Synthesizing Metrology Technologies to Reduce Engineering Time for Large CNC Machine Compensation

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ABSTRACT

Very large multi-axis CNC machines offer a special challenge for efficient and accurate machine compensation. Aerospace applications demand tight tolerances, but conventional compensation methods become expensive for large machines. Volumetric compensation offers an approach for reducing costs and improving accuracies. A unique control architecture enabled by volumetric compensation enables the use of a single part program by multiple machines. Combining multiple technologies (a proprietary volumetric compensation solver program, Spatial Analyzer, API's Active Target, a laser tracker and bespoke CNC-Tracker communication software for measurement triggering) significantly reduces machine compensation time. Available analysis tools also enable the engineer to evaluate measurement uncertainties and determine the best locations for additional stations as well as quantify the accuracy benefits such stations would offer.

INTRODUCTION

This paper is concerned with the compensation of “very large” machines. This might mean any machine with an axis travel of over about 10m, but especially includes any machine with more than about 2m of vertical travel. (Vertical travel that puts compensation measurement points out of the reach of an operator offers additional problems for efficient compensation). Some, or all, of the techniques described here have been successfully applied to a variety of geometrically different machines. These include off-the-shelf moving column floor milling machines, moving column automated fiber placement machines, gantry style automated fiber placement machines and multi-tower fastening machines with unique geometries. While the compensation process undergoes constant incremental improvement, the successful implementation with these radically different machines argues that the techniques used have broad application. Figures 1-2 show examples of machines which some or all of the techniques mentioned have been applied to.

Although the techniques described herein are aimed at machines with very large working volumes, such as in our examples, they might well apply to other machine tools. Before examining these processes it is worth looking at preconditions required for good compensation.

Figure 1. This two tower, yoke style wing assembly machine requires 6 axis compensation and features unique geometries.

Figure 2. This 5 axis moving column wing fastening machine has a working envelope far exceeding the operators reach.

SOME NECESSARY CONDITIONS FOR SUCCESS

Successful machine compensation does not happen in isolation. Many environmental and other factors come into play, and these must be considered and addressed where applicable.

FOUNDATIONS

Both long and short term machine performance is affected by something as basic as the machine foundation. A large CNC machine puts a considerable load on a foundation and may cause measureable -- and perhaps unacceptable -- deflection. Hopefully reasonable loads and allowable deflections were specified to the civil engineering team during foundation design.

But beyond the basics of design, there are other considerations for foundations. A foundation does not exist in isolation. It will be influenced by surrounding soil, nearby events, etc. Even extremely heavy machine foundations may crack during an earthquake, shifting the machine beds. Machines are frequently installed in groups or in conjunction with other projects. Earthworks next to an existing (usually newly aligned!) machine may cause significant shifting, sinking or other motion. New concrete changes shape during the curing process, especially during the first six months. These are all phenomena we have observed during installations. The environment should not be ignored in consideration of factors that will affect final machine accuracy.

A good machine foundation should include a Foundation Reference System (FRS) or metrology “control network” This is simply a set of steel laser tracker SMR nests epoxied into holes cored into the machine foundation and carefully valued. An FRS has many uses but is especially valuable in that it provides a universal reference frame that all other project systems can refer back to. Some such reference frame is essential for the most accurate metrology work, especially as the working envelope increases, as will be demonstrated later.

Instrument placement is related to the foundation design. A very large CNC machine (see Figure 3) may cause significant local foundation deflection as it moves in the X axis. Generally it will be unacceptable to have an instrument such as a laser tracker located where it will experience measurable movement as it will introduce error into the measurement session. Instruments should be checked for load-induced movement wherever it seems possible to exist.

Figure 3. Gantry style automated fiber placement machine with a large working envelope. The mass of such large machines may cause significant local foundation deflections that could affect the accuracy of a laser tracker placed nearby.

