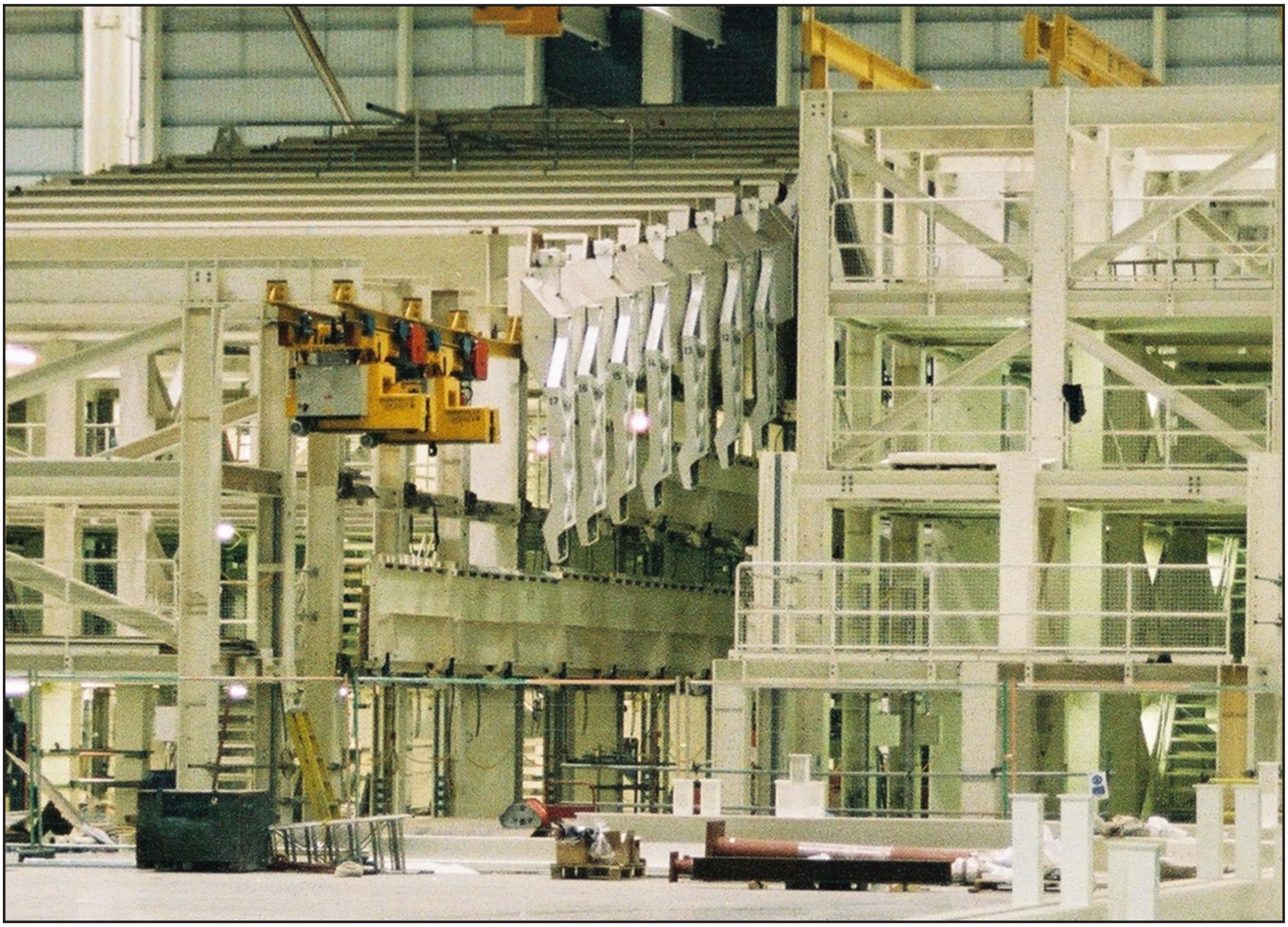

Developing a Control Network Crossing a Thermal Boundary: A Wing Jig Case Study with Best Practices

by Karl Christensen and Robert Flynn, Electroimpact Inc.

