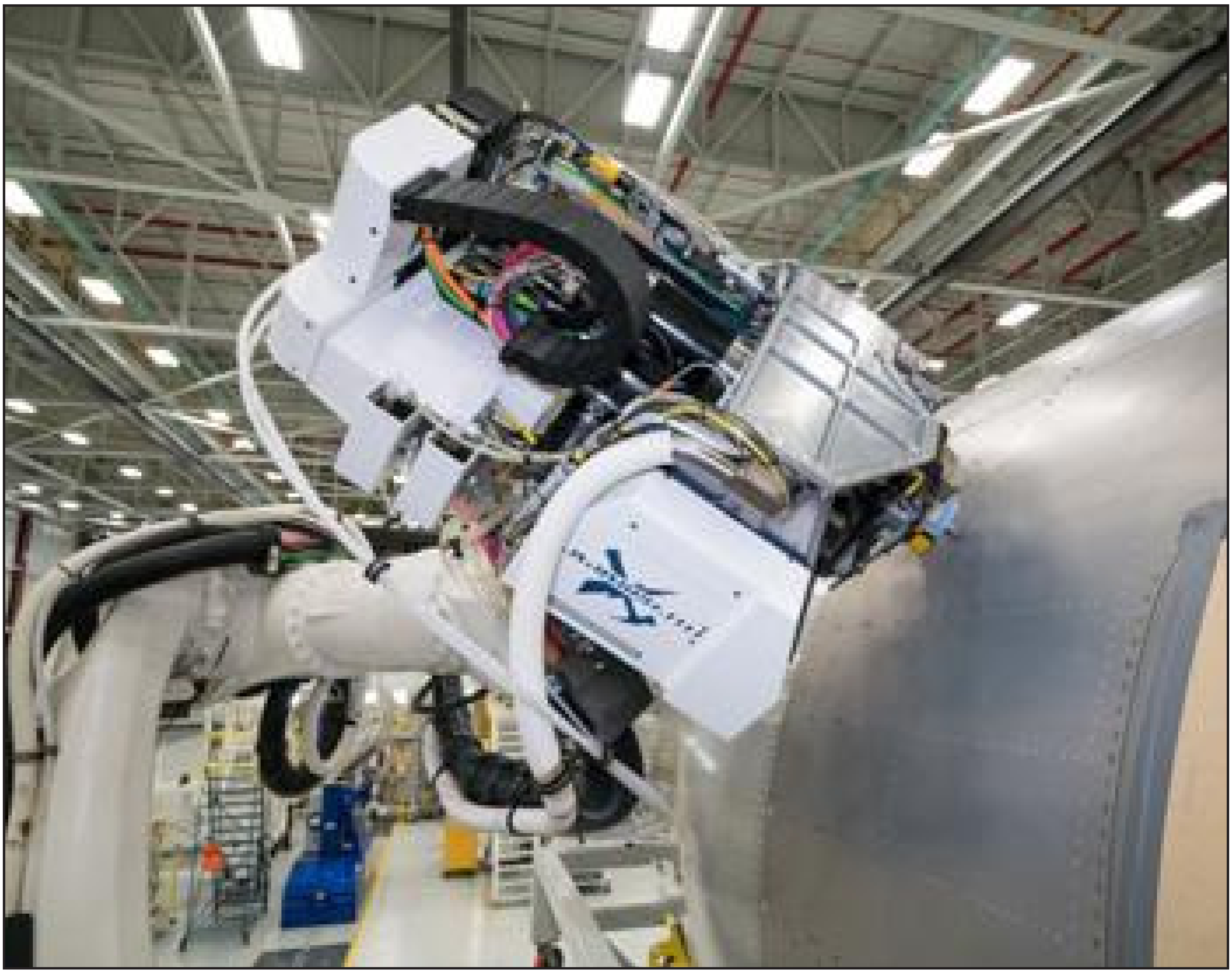

Towards Right-Sized Limits: A Beginner's Primer for Rationalizing Build Tolerances

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In activities such as aerospace tool building the metrology team is often faced with a demand to build to extremely tight, often impractical, perhaps even impossible, tolerances. Although there are many unknowns it is possible to estimate the uncertainties associated with any measure-and-build activity. Taking the time to analyze these factors prepares the engineer for a discussion with the customer about appropriate tolerances and can help him or her avoid making accuracy promises which cannot be kept. It is also a good opening for discussions on the high cost of tight tolerances and the use of local coordinate frames, relationship fitting, and other metrology tools to create a more sustainable fixture—in a word, to rationalize the build tolerances.

INTRODUCTION

It happens more often than it should: A team is struggling to set jig details, and the project manager is wondering why. A little investigation shows that the tolerances are so tight that the fixture may not hold those tolerances from day to day given temperature swings, instrument accuracy, and other factors. The customer wonders why the team gets different numbers while the metrology guys doing the setting burn hours and experience frustration with the results. Is there a better way?

A careful analysis of factors contributing to measurement uncertainty can help all parties better understand what tolerances are achievable. A recent, similar experience led a project manager to ask one of the authors of this article for some guidance in setting tolerances in large fixtures. This article is the result of that investigation; it originated in dealing with large aerospace structures, but the principles are applicable to other industries, given suitable adjustments.