COMPENSATION METHODOLOGY

There are many methods and tools used for machine compensation. But in most cases, conventional machine compensation involves the single axis compensation of each axis, one by one. Often each axis is considered in isolation, although some CNCs have "X for Y" type compensation tables. The limitations of the traditional methods have made a volumetric approach attractive, and volumetric methods are becoming more popular, with several vendors offering volumetric compensation services.

WHY VOLUMETRIC COMPENSATION?

Moving to a volumetric compensation model offers several advantages. Some are general, while others are peculiar to a proprietary Electroimpact controls architecture, and were first implemented as a near-complete solution in 2004 in a prototype automated fiber placement machine cell. This volumetric compensation scheme yields an accurate kinematic equation that is used by the CNC in real time for machine positioning. Traditional correction tables overlaid on the CNC position commands are not used. This has a number of subtle, but important benefits. Other advantages are more directly apparent.

Improved Theoretical Compensation Model

Depending on your machine geometry and CNC you may wish to enable more compensations than you are allowed by your CNC axis-for-axis compensation tables. A volumetric approach allows implementation of a generalized compensation scheme that accounts for the entire kinematic model. It allows for compensation for all repeatable interrelations between axes. Depending on many factors such as machine geometry, types of error present, etc., this could improve the resulting machine accuracy.

Probable Reduction in Machine Compensation Time

A volumetric compensation may offer a method to significantly reduce compensation time. Many volumetric compensations can be done with a single tracker setup, whereas single axis compensation requires setup, measurement, analysis, table generation and verification for each axis.

Elimination of Mechanical Compensations Required for Certain Axes

Single axis compensation may require mechanical compensations for certain axis-for-axis compensations. Where this is the case, it may be necessary to take tedious measurements, grind corresponding unique shims, install the shims and repeat until the desired tolerance is achieved. This process could take weeks, depending on many factors, but it can be eliminated using volumetric compensation.

Enables an Enhanced Machine Controls Architecture for Complex Machine Cells

Another advantage offered by volumetric compensation is more difficult to grasp, yet is significant. Volumetric compensation allows the synthesis of several features and ultimately enables an enhanced machine controls architecture. This becomes important where multiple machines must operate together on a single part. It allows the use of a common coordinate frame among multiple machines, with no unique offsets, which in turn allows the same part transform to be used for all machines in the cell, and, finally, permits decoupling of machines in a cell. Multiple machines working on a single part can now be decoupled in operation. Failure or stopping of one machine does not impact the second machine. This is a tremendous advantage for automated fiber placement (AFP) machines, and no doubt, some other types of CNC operations.

Enables Single Part Program for Multiple Machines and Multiple Machine Cells

A unique and significant benefit to volumetric compensation scheme/controls architecture is that only one part program is required for a given part, for all machines. There are a number of cases -- all of which except the left/right example are already impacting production situations -- where this is of great advantage:

• Identical machines on opposite sides of a part

• Left and right handed machines on a single part

• Multiple machine cells all working on the same part

• New machine designs building the same part as an existing machine

Having a single part program for all of these cases is a very positive advantage in terms of programming hours, part program version management and debugging time, especially for extremely large, extraordinarily complex parts such as a fuselage section.

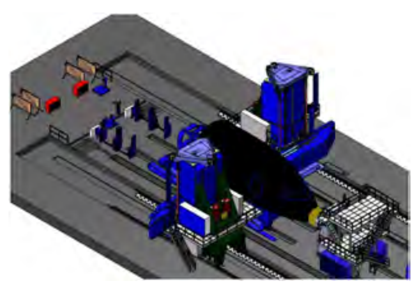

Figure 4. Rotator with AFP machine on either side. Decoupled controls architecture allows either machine to act independently of the other.