Large aircraft tooling jigs frequently require a control network to support good tool-building techniques. Such tools typically have steel structural members exposed to widely varying temperatures, sitting on heavy isothermal concrete foundations. A control network may often be required to cross the boundary between the varying temperature of the steel structure and the isothermal foundation.

A simple approach to bundling this network is to treat all points as a single data set, but improved results may be obtained by splitting the points into two data sets for the foundation and structure. The two approaches are compared on a new wing jig installation. Other practices are examined, such as the use of tracker internal levels vs. running level loops with a Leica DNA03 digital level, and the use of automated surveys to reduce measurement time.

We will first consider thermal growth and its effect on three different potential wing jig designs. We will then examine the method for developing a control network for our case study jig. The effect of differential vertical thermal gradients will be considered. Finally, we will make some suggestions for best practices in developing such a control network.

AN OBSERVATION ON JIG STRUCTURE MATERIAL

The coefficient of thermal expansion for steel is 7.3×10^{-6} in./in./°F. For aluminum the coefficient is about 12.3, or nearly double. Therefore, for a 90-foot (1,080 in.) steel jig, there is significant differential growth between a free-growing jig and the part, as seen in the table in figure 1.

This differential growth is nearly always undesirable, but it is not always reasonable to construct the jig of the same

	Delta Temperature, °F			
	1	2	5	10
Steel length Δ	0.008	0.016	0.039	0.079
Aluminum Δ	0.013	0.027	0.066	0.133
Δ length	0.005	0.011	0.027	0.054

Figure 1. This table shows temperature deltas and corresponding length changes for steel vs. aluminum

material as the part. Frequently the *x*-axis tolerances are more forgiving than the *y* and *z* axes, and this differential growth is acceptable. But even in cases where the jig is designed to allow considerable differential growth between the jig and part, a reliable reference system that scales predictably with temperature is still required. Such a jig provides a repeatable measurement process for recertifying the jig, and a reliable tool for detecting nonthermally induced changes in the jig. An excessively simple control network might not provide these qualities, and may hide out-of-spec changes in the jig. Conversely, a simple network may indicate an out-of-spec change where there is none.

AIRCRAFT JIG SCENARIOS

Large aircraft jigs vary greatly in design between different designers and aircraft manufacturers as well as between different parts, part materials, and build philosophy. The following configurations might be found in any factory with long, thin tools typically used for wings, spars, and other long parts. Each configuration will behave quite differently with regard to temperature changes. Common assumptions for these jigs include that the foundation temperature, and therefore size, will remain constant; and that the jig and part temperature will follow air temperature.

Piecewise thermally overconstrained jig

Consider a series of steel base modules bolted to a concrete foundation, such as those seen in the simplified illustration in figure 2. There is no uniform *x*-axis thermal growth in this example; *x*-axis growth may occur with each base module but will be centered on each base module and will occur in both positive and negative directions. Growth length will be piecewise and based on half of the length of the base module. Jig growth will not cumulatively work toward offsetting part growth.

