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# Inertial Sensor Components Achieving Higher Mechanical Precision with

# Profile Tolerancing

by

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Today's design, manufacturing and quality engineers are faced with the seemingly impossible task of clearly communicating the increasing complexity of surface geometries. The challenge is heightened by the simultaneous reduction in feature tolerances needed to meet reduced size, weight, cost, and time to market targets. These trends are driving the need for unprecedented precision in all technical disciplines. Precision GD&T featuring the use of profile tolerancing is emerging as the key solution for dimensioning and tolerancing practices for mechanical and electro-mechanical components and assemblies.

Figure 1 is a solid model of a gyroscope housing that represents typical complex surface geometries. The features on this part represent a collection of small arc radii and are used within this article to demonstrate the historical and ongoing weaknesses of linear (plus/minus) tolerancing and the tremendous value and precision of profile tolerancing.

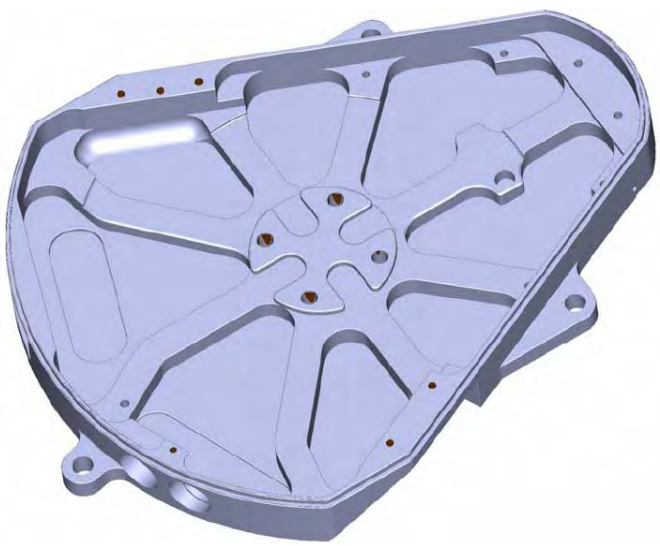

**Figure 1 – Solid Model of Gyroscope Housing**

This article will make visible common mechanical specification requirements that do not optimally represent the designer's true intent. It will also cover associated measurement errors and biases which lead to incorrect decisions, as well as solutions for optimizing specification requirements and associated measurement results, providing precise analysis to optimized design specifications. Finally it will close with recommendations to aid companies in their design, manufacturing and measurement optimization initiatives

**International Design Standards**

Mechanical components and assemblies throughout the world are defined with engineering standards, such as ASME Y14.5M-1994: Dimensioning and Tolerancing and ASME Y14.5.1M-1994: Mathematical Definition of Dimensioning and Tolerancing Principles. The ASME Y14.5M-1994 Standard is a core foundational standard however there are two principle methods of tolerancing specified within this standard: linear and geometric tolerancing.

**Risk to Industry**

Linear tolerancing results in product specifications which frequently fail to analyze the size and location of features. On the one hand, inspection results can look good and the product still fails, or on the other, the results look bad and the product can still work. In either situation the features specified with linear tolerancing do not address true design functionality of the component.

Physical geometry of any 3D part is controlled by four primary elements: size, form, orientation, and location. For example, size controls how large and how small individual features can be; form controls how cylindrical or flat a feature can be; orientation controls how perpendicular or parallel features can be to each other; and location controls the distance from the specified datum reference frame and between each of the features. Without getting down to controlling elements such as surface finish parameters, material properties and other considerations, these are the only four elements a designer is attempting to control per the ASME Y14.5M-1994 Standard. For information on surface finish requirements, see ASME B46.1-2010: Surface Texture (Surface Roughness, Waviness and Lay).

**Product Development Cycle**

The following steps are outlined as a potential sequence of events that take place in a manufacturing environment throughout a product's development cycle:

1. Define engineering intent on mechanical drawings/specifications or other digital media.
2. Manufacture components to engineering specifications.
3. Measure components to determine compliance to specifications, provide feedback to manufacturing engineering for process optimization and provide feedback to design engineering for tolerancing optimization.
4. Optimize design specification based on measurement and process feedback.
5. Optimize manufacturing processes.
6. Optimize measurement programs and measure optimized components.
7. Ship components and assemblies.

Steps 1, 3, 4 and 6 will be used to highlight the downside of linear tolerancing using Figures 2-5. Then Figures 6-9 will show the upside of using the optimized methods resulting from the more robust tolerancing methods of profile of a surface. Figures 10-12 will represent expanded implications for linear analysis of the small arc radii intended to solidify negative methods of definition and analysis. A 2D drawing example will be used initially to show a simplified case study and then the gyroscope housing component shown in Figure 1 will be used to fully describe the robust 3D application and solution using Figures 13-17.

Figure 2 is a simple 2D drawing example with engineering specifications commonly used by designers, showing multiple small arc radii defined as diameters. The size and form of the features are controlled using linear tolerancing while the orientation and location are controlled using position tolerancing. To minimize clutter on the drawings, consider all position callouts having associated BASIC dimensions defined in the CAD model and constrained to a standard A, B, C datum reference frame.

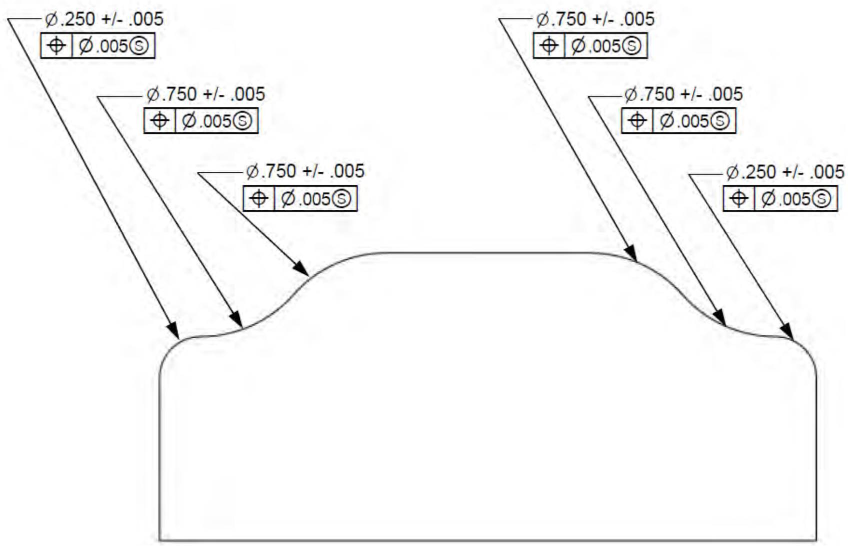


**Figure 2: Design Requirements Specified Using Linear & Position Tolerancing**

Figure 3 represents a set of measured points which are derived from a coordinate measuring machine (CMM) and commonly referred to as a measured point cloud or point array. Each of these measured points has an associated X, Y (2D) or X, Y and Z (3D) value which are then used in the calculations to determine the actual values. Each of these points reflects deviations from the perfect geometry due to inherent manufacturing and measurement variation. In this example the worst case deviation is .0034.