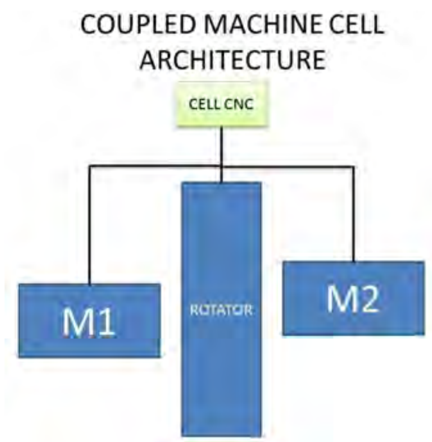

Figure 5. Traditional, coupled machine architecture.

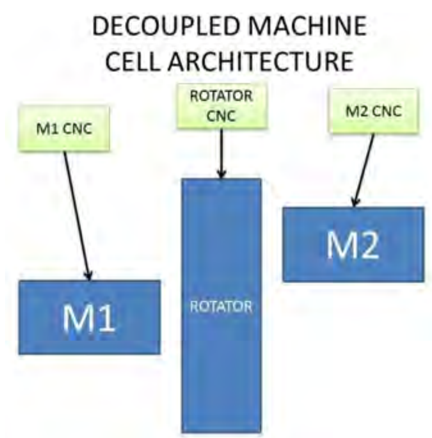

Figure 6. Decoupled machine architecture, enabled by multiple technologies, including volumetric compensation.

The three figures (Figures 4, 5 and 6) above show an existing machine cell and two distinct control architectures that have been implemented for the identical machine cell. The decoupled scheme has proven in practice to offer the distinct advantages noted, i.e. independent operation of M1 and M2 and identical part programs for both machines.

In short, there are several reasons to consider using a volumetric compensation scheme instead of a single axis: To improve accuracy, to reduce compensation time and for some multiple machine cells, a common part program and decoupled machine operation. On the other hand, volumetric compensation does pose challenges.

CHALLENGES OF VOLUMETRIC COMPENSATION FOR LARGE MACHINES

The benefits of volumetric compensation do not eliminate the difficulties in implementing it for large machines. How is the data taken and processed? How can we rapidly take the required measurements when we cannot reach the toolpoint? How can we effectively trigger a measurement? How can we plan our shoot so as to improve system accuracy?

VOLUMETRIC SOLUTIONS

There are several CNC manufacturers whose controllers support volumetric compensation solutions. Electroimpact developed a proprietary Solver and implemented the machine kinematics via a FANUC customer board. The details of these are unique to Electroimpact and will not be addressed in this paper, however, a number of the methods and techniques are applicable very broadly to machine compensation.

REDUCING TRACKER MEASUREMENT TIME

A large machine may require 1000 points or more to generate adequate compensation data. What tools are available to minimize this measure time? These include both hardware and software.

Active Target

The Active Target (see Figure 7) is an off the shelf self-positioning SMR that automatically “looks” or maintains its reflection axis oriented towards the laser tracker. This device is extremely useful when measured points are out of the reach of the operator, since the alternatives for changing the SMR angle (e.g., operator on a boom lift or ladder) are very slow and prone to cause interruptions due to positioning error in aiming the SMR. It is also helpful where the machine motion requires frequent adjustment of the SMR aiming angle, since the use of the Active Target obviates the need for this manual and error-prone process.

Figure 7. The Active Target is a tool that should not be overlooked when compensating very large machine tools.

Figure 8. There is no hope of an easy reach to the toolpoint on this moving column style automated fiber placement machine with its 6.4m (21') of vertical stroke. The Active Target becomes very useful when it is time to compensate this machine.

Improved Triggers

Watching a new machine move through a set of compensation points palls pretty quickly and when measuring hundreds of points manually, the tracker or machine operator are bound to hit a button at the wrong moment and require time consuming corrections. A series of triggering solutions are available to address this problem.

Spatial Analyzer's Stable Point To SA

The metrology program Spatial Analyzer has a "measurement profile" called "Stable Point To SA" (see Figure 11) which automatically measured a point after each machine movement stabilizes to a position.