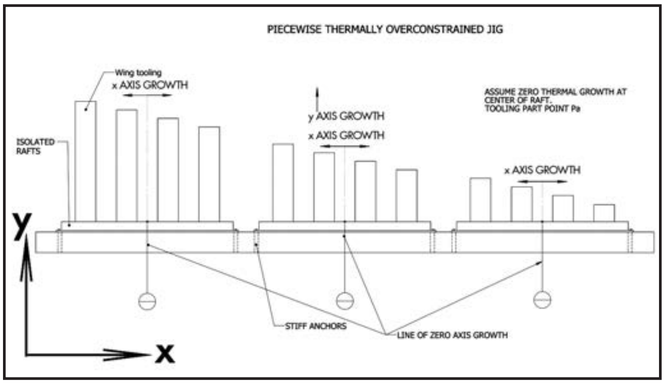

Figure 2. Simplified illustration of a piecewise thermally overconstrained jig

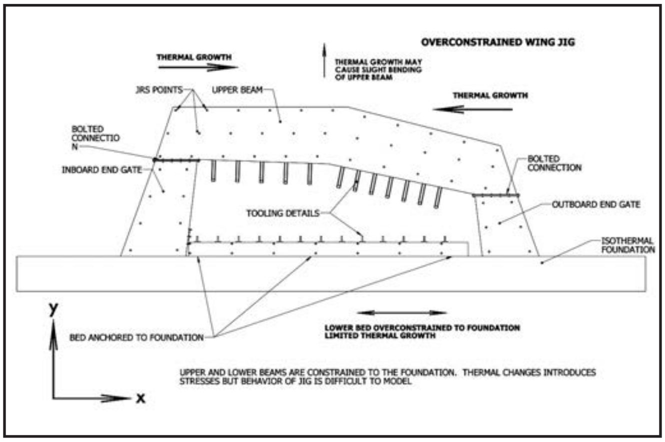

Figure 3. Thermally overconstrained jig

Thermally overconstrained jig

Another thermally overconstrained jig can be seen in figure 3. This has an upper beam fixed at either end and a continuous lower beam bolted to the foundation along its length. The upper beam will tend to deform upward as it heats up above its setup temperature. The lower beam will tend to bow upward slightly between the restraining bolts.

The behavior of these and other overconstrained jigs, such as the one seen in the image at the top of this article, is hard to predict because they are not free to move in all axes to relieve temperature-induced stress. A third jig configuration is presented that offers unconstrained movement in the *x* axis, and a more predictable behavior.

End-constrained jig

An end-constrained jig can be seen in figure 4. This jig has upper and lower beams that are fixed at the inboard end. Both beams float in the *x* axis on linear bearing rails except at the constrained end, which allows free growth in response to thermal changes. This fixture allows the indexes along the wing to thermally grow or shrink with the wing, although at different rates, since the jig structure is steel while the part

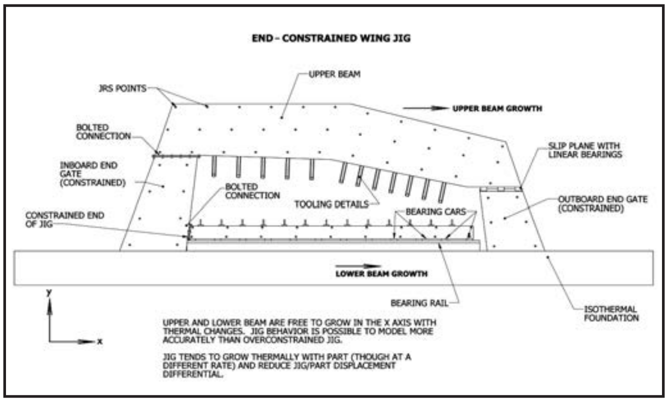

Figure 4. End-constrained wing jig

is aluminum. This end-constrained jig design was used in the jig described by our case study, a 90-foot-long wing assembly jig with a 110-foot-long × 36-foot-wide foundation reference system.

Establishing a control network for the case-study jig

For the end-constrained jig in our case study, we chose to measure the structure from 12 stations, six on each side of the jig, three hard up against the jig, and three far out to the outside of the foundation reference system (FRS). Reference points on the jig are referred to as "JRS points," while a combined control network that includes both FRS and JRS is referred to as the "enhanced reference system" (ERS). The stations measured for the enhanced reference system are seen in figure 5.

After measuring the reference points from all 12 stations, we analyzed the results, trying to determine the best method for bundling the data.

Control network across a thermal gradient

A comprehensive description of the data processing is beyond the scope of this article. But very briefly, the process is as follows:

- Measure points from each of the 12 stations, including level data from each position.
- Bundle all data (unscaled) to create the unscaled enhanced reference system.
- Bundle all FRS data into the unscaled FRS.
- Develop an average gravity vector.
- Scale all stations, using average jig temperature.
- Bundle all JRS points except the outboard end gate, creating a JRS set.
- Best-fit the JRS set to the unscaled enhanced reference system data set.
- Create a final ERS by merging the JRS set and the unscaled FRS.