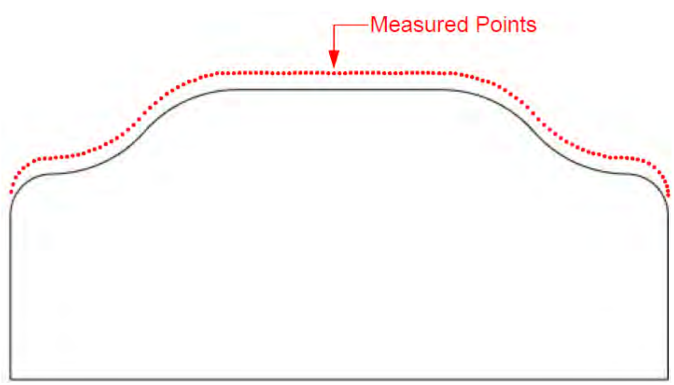


**Figure 3: Measured Point Cloud**

Figure 4 represents analyzed results based on the set of measured points from Figure 3**.** Results are derived from analytical software supplied with the CMM.

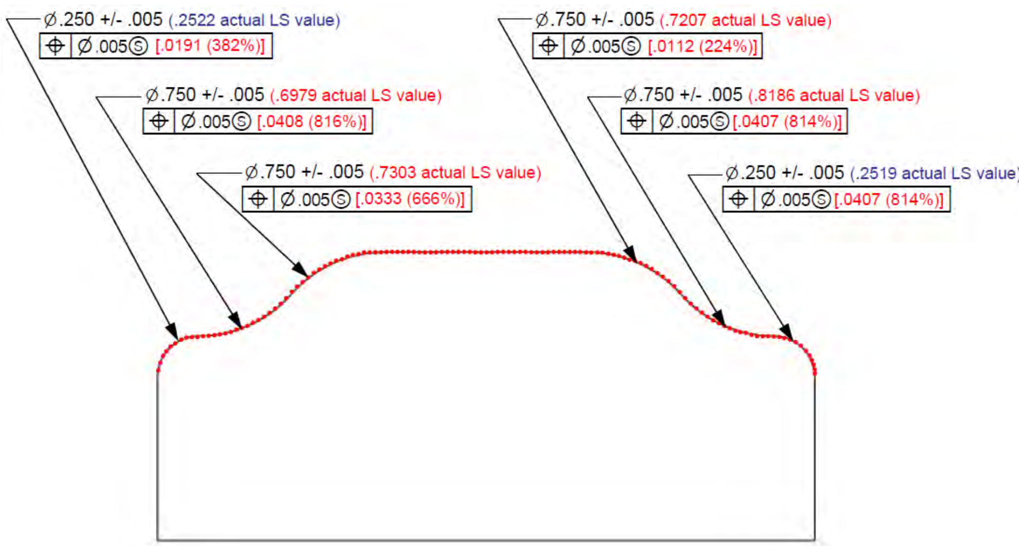


**Figure 4: Analyzed Results**

Figure 5 represents a summary matrix of the results shown in Figure 4 and includes additional information such as:

- Deviation ($\Delta$) in nominal size ranging from .0019 to .0686, out of tolerance value and % out of tolerance. The results are disturbing given total size tolerance is .010 (+/- .005).
- Deviation ($\Delta X$ & $\Delta Y$) from the theoretically perfect location (BASIC dimensions) are used to calculate the total positional tolerance used, ranging from .0014 to .0192. Again these results are disturbing given the total diametral position tolerance allowed is .005.
- Amount of position tolerance used is calculated as $2\sqrt{\Delta X^2 + \Delta Y^2}$

| Size & Position of Small Arc Radii | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Results for Size | | | | | Results for Position | | | | |
| Size | Result | Δ Nominal | out of Tol | % out of Tol | Position | ΔX | ΔY | ⌖ Result | % out of Tol |
| Ø.250 +/- .005 | .2522 | .0022 | 0 | 0% | ⌖ Ø.005 | -.0081 | .0051 | .0191 | 382% |
| Ø.750 +/- .005 | .6979 | .0521 | .0471 | 942% | ⌖ Ø.005 | .0081 | -.0187 | .0408 | 816% |
| Ø.750 +/- .005 | .7303 | .0197 | .0147 | 294% | ⌖ Ø.005 | -.0150 | .0072 | .0333 | 666% |
| Ø.750 +/- .005 | .7207 | .0293 | .0243 | 486% | ⌖ Ø.005 | -.0014 | .0054 | .0112 | 224% |
| Ø.750 +/- .005 | .8186 | .0686 | .0636 | 1272% | ⌖ Ø.005 | .0068 | .0192 | .0407 | 814% |
| Ø.250 +/- .005 | .2519 | .0019 | 0 | 0% | ⌖ Ø.005 | -.0085 | -.0185 | .0407 | 814% |

**Figure 5: Summary Matrix Based on Analysis of Size and Position of Linear Radii**

## Implications to Industry

The results from Figures 4 and 5 represent where the majority of the problems start in all technical areas of design, manufacturing and metrology. Technical disciplines attempt to rely on measured results to make decisions. Statisticians even utilize this same data to make predictions and recommendations to manufacturing and design in hopes of optimizing manufacturing processes and design specifications. All disciplines assume measured data is actually correct, which is one of the biggest mistakes that can be made if the true uncertainty is unknown.

Most assume that as long as the measurement results are repeatable and reproducible within some percentage of tolerance, then the results are valid. By itself this is a major mistake and results in high risk. Repeatable and reproducible results may not take into consideration large biases induced by many factors including the percentage of arc, the number of points measured on the features of interest (point density) or what fitting algorithm was used to derive the measured result (e.g. least-squares (LS), minimum zone, min/max, etc.).