To summarize a bit, here are some reasons to avoid unreasonable tolerances:

- All parties (fixture builder as well as customer) often cannot reproduce measurements.
- Verification measurements often indicate that a given part is out of tolerance.
- The fixture builder or the metrology team (or both) appears incompetent in the eyes of the customer.
- The fixture builder is forced to reset tooling details—often more than once.
- Metrology teams get frustrated and demoralized.
- The excessive hours spent on setting and resetting destroys the profitability of the job.
- The customer gets a product which he or she is unlikely to be happy with—because the tool may be considered "unstable" with many details that must be reset at each recertification.
- Fixtures have a high cost of ownership.

For all these reasons, it is important to set reasonable tolerances. What might be done to achieve this?

- Rely on representation by highly experienced managers to use their experience and authority to push back hard against customer if the tolerances are too tight.
- Focus on the high lifetime cost of ownership. Explain the high cost of tight tolerances to the customer—and point out that annual verifications will be really expensive if the tolerances are too tight.
- Suggest the use of tight local (vs. global) tolerances, where needed.
- Rationalize tolerances to get customer buy-in on appropriate tolerances.

Whatever method or combination of methods is used, a key element is to know what a reasonable tolerance is. How can a reasonable tolerance be established? There is no substitute for experience in this matter, but it is possible to follow a methodical process for quantifying an appropriate tolerance.

BACKGROUND

For the sake of clarity, we will first describe a few common practices and provide some definition of terms before proceeding. To begin, it is important to note that some aerospace companies make a practice of distinguishing between setting tolerances and recertification (i.e., "recert") tolerances. When building for such companies the fixture must set all details to within the setting tolerances and thereafter all verifications must meet the recert tolerances, which are typically much looser.

Some common terms and phrases include:

- **Best fit**. More properly "least-squares best fit," best-fit techniques are used to align a measured set of points (or other features) to the nominal values. Some error always exists, which is spread across all the points evenly using the least-squares algorithm.
- **Confidence interval (CI).** A statistical estimate calculated from observed data that gives the likelihood that a given data point lies within an interval. If an instrument is used that has specifications given at a 2σ CI, then there is a 95-percent chance that any measurement taken will be accurate to within those instrument specifications.
- **Coefficient of thermal expansion (CTE).** This is a measure of the expansion of a material as temperature changes.
- **Recertification ("Recert").** Most fixtures require a periodic (often annual) re-measurement of all details to ensure that none have changed. Recert tolerances are frequently, but not always, looser than original-setting tolerances.
- **Reference systems.** These are fixed points in a system which are used to build the system details. Also known as a "control network," reference systems are usually very carefully valued through using multiple station shoots. Such systems include a jig reference system (JRS), meaning points on the jig or fixture structure; a foundation reference system (FRS), with points in the foundation; and an enhanced reference system (ERS), which may have points in both the foundation and on a fixture or jig.
- **Setting.** Also known as "building," the process of "setting" tooling details means adjusting them so that they are in the required position for manufacture. This is often done with a laser tracker, though other instruments are used. After a detail is set it is locked into position, usually by torqueing bolts and often by doweling.
- **Spherically mounted retroreflector (SMR)**. This is a precision target mirror in spherical form used for laser tracker measurements.
- **SpatialAnalyzer (SA)**. This software is a commonly used program for laser tracker work in the aerospace industry.
- **Tooling.** In the aerospace industry, "tooling" is used to hold aircraft parts in the correct location for assembly. Note that the terms "tooling," "tool," "jig," and "fixture" are often used interchangeably.
- **Unified Spatial Metrology Network (USMN)**. This is an SA function that enables uncertainty analysis estimates, among other uses.
- **Verification.** Once a fixture has been "set," all details will be verified by re-measuring them, which generally occurs days, weeks, or even months from the initial setting of the first details built on the fixture. After the install team verifies the fixture, customers will often choose to do their own verification measurements. All measurements must fall within verification tolerances.

METHODS FOR ESTABLISHING TOLERANCES

What methods are used for determining tolerances today? One way is to use legacy norms, i.e., "What we did on the last aircraft” or rules of thumb. This approach may ignore issues involved in large or complex designs.

Instrument capability is sometimes used to establish tolerances. Used alone, this also can lead to excessively tight tolerances, since instrument accuracy is only one of many elements contributing to total uncertainty.

Another common method is to derive tolerances solely from design and manufacturing requirements. For example, a drawing may call out a stringer position to ± 0.03 in. and tooling allotted a quarter of that tolerance, leaving 0.03/4 = ± 0.0075 in. global tolerance for setting the tooling detail. The problem with this method is that it does not consider whether or not the tolerance is achievable, let alone consider immediate or long-term costs for the tight tolerance.

This does not mean that the engineer should ignore design requirements—that is the ultimate purpose of the tooling, after all. There is merely a limit to what is achievable with a given set of environmental conditions, foundation stability, tooling design, and available technology. Inexperienced engineers are sometimes tempted to ask, “How accurately can we measure that?” and simply use that instrument tolerance as a detail tolerance. A more holistic view is required, however. The tooling engineer must help the customer balance their requirements with practical capability and cost tradeoffs.