As we expected, it became apparent that our control network—the ERS—crossed a thermal growth gradient. The FRS points in the foundation did not behave in the same way as the JRS points in the steel jig. Furthermore, on closer examination, even the JRS points did not behave all the same way. The JRS points on the inboard end gate stayed in place, while upper- and lower-beam JRS points experienced positive *x*-axis growth with increased temperature, as would be expected. However, the outboard end gate, fixed as it was to the foundation, remained in place and did not experience thermal growth.

The vector plot seen in figure 6 illustrates the importance of treating data correctly. One data set was generated by bundling all JRS points together. In the second method, the outboard end gate was excluded from the dataset. There is a maximum delta of about 0.012 in. between any given point using the two methods, and an average of about 0.008 in. Clearly, it is important to consider thermal issues carefully and compare bundling methods to identify sources of systematic error.

Vertical thermal gradients

Other thermal considerations exist. There is a vertical temperature gradient in the typical aircraft manufacturing facility, as has been observed by anyone who has spent time on a boom lift or ladder. On the one hand, this gradient can be substantial. On the other hand, the vertical distance is generally not so great as to develop an unacceptable delta. Further, in this case the jig was set up and valued under a similar vertical temperature gradient, eliminating nearly all of the effect for the installed jig.

A vertical thermal gradient usually has no negative impact as long as it is constant in magnitude. So, for example, if the temperature gradient from the top to bottom of the jig is 4° F, the system will scale well. However, if the gradient significantly changes, geometry changes will occur, too. (See figure 9 for an illustration of how the vertical thermal gradient changes on the case-study jig. Point A has a thermal gradient of about 6° F, whereas point B has a gradient of about 2° F.)

In an end-constrained steel jig with upper and lower beam, a 2° F change in the relative temperature between the upper and lower beam results in a 0.008-in. shift at a point 45 feet from the end of the jig. This will obviously have a negative effect on fits when best-fitting into a reference frame. How can this be addressed?

One solution is to use reference points only into the upper or lower beam. This can work well, but in some cases there is insufficient "wheel base." This was the situation in our case-study jig. In such an example, the aspect ratio between the point-to-point

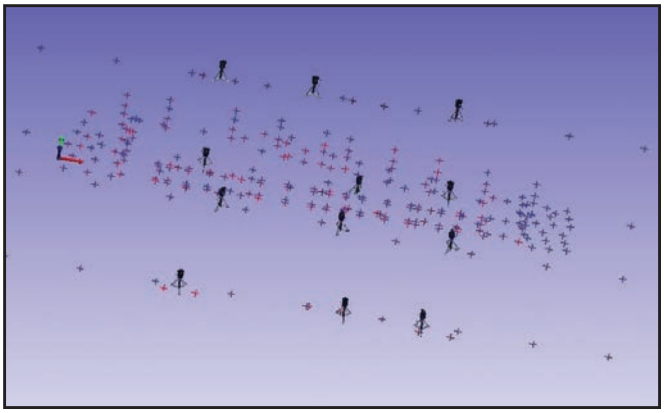

Figure 5. Stations measured for ERS

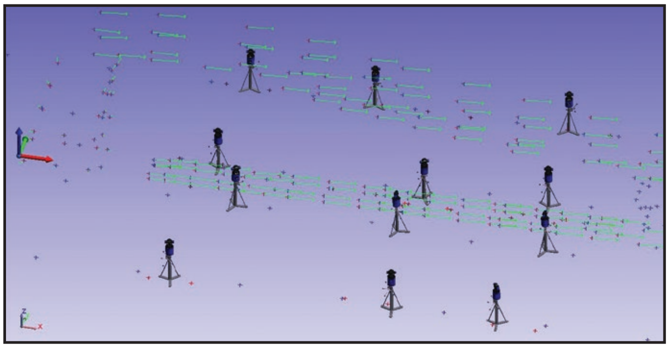

Figure 6. A vector plot shows the difference between including and excluding the outboard end gate from the JRS bundle