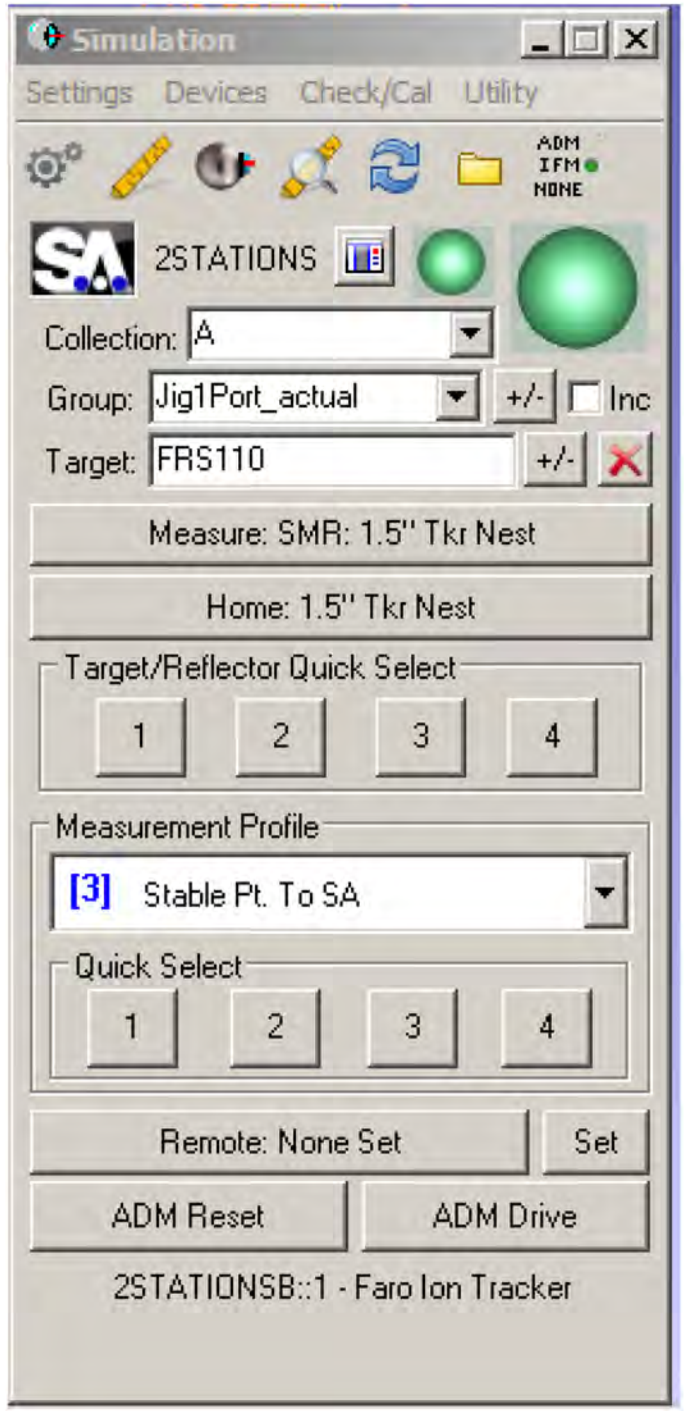

Figure 9. The SA measurement window has a "Stable Pt To SA" tool that is especially useful for machine compensation.

The CNC is programmed to wait the estimated maximum possible measure time required by the tracker prior to making each move. This is a simple and fairly effective method for automated measurement. The disadvantage is that the process does not allow for a convenient way to do an out of process move without triggering unwanted measurements. Nor does it allow for an easy way to pause the process should something go wrong.

CNC Software "Measure" Keys

Another method is to use the CNC to send a trigger message to the tracker PC to "press" the MEASURE button on the metrology software through an output relay. This has been successfully implemented via a Swifty USB interface key that converts the dry contact output into a USB input to the PC. This approach is quite functional, but again, inflexible, since the CNC must "assume" that the measure event was successful and gets no feedback from the tracker PC.