TOLERANCE COSTS

Every system requirement imposes some type of cost, and tolerances are no exception. Tight tolerances are more expensive than loose tolerances, and as the tolerance approaches the limits of part adjustability, instrument capability, system stability, etc., the setting cost skyrockets. Setting the detail is difficult, but more importantly verification becomes very difficult. Fixture recertification, usually taking place every six to 24 months, becomes an exercise in resetting many individual details which no longer are in tolerance. Cost of ownership becomes very high. Very often in such cases no value is added to the product because these tight tolerances are not really needed. It is in the best interest of the fixture owner (usually the customer) to apply an appropriate tolerance which both meets design needs and minimizes total cost of ownership.

TOLERANCE ANALYSIS METHOD

Tolerance analysis can be time consuming, therefore it does not make sense to follow the process for every situation. Where limits are easily met a formal analysis may be skipped. Some companies might find a rule of thumb useful, or a chart similar to the one seen in figure 1, with the *X* values filled in, and comments modified as appropriate for their typical work.

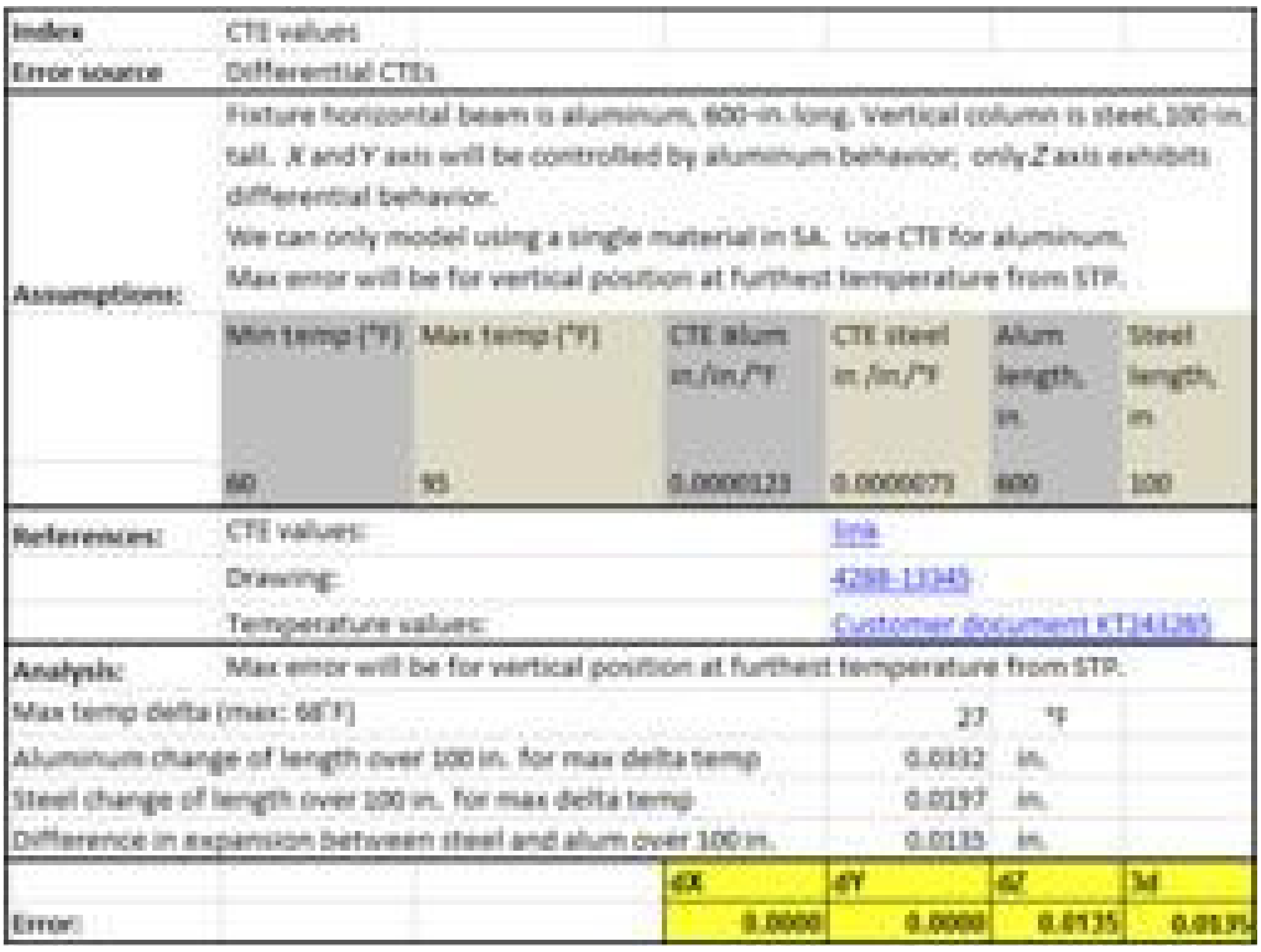
Rules of Thumb Chart for Tolerance Analysis

Tolerance range	± 0.0x in. and greater	± 0.0x in.– 0.0x in.	±. 0x0 in.– 0.0x0 in.	± 0.00x in.– 0.0xx in.	± 0.00x in. and less
Guideline	Easiest	Easy	Limited analysis	Always do thorough tolerance analysis for this range of limits	
Comments	Usually easily achievable on typical foundations	Usually easily achievable on purpose-built foundations	Also requires good environment	Also requires thermal stability, stable tool, experienced metrology team and no complicating factors	Also requires limited volume and excellent environment

Figure 1. *Some rules of thumb may assist inexperienced engineers in recognizing when they are in a “tight-tolerance danger zone”*

Having concluded that analysis is required, the first step is to list ALL the potential sources of error. Include every source of error, even if it seems negligible or impossible to calculate. At this brainstorming stage no plausible source of error should be ignored.