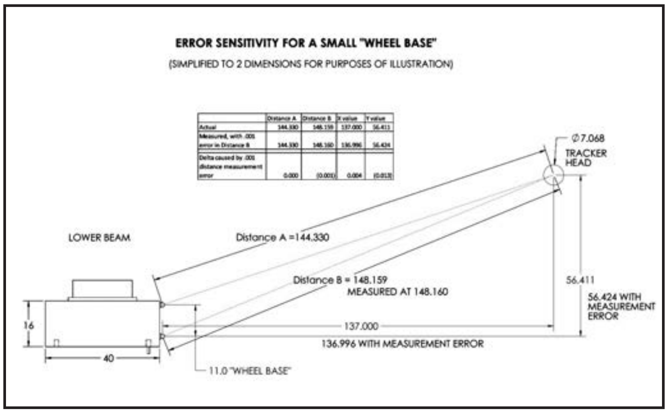

Figure 7. Error sensitivity for a small "wheel base" is very high

distance and the tracker head is such that a 0.001-in. error in measurement of distance to the tracker results in a 0.013-in. error in the vertical distance from point to tracker head, as seen in figure 7.

Obviously, it may be possible to correct for this error by taking a measurement from the upper beam, as shown in the wide "wheel base" example in figure 8. The aspect ratio here is much improved, and reduced sensitivity is the result.

However, this is actually a three-dimensional problem, and these sketches overlook the previously noted fact that the upper and lower beams might grow at different rates if the vertical thermal gradient changes. Because such change is expected, how can we use the upper beam without introducing distortion? One method is to de-weight the *x*-axis component of the points measured on the upper beam so that the *x* axis is derived only from the lower beam, which has good geometry for that axis.

Establishing the gravity vector

For many jigs, our case study included, it is important to establish an accurate gravity vector. Two methods were used for the case study jig: digital optical levels and laser trackers. For the first method, a Leica DNA03 digital optical level was used. Good practice for this instrument dictates that shots be kept short—in the 6-foot to 20-foot range—and that the distance to each target be nearly the same for any two measurements from the same station. (This minimizes axis nonsquareness error.) Only FRS targets are used. A level loop is done around the perimeter of the jig, closing back on the starting point. Closure to within 0.004 in. is required. Once the data are collected, they must be integrated into tracker data using SpatialAnalyzer software, a tedious process.

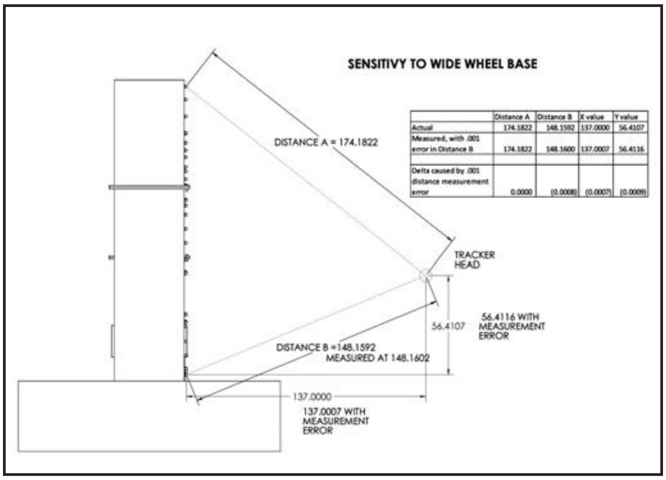

Figure 8. A wide "wheel base" is less sensitive to measurement error.