There are a multitude of problems that immediately jump out from Figures 4 & 5. For example, the size and position of most of these features indicate they do not conform to engineering specifications. Derived values indicate results for size are out of their allowable tolerance (+/- .005) in excess of 1,000%, and results for position are out of their allowable tolerance (.005) in excess of 800%. Often times this leads manufacturing into a rework loop that causes delays in lead time, has negative cost implications, indicates lack of manufacturing capability, or worse. Also note that all the results were derived from least-squares (best fit/averaging) fitting algorithms, which can be seen in Figure 4 in the results portion next to size as it indicates “LS.” In addition it is essential to note the worst case deviation in any of the points from their nominal geometry was .0034 which will be shown later in this article.

## Risk within Disciplines

The ability for designers to effectively communicate their true design intent is critical. Here are a few strategic questions we need to ask based on the previous linear example:

1. Are designers precisely defining their true design intent on engineering drawings?
2. How can designers defend their tolerance analysis, or any other analysis, if their specification requirements are deriving undesirable or un-defendable tolerance boundaries?
3. How can metrologists confidently state compliance to requirements if the fitting algorithms they are using are not correct or not optimum for the task specific measurement?
4. How can manufacturing optimize their manufacturing processes if the specification is ambiguous and measured results cannot be trusted?
5. How can designers optimize their tolerance analysis if the measurement data and the resulting process capability data cannot be trusted?
6. How can statistical data be of value when we lack confidence in the measured results?

**Robust Solution using Profile Tolerancing as Precision GD&T Solution**
Given the problems identified above, it is essential to provide solutions that designers can confidently embrace to achieve their future product goals while at the same time reducing product liability risks. Figures 6-9 represent optimized solutions from Figures 2-5 and are intended as positive examples designers can leverage to optimize their designs.

Figure 6 represents the optimized design specification using profile of a surface per the ASME Y14.5M-1994 Standard. This is optimized in comparison with the same features defined in Figure 2.

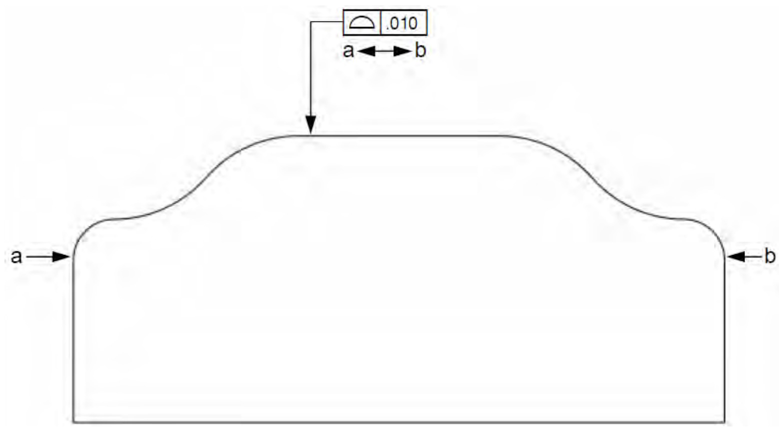


**Figure 6: Optimized Design Specification**

Figure 7 represents the derived uniform boundary from the specification defined in Figure 6.

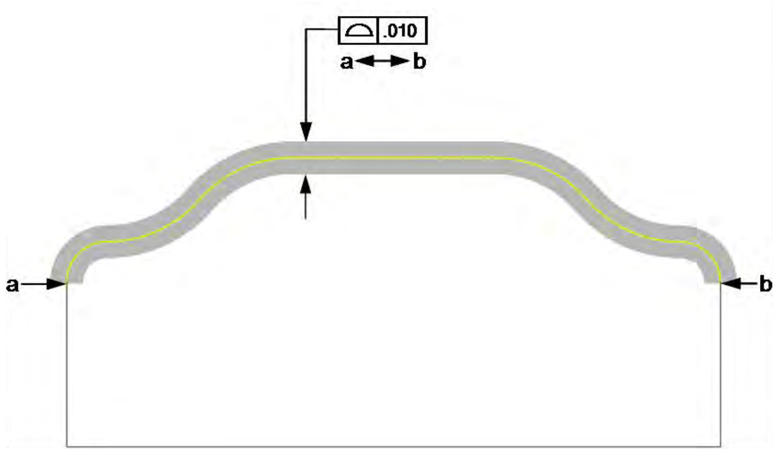


**Figure 7: Derived Uniform Boundary from Profile Tolerancing**

The uniform boundary defined in Figure 6 and shown in Figure 7 is a boundary that goes between point "a" and "b." This boundary is exaggerated in scale so it can be comfortably visualized. The derived boundary is a uniform boundary, .010 wide, and is derived perpendicular to the nominal geometry in the area specified. This boundary is displaced with a tolerance of .005 in the plus material direction ($t_+$) and .005 in the minus material direction ($t_-$). Out of convenience, this tolerance was derived simply from the size and position tolerances originally specified in Figure 2. Depending on the designer's true intent, this tolerance would need to be increased or decreased as appropriate.

The critical value of the uniform boundary derived from profile is that it actually represents the true desired boundary by all mechanical design engineers on greater than 90% of the component features. If we ask a designer what their true desired boundary is on the majority of the features, they will explicitly state that “all surface geometries must simultaneously fit within their respective uniform tolerance zones.” The only way to accomplish this would be using a profile control.

Figure 8 represents the analyzed profile using the exact same measured points shown in Figure 3. The expanded view in the upper left corner is showing individual point displacements as whiskers in the minus and plus directions from the nominal geometry. Measured results indicate the maximum deviation ($d_-$ and $d_+$) in points is .0034 from the nominal surface geometry. We can immediately see the magnitude of difference in the results from Figure 4, which indicated the actual size of the radii departed by up to .0686, which is a difference in excess of 2000%. The magnitude of impact is huge and shows how valuable profile can be to all technical disciplines.

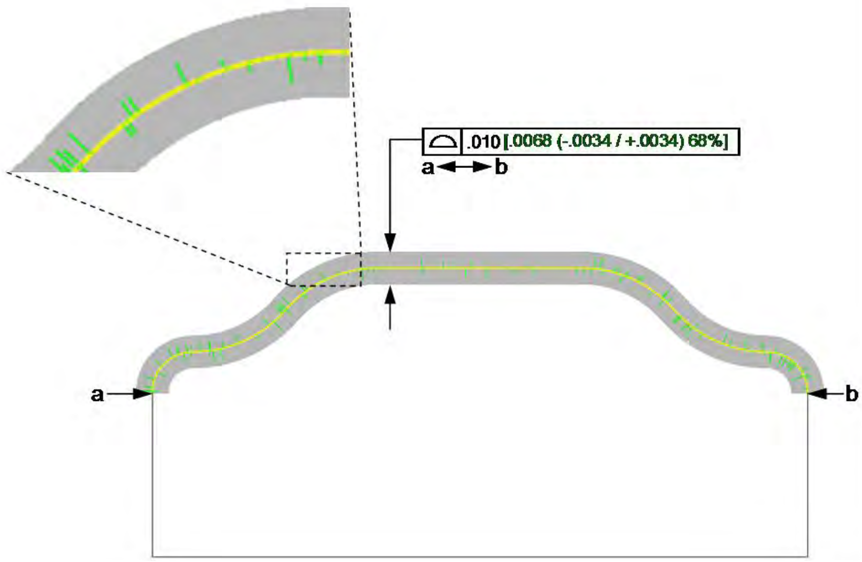


**Figure 8: Analyzed Results**

Figure 9 represents a summary matrix of the results shown from Figure 8.

