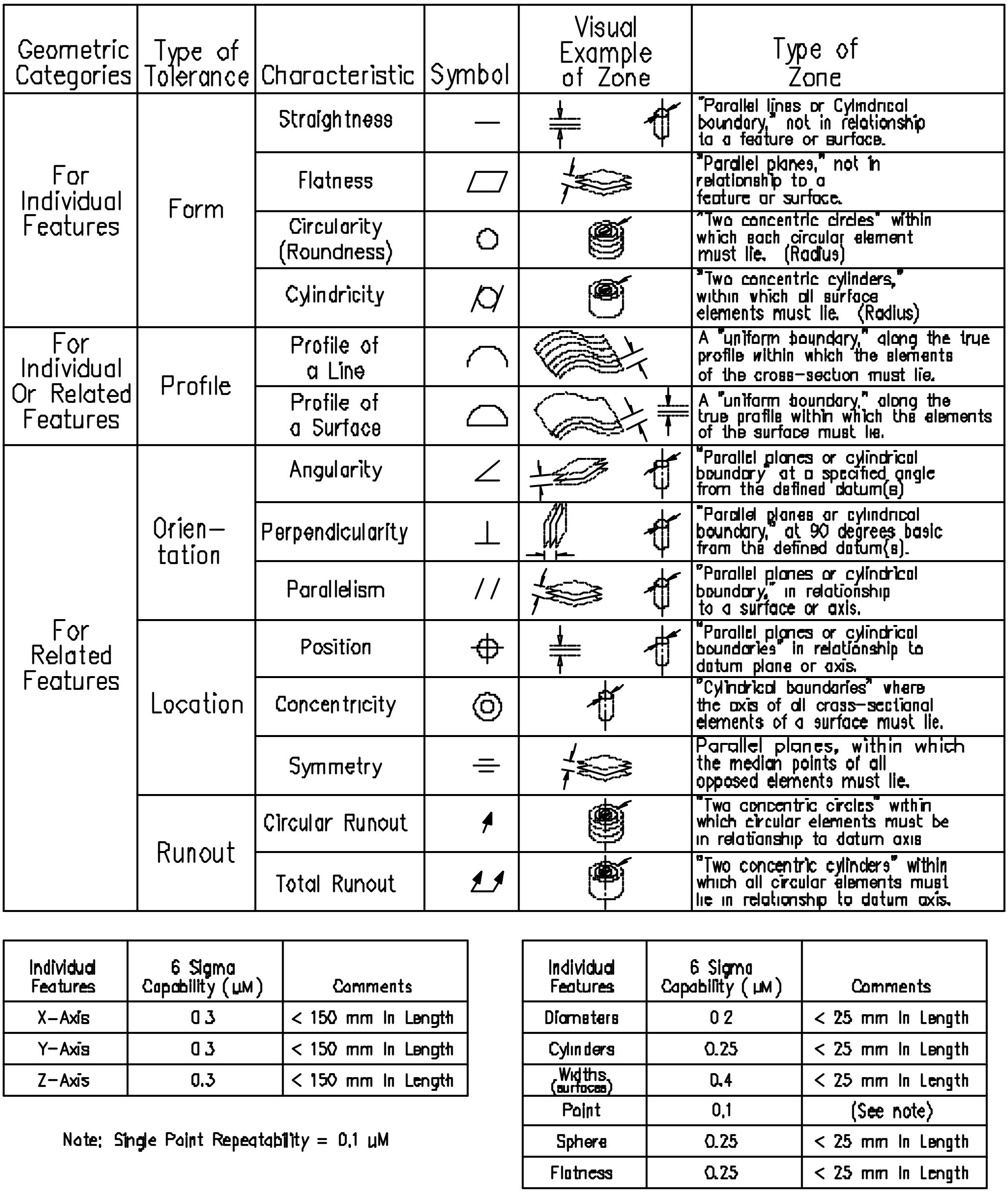
Figure 20-16 Circle features versus scanning speed

20.3.3.4 Surface Roughness

It is generally accepted that the surface roughness of a part/feature will affect the repeatability of a single point being measured. No testing was needed on this issue at this time since the surface roughness on the certified artifacts are within the same range (less than 0.2 μm) as the parts to be checked on an ongoing basis.

20.4 CMM Capability Matrix (see Fig. 20-17)

The following matrix is a summary of the feature-based testing done to date on the Leitz CMM. These tests were performed to determine (at a minimum level) the system's measurement capability for each of the geometric characteristics per ASME Y14.5M-1994. Individual features were tested for accuracy and repeatability and their Six Sigma values calculated.



Geometric Categories	Type of Tolerance	Characteristic	Symbol	Visual Example of Zone	Type of Zone
For Individual Features	Form	Straightness	⏤		"Parallel lines or Cylindrical boundary," not in relationship to a feature or surface.
		Flatness	⏥		"Parallel planes," not in relationship to a feature or surface.
		Circularity (Roundness)	○		"Two concentric circles" within which each circular element must lie. (Radius)
		Cylindricity	⌭		"Two concentric cylinders," within which all surface elements must lie. (Radius)
For Individual Or Related Features	Profile	Profile of a Line	⌒		A "uniform boundary," along the true profile within which the elements of the cross-section must lie.
		Profile of a Surface	⌓		A "uniform boundary," along the true profile within which the elements of the surface must lie.
For Related Features	Orien-tation	Angularity	∠		"Parallel planes or cylindrical boundary" at a specified angle from the defined datum(s)
		Perpendicularity	⊥		"Parallel planes or cylindrical boundary," at 90 degrees basic from the defined datum(s).
		Parallelism	//		"Parallel planes or cylindrical boundary," in relationship to a surface or axis.
	Location	Position	⌖		"Parallel planes or cylindrical boundaries" in relationship to datum plane or axis.
		Concentricity	◎		"Cylindrical boundaries" where the axis of all cross-sectional elements of a surface must lie.
		Symmetry	⌯		Parallel planes, within which the median points of all opposed elements must lie.
	Runout	Circular Runout	↗		"Two concentric circles" within which circular elements must be in relationship to datum axis
		Total Runout	⌰		"Two concentric cylinders" within which all circular elements must lie in relationship to datum axis.