Estimate an error value for every element contributing to the total error. State all assumptions. Errors should be expressed in *X*, *Y*, and *Z* elements and in a common confidence interval, e.g., 2σ is convenient. For more complex error sources such as tracker measurements based on best-fits it may be useful



Index: CTE values

Error source: Differential CTEs

Assumptions:

Fixture horizontal beam is aluminum, 600-in. long. Vertical column is steel, 100-in. tall. *X* and *Y* axis will be controlled by aluminum behavior; only *Z* axis exhibits differential behavior.

We can only model using a single material in SA. Use CTE for aluminum.

Max error will be for vertical position at furthest temperature from STP.

Min temp (°F)	Max temp (°F)	CTE alum in./in./°F	CTE steel in./in./°F	Alum length, in.	Steel length, in.
60	95	0.0000123	0.0000073	600	100

References:

CTE values: link

Drawing: 4288-12345

Temperature values: Customer document KT34-1265

Analysis: Max error will be for vertical position at furthest temperature from STP.

Max temp delta (max: 68°F)	27	°F
Aluminum change of length over 100 in. for max delta temp	0.0332	in.
Steel change of length over 100 in. for max delta temp	0.0197	in.
Difference in expansion between steel and alum over 100 in.	0.0135	in.

	dX	dY	dZ	3d
Error:	0.0000	0.0000	0.0135	0.013

Figure 2. *Individual error sources should be calculated with all assumptions and references noted, leaving an auditable trail for later review*

to estimate uncertainty using SA's USMN. Tolerances for purchased parts may be assumed to be at 2σ. SA USMN simulations are typically 1σ. Uncertainties can be converted from 1σ (68.3% CI) to 2σ (95.5% CI) by doubling the tolerance value.

Sum all errors in a spreadsheet. A good practice is to calculate each type of index on its own sheet with all relevant references, links, and assumptions (as seen in figure 2) with a separate summary sheet (as seen in figure 3).

COMMON SOURCES OF ERROR ENCOUNTERED IN AEROSTRUCTURE FIXTURES

Every job brings its unique sources of error. Every error has a common demand: The engineer should eliminate, minimize, or quantify the error. Any of these actions may well require action in concert with the customer or tooling design teams early in the process.

There is no substitute for careful analysis of each part of the system. However, a typical fixture will include many of the factors seen in the following sub-sections.

Setting details

- **Setting allowance.** Ideally every detail would be set so the tracker software reads 0.000-in. deviation, but the reality is that it is often very difficult to eliminate the remaining error as it gets small. A well-designed detail with good adjusting features might make it easy to adjust in 0.001-in. increments. A detail with several targets requires additional allowance because adjusting to improve one target may worsen the other target reading.

The key point to recognize is that the setting allowance is the only factor that is arbitrary and negotiable, not merely descriptive. Tighter setting allowances are usually achievable given enough time but there are diminishing returns. The target value should be reviewed after all the other error sources are quantified and only reduced if it is a significant portion of the total.

Fixture error sources

There are a number of sources for errors on a large fixture. These include thermal influences, moving elements, and removable elements:

- **Thermal transient errors.** Few aircraft assembly sites are fully air conditioned, so large temperature changes are to be expected. Uniform temperature change can be compensated for in software, but non-uniform temperature changes cannot. This frequently causes bending deflections, not just size change. Because fixtures are usually tall there is typically a vertical thermal gradient, but there is often a horizontal gradient as well. Heat or cooling sources such as sunlight, air conditioning, and heater ducts will often apply an intense, localized thermal change on the fixture, especially when the ducts lack diffusers, and the results are sometimes surprising. It is also worth noting that in those locations such as cleanrooms where stringent temperature controls are applied there is noticeable improvement in fixture thermal and dimensional stability. For example, recently a puzzled metrology team struggled to make sense of some strange measurements until they realized that the upper beam of a fixture was being efficiently and dramatically cooled by a row of air conditioning ducts that turned on every afternoon. In short, varying thermal gradients across large parts create a source of error. Because thermal effects can be so marked for large-scale 3D metrology, it is recommended that both air and fixture temperatures be monitored at several points around the fixture. For large fixtures (such as for wings) it can be useful to take temperatures at high and low points on the fixture, to observe the vertical thermal gradient, as well as to take observations at the extremes or several points along the length. Inexpensive temperature loggers make it easy to set up permanent logging systems for the duration of the installation to take automatic hourly readings for both air and the fixture itself. A key takeaway is that this type of error is difficult to quantify so it is often better to work to reduce or eliminate it rather through design changes or environmental controls.
- **Differential CTEs errors.** Differential CTEs are another thermal source of error. Aircraft fixtures are often a combination of steel and aluminum which have quite different coefficients of thermal expansion. For example, a fixture might have a steel beam (X axis) and an aluminum vertical board. The CTE compensation can either be set for