| Profile | | | | |
|---|---|---|---|---|
| Specification | ⌓ Result | d- | d+ | % of Tol. Used |
| ⌓ .010 | .0068 | .0034 | .0034 | 68.00% |

**Figure 9: Summary Matrix**

The result of all the above analysis is that even with limited variability of the point array, the measurements completed on the linear example would have forced multiple repeated measurements by the metrologist, which would have resulted in repeatable and reproducible results clearly not representing true process variability. Manufacturing would have attempted to make changes to their process which could have made bad parts look good. Profile tolerancing is clearly the robust solution that not only better represents the designer’s true intent, but also greatly reduces measurement and manufacturing bias.

**Broader Evaluation of Small Arc Segments**
The ability of designers to effectively calculate potential scenarios prior to parts being manufactured and inspected can tremendously reduce mathematically predictable problem areas and significantly reduce time to market and cost. Designers are challenged daily with determining how much tolerance is available between interacting features and furthermore the distribution of that tolerance between those features.

Many designers utilize tolerance analysis software to predict the amount of variation that can be expected based on input variables. For the most part these come from speculative estimates on their part or from manufacturing engineers who may have an optimistic view of the statistical process capability. While this type of software is tremendously valuable, it can only be as good as the input variables and also only as good as the software will allow the true component features to vary within their allowable tolerance range. Most tolerance analysis software packages are not robust enough to successfully accomplish the desired tasks put forth by the designers.

One software package which is truly capable of not only including component variability but also has the unique ability to include specific CMM performance information is called PUNDIT ™. Developed by MetroSage, PUNDIT is a simulation and analysis software package capable of doing sensitivity analysis listing each uncertainty source, its magnitude, effect on the result, correlation with other uncertainty sources, and combining all the input variables appropriately. The end deliverable is full "uncertainty budgeting." The following two figures show the fundamental capability of the PUNDIT software and to illustrate how significant the results can change as a function of only a few key variables.

Figure 10 is a graphical model of multiple small arc radii with input variables based on the following criteria:

1. Nominal Arc Radii: 50, 90, 130, 170, 210, 250 mm
2. Arc Segments: 15$^o$, 30$^o$, 45$^o$, 60$^o$, 90$^o$, 120$^o$
3. Sampling Points over Arc: 15, 30, 60, 80, 100, 120
4. Random Form Error with $\sigma$ = 0.65 μm (26 μin)

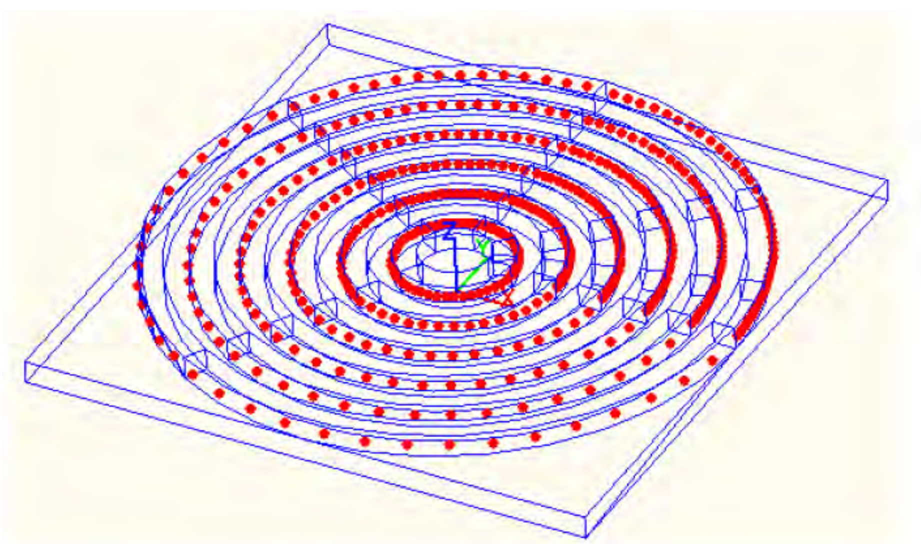

**Figure 10: Graphical Model of Multiple Small Arc Radii**

Figure 11 is a 3D plot derived from Monte Carlo simulations and the inputs defined in Figure 10.

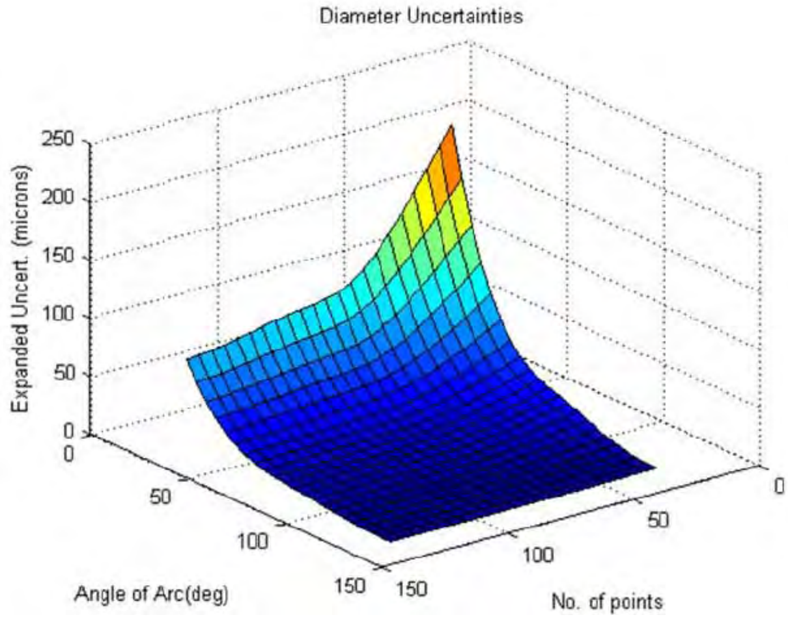


**Figure 11: 3D Plot Derived from Monte Carlo Simulations within PUNDIT**

The 3D plot shows results that reflect significant deviations based on percentage of arc of less than 50 degrees and number of sampling points of less than 50 over the respective arc. Size uncertainties are for the most part insensitive due to nominal arc radii. Naturally, the magnitude of error is dependent on each of the input variables and will only get worse when the form error increases. Form error can come from the physical features on the part but can also be influenced by the CMM probing, which can vary dramatically based on the probing configuration and other influencing factors. Features on parts will always have some level of form error as all surfaces will have varying degrees of roughness and waviness. The ability to distinguish the difference between the errors will be the core elements that the manufacturing and quality engineers need in order to optimize their processes.