For the second method, laser trackers were used, including the FARO Xi and the Leica AT401. These both have internal levels, and by using SpatialAnalyzer to record data, establishing a gravity vector is quick and easy. Level readings were taken at the beginning and end of each tracker station. When all stations were complete, the level vectors were all averaged to form a composite gravity vector. Each individual contributing gravity vector was then compared with the average, and any outlier vector readings removed. Then a new average was taken. Incorporating the gravity readings is a trivial chore for tracker readings, compared to the process for the digital optical level. The difference in gravity vectors between the digital optical level and the internal tracker levels was about 0.24 arc-seconds.

BEST PRACTICES FOR CREATING CONTROL NETWORKS

Long and sometimes painful experience has brought home a few lessons worth remembering while creating control networks.

Model for clarity

Draw a simplified diagram of your structure. Imagine huge thermal shifts and their effect on the structure. Try to illustrate the effect of these exaggerated shifts, and then consider the effect of thermal changes.

Document your setups

It is safe to assume that anything you do not record will soon be lost in the mists of time. Take careful notes of your setups. What was done and how to interpret the data will be far less obvious a few months hence. By "temperature," did you mean "part temperature," "air temperature," "jig temperature," or "scale bar temperature?" By "scale bar," did you mean the "32-in. Invar scale bar," the "60-in. aluminum scale bar," or the "60-in. steel scale bar?" And so on. Likewise, name data sets carefully. If possible, use descriptive notes within the data file itself. It is easy to separate descriptive files from the data file.

Examine the foundation

Get drawings of the foundation. Where are the expansion joints? Does your control network extend past the expansion joints? There is a significant risk of differential movement for such cases. Is the foundation designed for the given load? What are the allowable deflections?

Is the foundation new? New foundations are constantly changing shape as they cure. Expect very significant changes within the first six months and measurable change for a year.

Check the control network after the first year to see if it must be reshot. For this case study's system, after 18 months the FRS points moved an average of 0.014 in. and a maximum of 0.033 in. Although this was broadly a shrinking action, it is not a uniform process, and a best fit to a local part of the system could introduce significant error. Worse, choosing different fit points results in a different fit.

Live loads

Are there large live loads to consider? A very heavy machine may cause measurable foundation deflections, even on a stout foundation. Worse, a nearby live load may cause your instrument to move. Try to keep large live loads away from your work area.

Temperature measurements and applications

It is important to get good temperature readings, but where to measure isn't always obvious. Review the surroundings. Where are the building heaters? Are there ducts nearby? Are there large doors that will be opened? Is it possible to keep the doors shut? Thermal gradients in the air will add to your challenges. Air temperature should be measured at about the same elevation as the tracker and should be measured in several locations to check consistency.

Thermistor thermometers offer good accuracy and have a variety of probes, including those designed for air and surface-temperature measurement. Probes can be inserted down a hole in the part (preferred) or simply taped to the surface. Thermally conductive paste should be used to ensure a good reading. A small piece of foam can be taped to the "air side" of the probe to ensure that the reading is providing a part temperature and not an air temperature.

Air temperatures should be taken as a reference to help maintain an awareness of air temperature fluctuations, as seen in figure 9. Radical shifts in air temperature will affect measurement accuracy.

For scale bars, a scale-bar temperature should be taken for greatest accuracy. Note that a 2° F change in a 60-in. aluminum

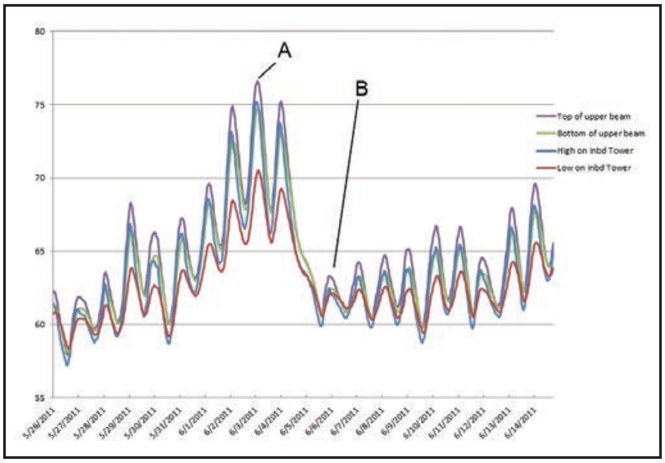

Figure 9. Temperatures varied by nearly 20° F over three weeks, as hourly monitoring shows; note change in temperature spread between points A and B, indicating a varying vertical thermal gradient