Figure 3. Example error summary sheet

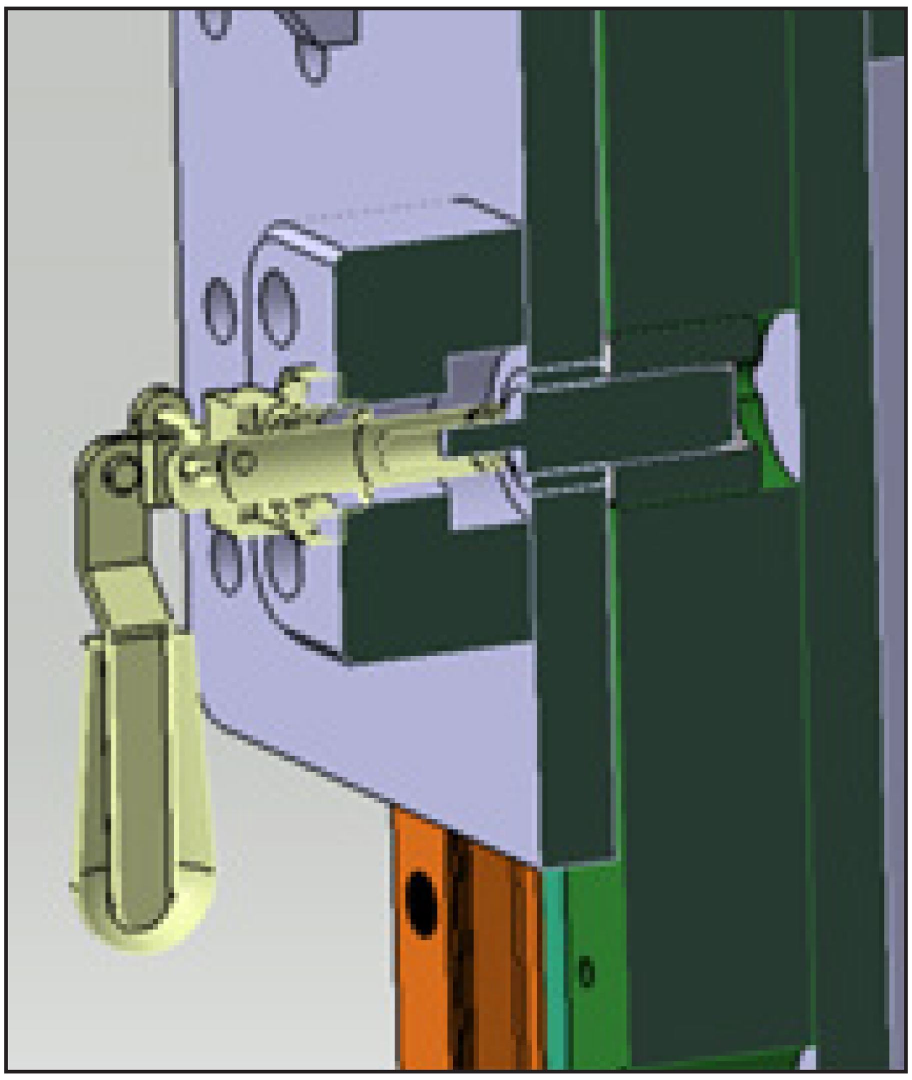


Figure 4. Pin-off details sometimes allow very significant variation; any removable or adjustable element should be tested very early in the process to ensure acceptable variability

steel or for aluminum, but not both; the result will either be an *X* axis scaling error or a *Z* axis scaling error (or a compromise with a smaller scaling error in both axes). It is very common for the tooling to be a different material than the product, for example, a large, mostly steel fixture is used to build an aluminum wing. The differing CTEs in such cases can create significant errors. Although the metrology team might not be directly responsible for this source of error, this is exactly the kind of error which should be discussed with the customer very early in the design phase.

- **Moving and removable elements repeatability.** Modern fixtures often have sliding or rotating elements, either manually positioned or servo-driven. Such elements will have some repeatability error as they are moved into and out of position. Likewise, fixtures will have removable elements. Errors for these are best determined by early prototype testing, as methods such as pin-offs can easily have very large errors (0.015 in. or more) as seen in figure 4. On the other hand, servo-driven systems can be extremely repeatable, especially if secondary feedback via scales is used (less than 0.0003 in.). Test your system.
- **Removable elements variability (interchangeability).** Removable components often have multiple instances, meaning that perhaps any number of nominally identical details must fit into the same receiver. In such cases it is necessary to include the machining tolerances of the removable part in the analysis as seen in figure 5. Note that any removable element has a six-degree-of-freedom (6DOF) repeatability issue (location and orientation). The Hidden Point Fixture feature of SA may be useful for evaluating removable element variability.