Figure 12 is an exaggerated 2D example of the measurement of a full cylindrical feature of size showing results based on multiple methods of analysis (maximum inscribed, minimum circumscribed and least-squares), which would derive completely different results. It can be seen that if only part of the cylindrical feature were measured (small arc), then the results could have a tremendous range not only in size, but also the location.

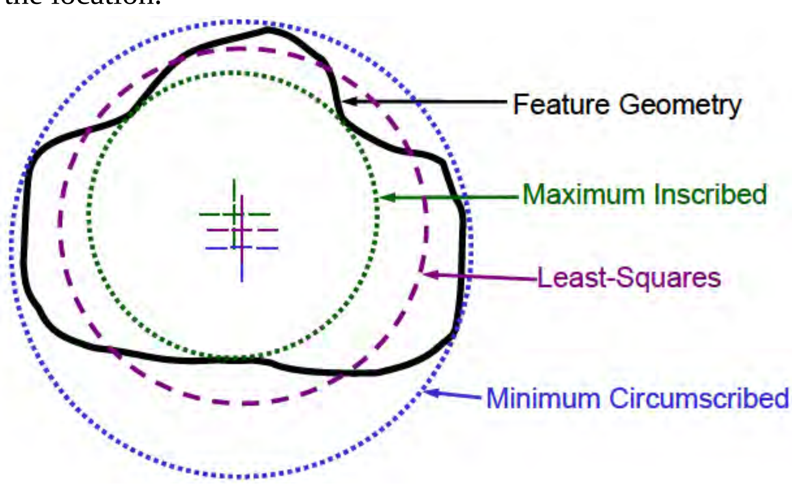


**Figure 12**: **Multiple Methods of Analysis of a Cylindrical Feature of Size (Cross-Section)**

**Compliance Issues**

The majority of CMM software defaults to least-squares fitting to determine the features size as well as the location of its axis. Unless otherwise specified by the designer, using least-squares analysis to derive all three measurements will conclude with the incorrect results per the ASME Y14.5M-1994 Standard. These results can be repeatably and reproducibly incorrect. The correct results would require analysis of the maximum inscribed cylinder or the minimum circumscribed cylinder depending on the feature being an internal or external feature and the considered feature modifier applied by the designer. While the majority of analytical software has the ability to apply maximum inscribed and minimum circumscribed algorithms, in most cases the metrologists are not incorporating these fundamental algorithms and are not even aware of the broader limitations of the analytical software.

Senior metrologists have known for years about the problems associated with measuring small arc radii and have attempted in many cases to influence designers to change their engineering specifications accordingly with minimal success. They also know that to derive a variable result on a small arc radii using a CMM, they would have to use a least-squares fitting algorithm to get such a result. It also must be understood that if the measured result for size is based on least-squares then it must also be understood that the analysis of position is also based on this same fitting algorithm. This simply compounds the problem.

**Self Assessment Test**

Anyone can do a simple test using their particular CMM to determine how large the respective errors are for a particular percentage of arc on a cylindrical feature. Here is one procedure to consider:

1. Depending on whether the feature is an internal or external diameter, start out with a precision artifact (ring gage or plug gage) of a particular grade level. Which grade-level artifact used should be dependent upon the tolerance of interest. How much variation in size and form the artifact will have is dependent on the grade level of the artifact being used. For additional information on grade levels of ring and plug gages, see ASME B89.1.5-1998: Plug Gages or ASME B89.1.6M-1984: Ring Gages.
2. Measure the full 360 degrees of the gage with the number of points you would normally use to measure the part feature. Do not use more points just because you are measuring an artifact as it is critical you are consistent with the point density.
3. Analyze the measured points to determine the size of the artifact to ensure reasonable calibration. Given you already know the traceable size of the artifact the results should be within reason of the capability of the CMM. Once comfortable with acquiring the size of the artifact then set X/Y zero at the center of the artifact.
4. Analyze the already-measured points in step 2, but only use the points for the percentage of arc in which you are interested to now determine the size and location of the radii. The percentage of arc and the number of points taken will determine the deviation for size and location. Note that there is no additional measurement error in these results as the points came from the original point array from measuring the artifact. For angles less than 90 degrees of the arc you will see larger variations based on the smaller percentage of arc.
5. Once you've proven to yourself that size of the small arc radii and position of the axis of the center of the radii will vary significantly, then create a more realistic example which would represent the true variation in form you would expect to see from your manufacturing process. Then redo steps 2, 3 and 4 to see how large the true errors will be, as they can be drastic. In addition, see how you can influence the results based upon how many points you take on the feature. The fewer points you take, the worse the results will look.

**Criteria for Precision Measurement**

Precision measurement requires high confidence that the measured results reflect differences between parts and not differences due to errors of measurement. To accomplish this, the metrologist must ensure the following:

1. Precise definition of the specification requirements per ASME Y14.5M-1994 Standard.
2. Qualified metrologists to perform the required tasks at a sufficient level.
3. Precise measurement instrument capable of measuring the feature and placed in an environment conducive to the level of precision measurement required.
4. Sound measurement procedure to ensure true characterization of the features.
5. Robust measurement software capable of completing the analysis per the defined standards such as ASME Y14.5M-1994 and ASME Y14.5.1M-1994 or other applicable standards. Software such as SmartProfile™, developed by Kotem Technologies, defaults to the ASME Y14.5.1 Standard. This software has been extensively tested with mathematically defined datasets for profile and position tolerancing with and without datums and fully invoking the rule of simultaneity. A word of caution: the majority of coordinate measuring machines (CMM) software used in all industries currently default to using least-squares fitting algorithms, which simply means they are averaging the measured results.
6. Proper analytical methods for evaluating the uncertainty of the measured results. ASME B89.7.3.2-2007 Technical Report provides Guidelines for the Evaluation of Dimensional Measurement Uncertainty and is a simplified guide for metrologists to evaluate all the contributing factors that influence the measured result.