Both of the above methods suffer in that rely on determining and running against the longest possible measure time. With some laser trackers, at least, this is significantly variable and the unnecessary dwell time adds to the measurement session. In addition, with any instrument the unexpected may occur, requiring manual intervention in the measurement process. The CNC has no knowledge of such manual intervention and must be manually stopped, resulting in lost time and possible missing or duplication of measured points.

Closed Loop Tracker Trigger

A more effective method for measurement triggering uses a custom software solution (see Figure 12) that closes the loop between the tracker PC and the CNC via Ethernet connection. The CNC commands a measurement only when it is in position and the PC acknowledges that it is ready for a new move the instant the metrology software records a completed measurement. This closed loop trigger approach allows for easy handling of interruptions to the process, reduces measurement errors, records measured points and reduces overall measurement time significantly. Although this solution is proprietary to Electroimpact and designed for Spatial Analyzer and FANUC CNCs, a similar tool could be developed for any CNC.

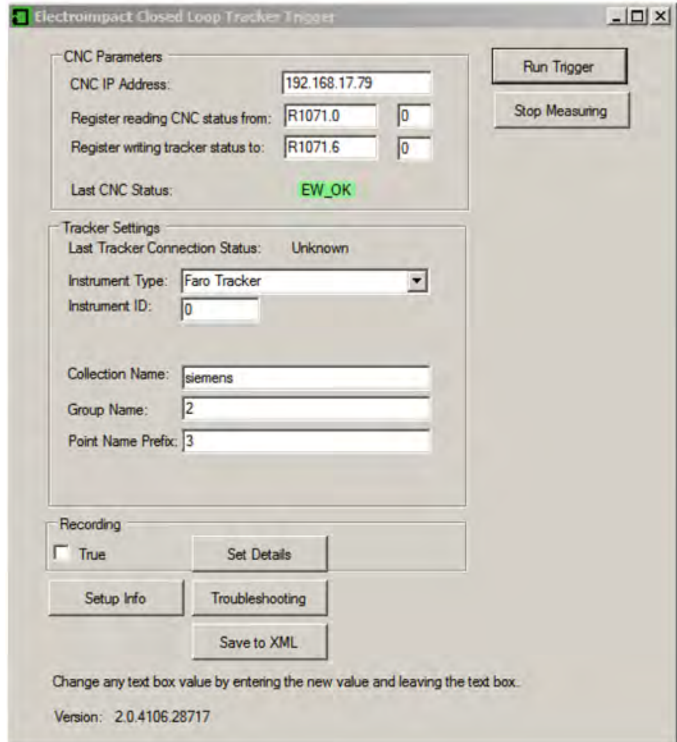

Figure 10. This Electroimpact Closed Loop Tracker Trigger program facilitates two way Ethernet communication between a FANUC CNC and a tracker PC running Spatial Analyzer.

IMPROVING ACCURACY

For some large machine cells it may be possible to improve the quality of the machine compensation through the use of multiple tracker stations. The use of multiple stations will allow programs like FARO Insight or Spatial Analyzer to "bundle" the measurements, a mathematical procedure that finds the optimal location for every point in the bundle while weighting the calculations to the strengths of the instrument used. The result can be a significant improvement in accuracy of the measurements. However, the use of additional stations is time consuming, and it is useful to analyze the impact of each proposed additional station on the uncertainty of the measurements to determine whether or not the addition of the station is worthwhile.

UNCERTAINTY ANALYSIS WITH SPATIAL ANALYZER

Spatial Analyzer offers tools for approximating the uncertainty of given measurements. This allows the engineer to test and evaluate a prospective metrology plan, that is, to propose one or more instrument locations, establish target locations, simulate measurements to those targets and approximate the resulting uncertainty for measuring those targets. The simulation process enables the engineer to move beyond time consuming trial and error and permits the quantitative evaluation of a metrology plan.