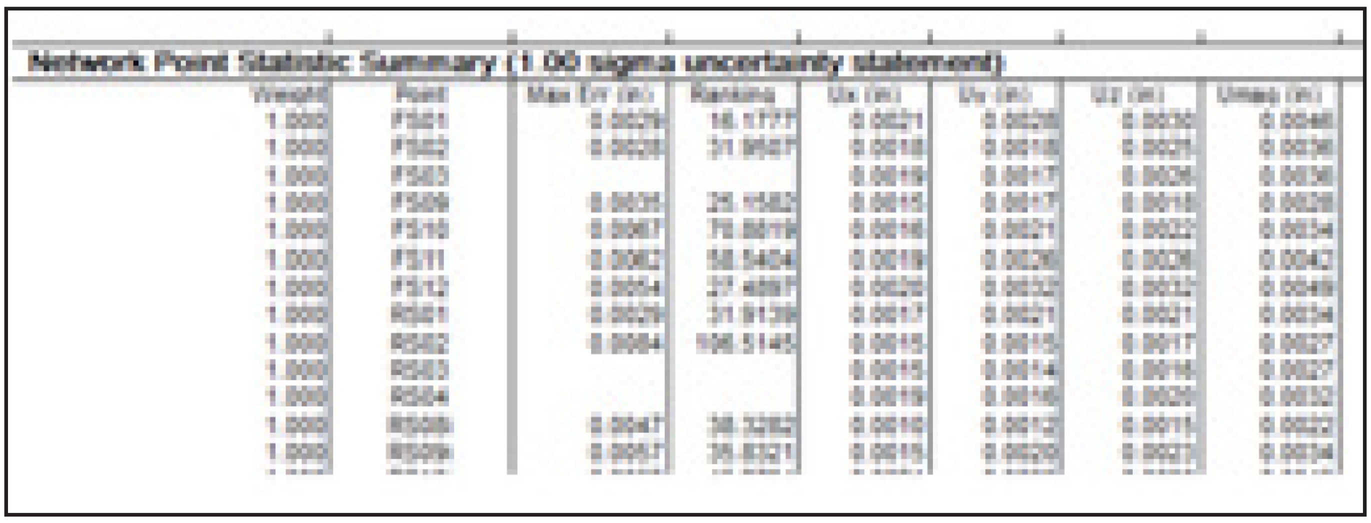
Figure 5. Removable features create special challenges for analysis of tolerance stack-ups

A tangential issue is system deflections. Complex systems will tend to have moving or removable elements and therefore varying loads on certain system components. Generally, the assembly being manufactured is not in place during fixture setting, and therefore the weight of the assembly is not present during setting. These loads will induce small deflections which may contribute to system error.

Instrument-related errors

We may consider two scenarios for instrument use. In the simple case, a tracker is used to directly measure common references, all of which are always used to set all details for a given fixture. In other cases, a reference system is used, and the tracker is placed in different locations using a subset of that reference system to "shoot in." In the simple case, measurement uncertainty is just the uncertainty for measurements at the typical distance to the part. Where a reference system is used the quality of the reference system will affect the result, and therefore it too must be accounted for.

- **Reference system (control network) error.** Every reference system has an associated uncertainty for each point location, no matter how carefully measured. SA's USMN feature calculates uncertainty for all points in a control network as seen in figure 6.
- **Tracker-reference system fit error.** When a tracker is best-fit into a reference system the resulting error will be influenced by the number of points used and the quality of the fit. The RMS error of the fit can be used to estimate this error.
- **Tracker uncertainty**. This is simply the published tracker measurement uncertainty for target measurement at the maximum distance measured.
- **Global measurement error.** As an alternative to using the three previous measurements (i.e., reference system error, tracker-reference system fit error, and tracker uncertainty) the global measurement error can be captured in a single calculation. The associated uncertainty can be estimated via SA's "USMN with Point Groups" function, assuming that the SA file used to create the USMN for the control network is available, which is enabled in SA by choosing the single instrument being located and the reference points (from a previous USMN) as the nominal group. The reference group will behave as a fixed instrument and the measured points will receive uncertainties which include both the instrument and control network contributions. This method captures the tracker uncertainty from the immediate measurement, making that line in our estimate spreadsheet zero. In some cases (such as where local tolerances are being used) it may be useful to calculate them separately instead.
- **Leveling errors.** If the fixture must be level, then a gravity vector must be established and instrument error factored in.
- **SMR errors.** The dominant error is usually the centering error of SMR.