The above should be considered a beginning list of requirements the metrologist should consider when developing an inspection plan. For insight to inspection planning users can reference ASME B89.7.2-1999: Dimensional Inspection Planning, which provides guidance for ensuring compliance with requirements.

**Global Tolerancing Transformation**

Designers' expectations dictate that all variations on the surfaces of their component parts lie simultaneously within a uniform boundary. While the allowable variation of these boundaries, also known as tolerance zones, might vary from one surface or set of surfaces to another, they are all still expected to meet those requirements. The application of profile tolerancing precisely conveys true design intent and provides a robust solution that significantly improves precision measurement in manufacturing and metrology, and also significantly reduces costs and lead times. Figures 13 thru 17 show an optimized sequence of deliverables and activities to ultimately achieve desired goals in precise design definition and analysis and precision measurement.

The precision language of profile tolerancing is explicitly defined in the ASME Y14.5M-1994 Standard and mathematically complemented by the ASME Y14.5.1M-1994 Standard. Both of these Standards form the basis for precise definition of complex surface boundaries and should be the basis for 3D tolerance analysis for designers and also for 3D precision measurement analysis for physical metrologists.

Profile tolerancing has the ability to control all aspects of the physical surface geometry including size, form, orientation and location of any and all surfaces. Profile tolerancing also has the ability to control each of these parameters independently when required to constrain or relax the feature or set of features as necessary, to optimally represent the functional intent.

Designers must specify all requirements through a precise engineering language and communicate these requirements through a mechanical drawing or electronically through the 3D CAD model and a minimally dimensioned drawing per ASME Y14.41-2003, Digital Product Definition Data Practices. Figure 13 shows an engineering drawing example that depicts profile tolerancing of all 3D surfaces being fully defined with four explicit profile callouts per the ASME Y14.41-2003 Standard.

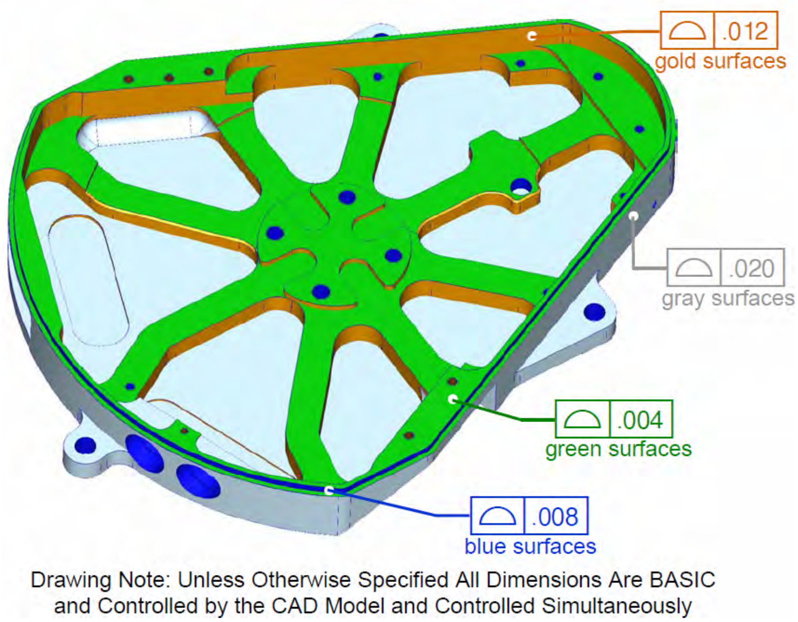


**Figure 13 – 3D Engineering Drawing Example per ASME Y14.41-2003**

Once specification requirements are documented effectively by the designer, it is expected that manufacturing and quality engineers will be able to interpret these engineering requirements precisely to manufacture and inspect the component parts to ensure compliance with all requirements. Ideally, this communication is accomplished using the same optimized CAD model so additional errors are not propagated throughout manufacturing and quality. An optimized tolerance model results in smooth transitions between individual adjacent features.

As design and manufacturing require highly confident measurement data to make technical and business decisions, it is essential we focus some attention on precision measurement and what it takes to provide precise results. Precision lost on the product specification and measurement side will have to be compensated by using more accurate machine tools to reduce variation. This will be more expensive than educating engineers about the principles of GD&T and measurement uncertainty.

**Precision Measurement Technology**

Historically, metrologists have found measurement of profile tolerancing too complex due to CMM software limitations. Today, profile tolerancing is considered one of the simplest ways to analyze complex surface geometries, as long as the users have the applicable software. The software used to complete this analysis (Figures 14-17) is SmartProfile™ by Kotem Technologies.

Measurement technology has advanced significantly over time. In today's environment, CMMs are commonly used to measure parts and have the ability to generate a 3D high-density point cloud. Single sensor and multi-sensor CMMs use sensors such as tactile, vision, laser, white light, and other technologies to optimally capture the measured point arrays and characterize physical variations induced by the broad spectrum of manufacturing processes such as machining, stamping, castings or injecting molding.

Figure 14 represents a set of 3,130 measured points, each having an associated X, Y and Z value, which are then used in the calculations for profile. One of the most common uncertainty contributors can be influenced by how many points are measured by the metrologist, so the higher the point density the better the confidence will be in the measured results. The CMM can simply be considered the "point collector."

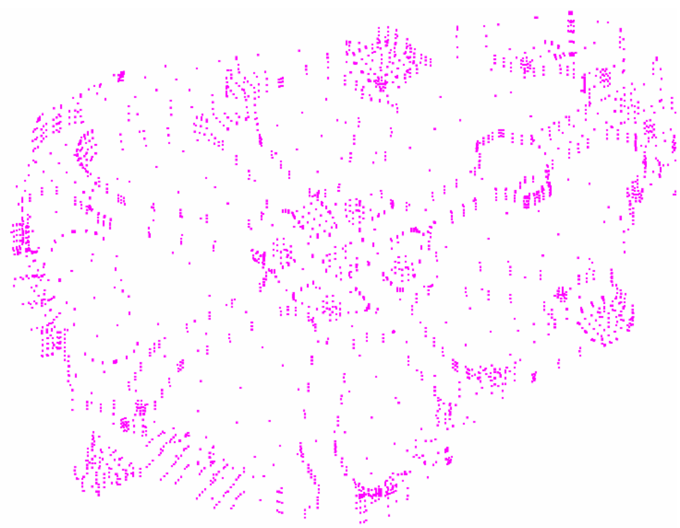

**Figure 14 – Measured Point Array**

Figure 15 represents the measured point array integrated into the CAD model which is then used to analyze the results.