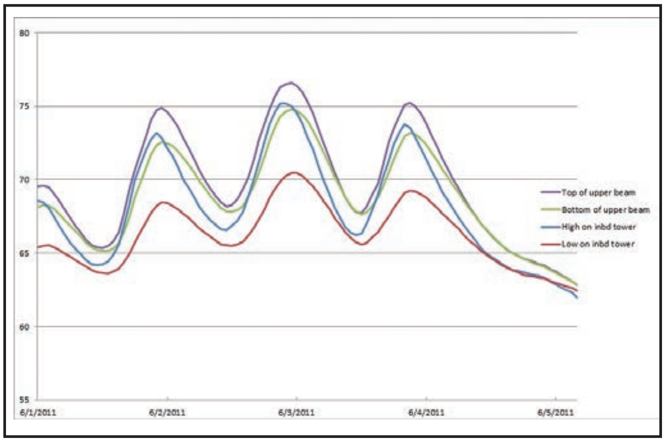

Figure 10. Hourly temperature recordings indicate a daily temperature swing of nearly 8° F.

scale bar causes 0.0015 in. of length change, so accurate temperature readings are important.

When measuring a fixture temperature, in many cases the average jig temperature will be required. For this situation apply thermistor probes at high and low points on the fixture as well at each end. Experience may show that some of these measurements can be eliminated, but initial measurements should be more comprehensive. Note the values at the beginning and end of every station. Average the measurements to establish the working jig temperature.

Sunlight can have a strong and, for practical metrology work, immediate effect on part temperature, even on very large, massive parts, as seen in figure 10. Be prepared to block sunlight, cease work during certain hours of the day, or otherwise adjust for the effect. Sunlight can also affect your station.

Methodological approach

Control network development can get complex, and it can be easy to forget a step. Write down a detailed plan for the process. This will help you identify needed equipment, find weak spots in the plan, and allow you to subject the plan to review.

Validation

How can you check your work?

- Try to understand the source of any systematic errors, even if small. Maybe a bigger error is hiding there.
- Start with a simple approach, then refine it for improved accuracy.
- If something feels "off," keep pursuing it. Something is probably wrong.
- Is there a way to rough-check your work? Take advantage of it. Compare with last year's data or data taken by others in the past.
- Split the stations into two geometrically balanced sets. Bundle them individually and compare them to each other. Because these are completely independent data sets, they will provide a good test for the system's accuracy.
- Is a second laser tracker available? Use it for some of the stations.

Temperature-controlled environments

It is worth noting that many of the above issues, and other, more complex thermal problems, may be avoided or minimized by using a temperature-controlled environment. Experience in sites featuring high daily temperature swings has consistently shown such sites to be more challenging measurement environments. Conversely, metrology work in cleanrooms, where temperatures are tightly controlled, have borne out expectations of more stable parts, machines, and lower uncertainties for instrument stations. With very large parts featuring tight tolerances, it may prove a good investment to control temperatures.

FUTURE EXPLORATIONS

Several interesting questions arose during the course of this project, which could be the subjects of future studies. What are the thermal gradients within a foundation? How much do these vary with air temperature changes? Is foundation shape truly constant, or does it vary seasonally with air temperature? What are typical vertical temperature gradients within a factory? How much do they vary seasonally? Can we generalize about such gradients, or must we measure data for each factory?

CONCLUSION

Several different jig designs were examined with respect to their behavior under thermal change. It was observed that some jig types, such as the end-constrained jig, are easier to predict for thermally caused growth than overconstrained jig types. The effect of a varying vertical thermal gradient was addressed, and one methodology for reducing its negative effect was proposed. Finally, some best practices were suggested, which, if not already implemented, should contribute to a more successful control network in the future.