Network Point Statistic Summary (1.00 sigma uncertainty statement)

Figure 6. *SA's USMN provides uncertainty estimates for each point in the network*

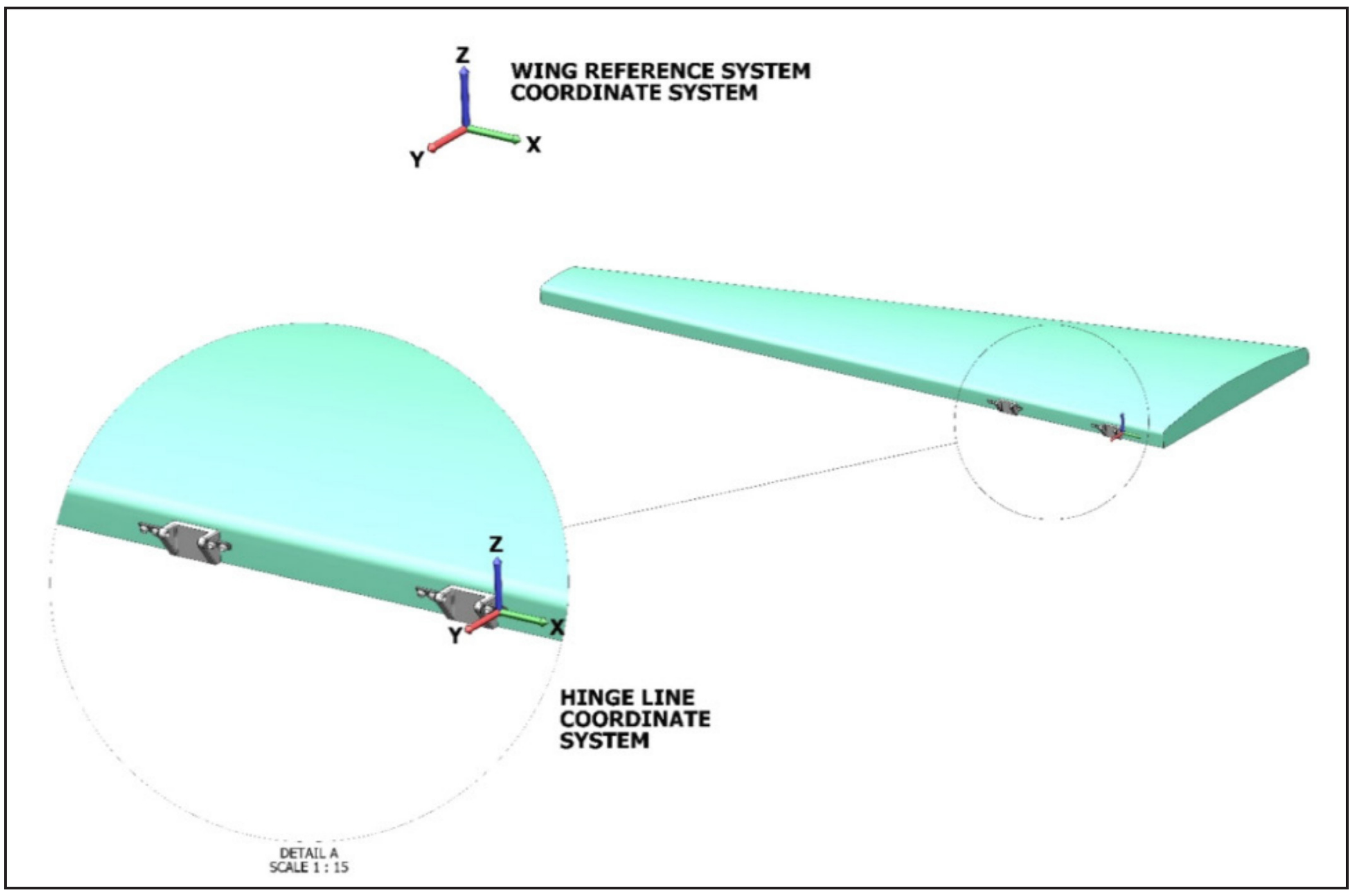


Figure 7. Part of developing rational tolerances is ensuring that the correct relationships are established

- **Permanent nest error.** Permanent nests are preferred in many cases because they eliminate much of the variability associated with pin nests. The error can be caused by debris.
- **Pin-nest error.** Pin nests add a hole-fit error and a potential error for debris between the pin nest and surface.

Foundation-related errors

Like other error sources, foundation-related errors will vary with each system. In most cases the authors have assumed that a) the foundation does not change temperature, b) the foundation does not move, and c) the foundation does not change shape. In reality, these assumptions are not always correct. It is worth considering the foundation design, shape, and the distance from the edge of the foundation to the nearest tool. Can the engineer eliminate, minimize, or quantify the error? Steps can be taken prior to pouring concrete, but after that efforts are usually limited to quantification.

Other factors exist of which the engineer should be aware, if only in preparation for recerts:

- **Concrete curing distortion.** Foundations change shape slightly as they cure, especially in the first six months. These changes are not insignificant. The authors have observed local vertical changes in excess of 0.03 in. across a foundation as well as changes in other dimensions.
- **Foundation mass movement.** External influences can cause foundation deflection or movement, for example, from nearby excavation or even earthquakes. These factors are probably not subject to estimate and are only noted here because they are realities which sometimes must be addressed. Nearby excavation should prompt monitoring of the system control network. An earthquake should be followed up by a quick control network measurement.
- **Foundation deflection.** Very large, heavy machine movement can cause temporary foundation deflections. High-performance aerospace foundations should be designed to meet a particular deflection allowance given the machine weight, and where this is the case this should be a minimal factor. Often the fixture will deflect with the foundation, thereby minimizing the differential movement between fixture and machine.