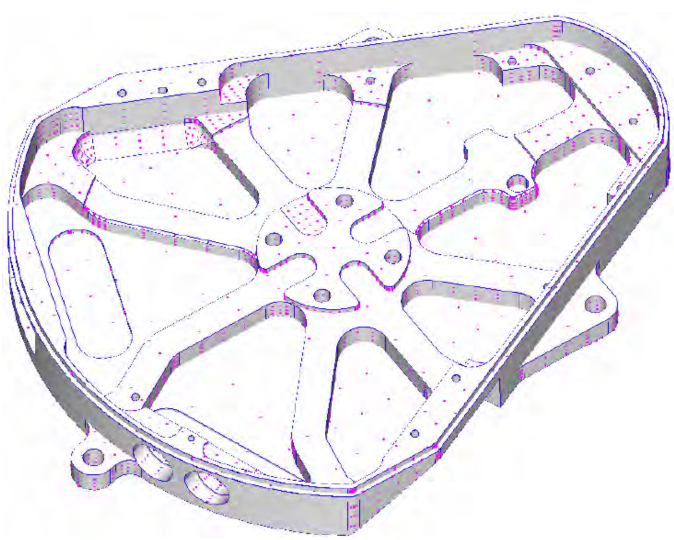

**Figure 15 – Combined CAD Model and Measured Point Array**

Figure 16 shows the graphical output of profile tolerancing. The color-coded surface profiles are shown as a topographical map and quickly communicate compliance or non-compliance to the specified tolerance. The software integrates a color bar graph showing percentage of tolerance used as associated with each of the individual tolerances, so users can quickly analyze the true magnitude of variation on each of the surfaces in the plus and minus material directions.

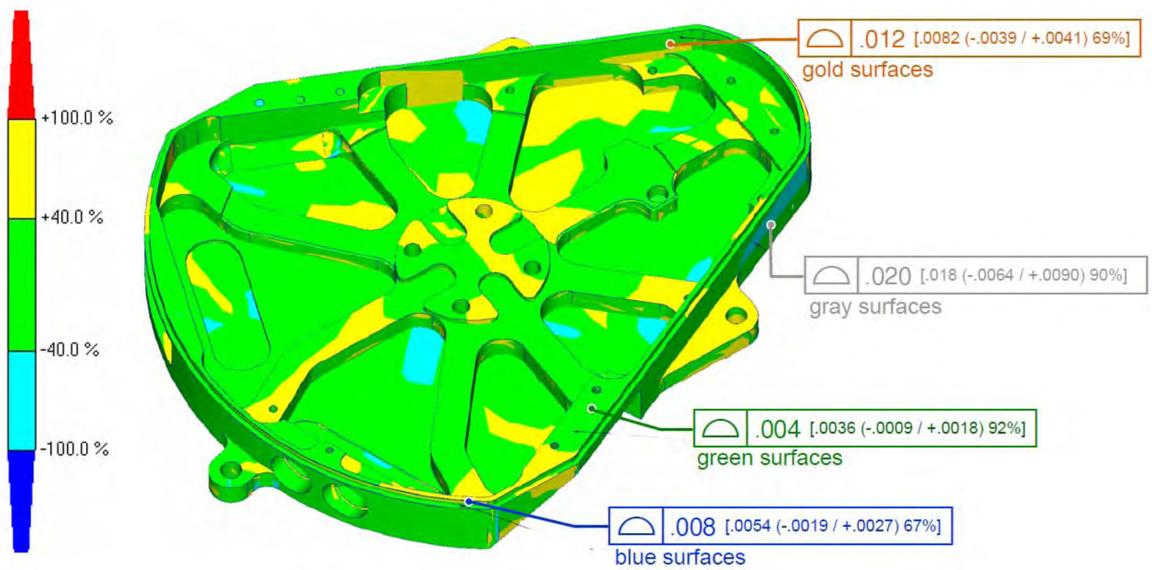


**Figure 16 - Profile Tolerancing Showing Deviations as Percentage of Applicable Tolerance**

Out of tolerance conditions can be seen in the expanded feature control frames via the additional information shown in brackets. The first value in brackets is the value that is compared directly to the specification requirement, which is the first indication of compliance or non-compliance to the specification requirement. If the value is less than the specification requirement then it is in compliance. The second and third values in the brackets (shown in parentheses) indicate the worst-case deviation in the minus and plus material directions. The fourth value in the brackets indicates the percentage of the specification tolerance used, which is valuable to manufacturing and quality as it is a quick indicator of how good the process is operating.

The graphical information shown in Figure 16 allows manufacturing and engineering functions to immediately see root-cause effects resulting from the manufacturing process, and provides indications on how to optimize the process to achieve better results. If the manufacturing engineers cannot see the variation, then process optimization is much more difficult.

Figure 17 shows the graphical output of profile tolerancing as absolute deviations based on the worst-case range of results. The color-coded topographical map quickly communicates to the user the true magnitude of variation on each of the surfaces throughout the entire range of results.

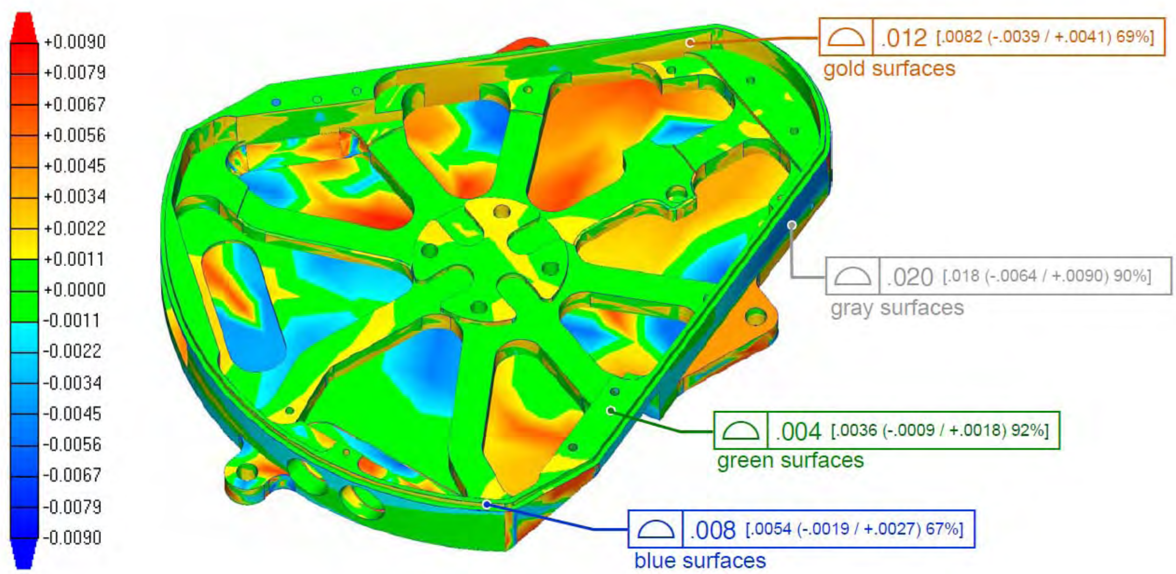


**Figure 17 - Profile Tolerancing Showing Actual Deviations**

Profile analysis software, such as SmartProfile, makes complex profile analysis much simpler than ever before. The procedure required to achieve these results is as follows:

1. Import a translated CAD file such as STEP, IGES, DXF and others as shown in Figure 1.
2. Select the CAD features and apply the GD&T as displayed on the engineering drawing as shown in Figure 13.
3. Import the measured points from any CMM, as shown in Figure 14.
4. Click on the quick align icon to roughly align the measured points to the CAD geometry which results in Figure 15.
5. Click the evaluate icon to complete the analysis, which results in what is shown in Figures 16 & 17.
   - The SmartProfile software performs an optimization fit (not least-squares fit) analysis of the measured points to the CAD model by translating and rotating the measured points until the optimum fit is achieved.

Profile analysis software can also solve software validation efforts on every metrology software package, as many companies are not capable of analyzing results to the ASME Y14.5.1 Math Standard. Software validation can be reduced to one core software that can be used no matter which type of CMM users have. Supplier engineers, development engineers and others can simply request the measured point array from the metrologist and analyze the results in minutes rather than rely on confusing inspection reports. It also assures evaluation uniformity within the whole manufacturing process no matter how and on what measuring device the raw data was collected.

## Corporate Transformation

Within the last decade the problems associated with linear tolerancing are becoming more visible within design engineering groups. Individual company champions are driving global education of precision GD&T to optimize their tolerancing. They are advocates for all the applicable technical disciplines on how to better optimize their designs through advanced engineering tools, such as profile and advanced analytical software robust enough to use optimization algorithms beyond the standard least-squares fitting algorithms. Software such as SmartProfile™ by Kotem Technologies (the software used to do the profile analysis within this article) and PUNDIT™ by MetroSage (the software used to complete the Monte Carlo simulations and predict the uncertainties of various scenarios), are key analytical tools of the future, that will aid designers and metrologists to achieve their optimal goals.

Figure 18 shows geometric dimensioning and tolerancing (GD&T) per the ASME Y14.5M-1994 Standard as the core foundational element that provides a precision engineering language to be used across all technical disciplines and enables precision products to meet required needs.

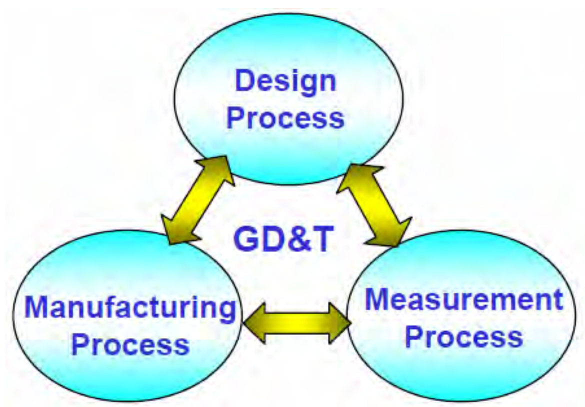


**Figure 18 – GD&T as the Core Foundational Language**

Profile tolerancing, which is one of the GD&T requirements, was developed decades ago as the primary solution for controlling complex surface geometries. This precision language has been utilized within a variety of industries for decades. Within the last decade profile tolerancing is becoming more visible as it is the robust solution for not only complex surface geometries but also for simple geometries. However, its challenge is to be fully embraced by the majority of designers.

These critical challenges are propagated by many things, one of which is that the majority of graduates from universities around the world are not adequately trained in mechanical drawing interpretation per the ASME Y14.5M-1994/ASME Y14.5.1M-1994 Standards. For the most part, there is no foundation in the core curriculum that provides a basis for mechanical and manufacturing engineering students to acquire fundamental and advanced knowledge in these concepts.

As a result, companies must make a tremendous investment to educate their employees on fundamental interpretation of dimensioning and tolerancing practices, and also advanced concepts at multiple levels, to ensure optimum application and analysis of these critical principles. Given the majority of engineering disciplines are not adequately trained in these concepts at the university level, this is a significant investment of time and money to industry at all levels.

University programs need to understand the negative implications to industry of not having core curriculum to meet this critical need. Device manufacturers and suppliers that produce mechanical and electro-mechanical components and assemblies need to communicate this glaring need to universities so that students graduate with these core competencies, ensuring they are more valuable when they are hired. In addition, more training is needed for individuals already employed throughout the industry.

The recommendation to all universities with undergraduate and graduate level programs in the mechanical, electro-mechanical and manufacturing arenas would be to have all the applicable professors attend core training in fundamental through advanced GD&T to gain direct insight to all of these concepts. They then could establish a strategy to integrate core concepts into the curriculum so all future students have the critical knowledge necessary to be of greater value when hired by companies.

**Conclusion**

Miniaturization of components and reduction in feature tolerances make it mandatory for components and assemblies to be defined with precision GD&T using profile tolerancing to ensure functional intent of the design is truly met. This precision language, when supported by optimum manufacturing equipment, precision measurement system, capable analytical software, and competent, well trained individuals, will allow OEMs and suppliers to meet their goals.

**A Customer and Supplier Partnership in Profile Tolerancing**

A commitment to precision GD&T using profile tolerancing and other key geometric controls is essential for establishing a true partnership between OEMs and suppliers. Only by investing in and committing to precision GD&T can both parties experience its full benefits – clear communication of design intent, reduced measurement error, lower costs, faster time to market, and ultimately, higher profit.

The following are questions you can ask to ensure both OEMs and suppliers are committed to achieving precision GD&T through the use of profile tolerancing:

1. Are both parties working together to define and understand areas of weakness within current designs, manufacturing process, and measurement processes to optimize upon future product and process platforms?
2. Are all critical team members trained in precision GD&T to the degree necessary to perform their respective tasks?
3. Are designers precisely defining surface geometries using profile tolerancing?
4. Do OEMs and suppliers have adequate software to complete optimum tolerance and sensitivity analysis at the design level and measurement analysis at the metrology level per the ASME Y14.5M-1994 and ASME Y14.5.1M-1994 Standards?

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