Individual Features	6 Sigma Capability (μM)	Comments
X-Axis	0.3	< 150 mm In Length
Y-Axis	0.3	< 150 mm In Length
Z-Axis	0.3	< 150 mm In Length

Note: Single Point Repeatability = 0.1 μM

Individual Features	6 Sigma Capability (μM)	Comments
Diameters	0.2	< 25 mm In Length
Cylinders	0.25	< 25 mm In Length
Widths (surfaces)	0.4	< 25 mm In Length
Point	0.1	(See note)
Sphere	0.25	< 25 mm In Length
Flatness	0.25	< 25 mm In Length

Figure 20-17 Leitz PPM 654 capability matrix

Zone Modifiers Allowed Y/N	Datum Usage Y/N/Option	Type Of Feature	Dependent Variables				Six Sigma Capability (µм)	Comments:
			Size	Form	X	Y		
No=Surface Yes=Axis	No	Surface		✓			0.3	
		Axis	✓	✓			0.3	
No	No	Surface		✓			0.25	
No	No	Surface (Circle)	✓	✓			0.35	# Of Pts Dependent
No	No	Surface (Cylinder)	✓	✓			0.45	# Of Pts. Dependent
No	Option	Surface		✓	✓	✓	0.7	From Datums
							0.4	2D Best Fit
No	Option	Surface		✓	✓	✓	0.8	From Datums
							0.5	2D Best Fit
No=Surface Yes=Axis	Yes	Surface		✓			0.3	
		Axis	✓	✓			0.3	
No=Surface Yes=Axis	Yes	Surface		✓			0.3	
		Axis	✓	✓			0.3	
No=Surface Yes=Axis	Yes	Surface		✓			0.3	
		Axis	✓	✓			0.3	
Yes *See Rule #2*	Yes	Axis	✓	✓	✓	✓	0.7	
		Plane	✓	✓	✓	✓	0.8	
No	Yes	Axis	✓	✓	✓	✓	0.5	
No	Yes	Plane	✓	✓	✓	✓	0.5	
No	Yes	Surface (Circle)	✓	✓	✓	✓	0.4	
No	Yes	Surface (Cylinder)	✓	✓	✓	✓	0.5	

Comments Regarding "Form"

1) For Cylindrical Features, This Represents Total Size Variation (—, ○, ⌭, ∠, ⊥, //, ⌖, ◎, ↗, ⌰)

2) For Surface This Represents Flatness (▱, ∠, ⊥, //)

3) For Some Features This Represents The Equivilent To The Geometric Result (▱, ⌭)

Figure 20-17 continued Leitz PPM 654 capability matrix

Some of the NIST-traceable artifacts used for determining system accuracy and repeatability, and the types of features checked are listed below.

- 450-mm Moore bar (step gage used to determine linear displacement “X, Y, and Z”).
- 25-mm cube (used for size, point to point, parallelism, flatness, straightness of a surface, perpendicularity of a surface, angularity of a surface, profile of a line, and profile of a surface).
- XXX ring gages (used for size, circularity, cylindricity, concentricity, runout, total runout, straightness of an axis, parallelism of an axis, perpendicularity of an axis, angularity of an axis).
- 10-mm and 25-mm XXX sphere (used for system probe calibration, size, circularity, and sphericity).

Due to the majority of features of interest being less than 25 mm, the above artifacts were highly adequate to determine a solid starting point for short-term system capability needs. It is essential to note that these tests are speculated to represent approximately 75% of the testing needed for the system. Unique features will need to be tested as needed, and when deemed necessary due to tight tolerances, new artifacts will need to be built or purchased (and certified) to ensure optimum reduction of bias in measurement results.

The capability matrix represents all 14 geometric characteristics, as well as individual features used in one way or another, the by-product of which represents the capability of each geometric characteristic. The X, Y, and Z axis locations of diameters, cylinders, widths (surfaces), points, spheres, and planes were all individually evaluated.

Knowing the specific capability of each feature listed, there should be adequate information available to determine the capability of each geometric characteristic, with a high degree of confidence. It is essential to note the matrix results were based on optimum programs using low-probe deflection values (<0.4 mm).

In addition, the following is a summary list of variables that need to be considered when programming and analyzing parts. These variables have the potential of decreasing the Six Sigma capability of the results shown on the matrix (either in accuracy, repeatability, or both).

- Utilization of multiple probes from the probe changer or star probes
- Probes with greater than 0.4-mm probe deflection. Note: A probe deflection matrix has been developed with studies done showing Six Sigma repeatability. (This data should be very beneficial in predicting the effects of a specific feature or geometric characteristic to overall capability.)
- Short-term temperature fluctuations
- Contamination
- Loose probe tip (should be able to detect by evaluating form and deflection values)
- Surface finish
- Number of probing points

The list of variables that need to be considered is lengthy. Up to this point, tests and calculations have been fairly straightforward. Chapter 25 addresses some of the capability calculations currently used to determine gage repeatability and reproducibility (GR&R). Some of the variables have not been taken “fully” into consideration and will spur tremendous development efforts for many years to come.

20.5 References

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