In addition, foundation thermal transients, for example daily thermal changes such as sunlight on a foundation and large daily temperature swings, can induce significant foundation shape change, especially very close to the edge of a slab. As an example, one fixture exhibited transient instability, and after much head-scratching it was observed that the foundation edges moved about 0.008 in. vertically on a daily basis. Longer-term transients also exist, since an unconditioned factory may spend summer weeks at 100° F and winter at closer to 60° F. Again, these temperature changes will affect foundations edges the most.

Worst case or statistical stack-up?

There is room for debate on which method should be used to analyze tolerance stack. Simply summing the worst-case deviation from each error source is the most conservative approach and is a good starting point. In some cases, this will produce unrealistically high results so statistical methods such as root sum squared (RSS) with a multiplier or Monte Carlo simulation should be considered. This topic is beyond the scope of this article and is well addressed elsewhere.[1]

Tips for successful analysis

These tips may improve the analysis:

- **Reality check.** Is the resultant tolerance number within the range of similar work? If not, why not?
- **Outside review.** Have an experienced non-participant review your work.
- **Refresh review.** Complete the analysis and then review it after a break of several weeks to refresh your perspective.

SMARTER TOLERANCES

Sometimes tolerances are set in ways that fail to focus on the actual needs of the assembly. Perhaps global tolerances are used for a tight subassembly when really what is important is the relative location of a few parts. An example will be helpful to clarify this. Consider a large aircraft wing with an important hinge line for the flap as seen in figure 7. The tolerances for the coaxial hinge fittings must be very tight to ensure proper function. These might be expressed as global positional tolerances, but because the key requirement is that the fittings are coaxial, they are much better expressed in a local frame, with the tight tolerances controlling the relationship between the hinge fittings rather than to global wing features. A looser global tolerance can be applied to ensure that the fittings still meet global requirements. A similar tolerance scheme can then be applied to the matching tooling.

Whether applied via the use of geometric dimensioning and tolerancing (GD&T), a local coordinate system, or some other method, providing looser global tolerances and restricting the tight tolerances to smaller volumes helps create a more robust tolerance scheme.

BENEFITS OF RATIONALIZING TOLERANCES

There are a number of benefits to making the effort to calculate proper tolerances. First, working through all the factors may reveal significant error sources which may have been overlooked. For example, perhaps an engineer plans to pin-off a sliding detail with a method that leads to an additional 0.02 in. *X* axis uncertainty. Identifying this uncertainty early allows for a design improvement before expensive hardware has been built, and likewise can push improvements in design, technologies, and methods.

A second advantage is that the hard choices appear early in the design phase where they can get the attention they deserve. Instead of the metrology team—and the customer—being surprised with bad news during fixture-setting, the issues are visible very early. Difficult choices can be made with all those options which later decisions will close off.

Well-rationalized tolerances mean that the installation and buyoff requirements are achievable and therefore the buyoff process is much more satisfactory to all parties. Fixture builders can hit their tolerances, the customer sees far fewer exceptions, and when the customer executes independent verifications the details will pass.

Finally, a good tolerance scheme will greatly reduce maintenance costs and total cost of ownership. Aerospace customers recertify fixtures on a regular schedule (every six months to two years). Well-designed, stable tools with appropriate tolerances have details that generally pass inspection. Overly tight tolerances directly lead to details failing recertification. These details must be loosened, have dowels removed where applicable, reset, rechecked, and then verified—a very time-consuming process. During this time, the fixture is, of course, out of production. A long recert cycle can potentially keep fixtures out of production long enough to require the addition of another fixture to maintain rate. Appropriate tolerances will help to avoid this cycle and result in a significantly lower maintenance and total cost of ownership of the fixture.

SUMMARY

Tolerance schemes determined in isolation from the considerations of measurement, tooling. and environment are often excessively tight, leading to tooling that has a high cost of ownership. A careful estimate of error which includes setting allowances, thermal effects, moving and removable element effects, and instrument errors as well as other common factors offers the possibility of setting more achievable tolerances. Our hope is that this primer will provide a starting point for rationalized tolerances and consequently more successful fixture installations with lower costs of ownership.

ACKNOWLEDGEMENTS

Although the authors have had assistance from others, any errors are our own. Thanks to Scott Sandwith and Steve Seiler of New River Kinematics for assistance with uncertainty modeling techniques.

REFERENCES

[1] Taylor, W. A., *Process Tolerancing: A Solution to the Dilemma of Worst-Case Versus Statistical Tolerancing*, Taylor Enterprises Inc., 1997.

- Berk, J., “Statistical Tolerance Analysis,” *ECN Magazine*, 2013.
- Christensen, K. and Flynn, R., “Developing a Control Network Crossing a Thermal Boundary: A Wing Jig Case Study with Best Practices,” *The Journal of the CMSC*, Vol. 7, No. 2, pp. 4–9, Autumn 2012.
- Scholz, F., Tolerance Stack Analysis Methods,” Research and Technology Boeing Information and Support Services, Dec. 1995.
- Estler, W. T and Phillips, S. D., “Economics of Measurement Uncertainty and Tolerances,” *Proceedings of the ASPE 2009 Summer Topical Meeting: The Economies of Precision Engineering*, July 2009.