Spatial Analyzer Steps in Brief

• Create the hypothetical FRS points.

• Create the proposed machine compensation points.

• Add instruments (stations) which will be used to value the FRS points.

• Add instruments (stations) which will be used to value the compensation points.

• For each instrument create point group(s) containing all points which will be measured by that instrument (these will share the same names as the points already created, but each instrument needs its own set of points to populate with simulated measurements).

• Fabricate measurements (injecting error that falls within the instrument uncertainty for your instrument) for each instrument for those point groups which it will measure.

At this point you have simulated the real life process of setting up the instrument, taking measurements of all points, moving to the next station, measuring all points, etc., and your SA file will look just as if the measurements had been taken on site.

• Now run a Unified Spatial Metrology Analysis (USMN). After solving, select the BEGIN button to do the Uncertainty Field Analysis. Increasing the time limit may be necessary to improve accuracy.

• Apply the USMN results to create a USMN Composite group. This group represents the measured values of each of the points of interest. Each point can be examined for the approximated uncertainty for its measurement. Average uncertainties for point groups are also calculated.

See Figure 9 at the end of this paper for a view of the SA window for USMN.

Uncertainty Analysis of a Machine Cell for Machine Compensation

Using the method described above we may consider several measurement plans for a hypothetical 40m long machine cell, each with a differing number of laser tracker stations. See Figure 12 (at the end of this paper) for the uncertainty analysis for this 40m cell using a single laser tracker. In this case the tracker is place at one extreme end of the cell, as might be required in some circumstances. Note that the size of the uncertainty clouds (exaggerated for visibility) grows considerably at the far end of the cell, reaching a maximum of 0.29mm (0.011″). How might we improve our compensation measurement accuracy for this cell?

Adding a second instrument station to the metrology plan significantly reduces the measurement uncertainty. (See Figure 13 at the end of the paper). The resulting maximum uncertainty is now found in the center of the cell, furthest from either instrument, and is now 0.11mm (0.004″), or 38% of the uncertainty for a single station.

The results can be further improved with a third station. (See Figure 14 at the end of the paper). Maximum uncertainty is now 0.062mm (0.0024″) or 21% of the uncertainty for a single station.

Using the uncertainty analysis tools in SA provides a useful way to quantitatively evaluate uncertainty for a variety of "what if" scenarios. Uncertainty analysis should be part of the engineer's toolbox for machine compensation.

VALIDATION AND LONGEVITY OF COMPENSATION SOLUTIONS

Validation of the compensated solution is provided via the random points measured as part of the measurement session. The random points are not used to generate a solution, but once the kinematic equations are generated the compensated point locations are compared with the measured locations. This comparison yields an excellent evaluation of the quality of the measurement session and kinematic solution. Independent post-compensation tracker measurements have confirmed that the random point comparison can be relied upon as a test of the solution.

Compensations have a limited useful life. Machine kinematics change slightly over time, therefore to maintain machine accuracy a new volumetric compensation is required. Experience has shown that large machines drift or settle, and should be compensated about six months after installation and then annually. What is causing this settling? Foundation shrinkage due to curing concrete is one factor. But the different factors are not well understood and the changes are subtle enough so as to be difficult to identify and isolate.

SUMMARY

Judicious use of available technologies, especially combined with custom software solutions, can reduce alignment and measurement time for machine compensation and improve resulting accuracy. Volumetric compensation offers special advantages of a more complete compensation model and has more potential for reducing overall compensation time. Off the shelf tools give the engineer the capability to evaluate the uncertainty for his proposed measurement plan, and test it against other schemes before choosing the best to implement.

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DEFINITIONS/ABBREVIATIONS

SMR
Sphere Mounted Retroreflector

BMR
Ball Mounted Retroreflecto

FRS
Foundation Reference System

APPENDIX

ADDITIONAL FIGURES

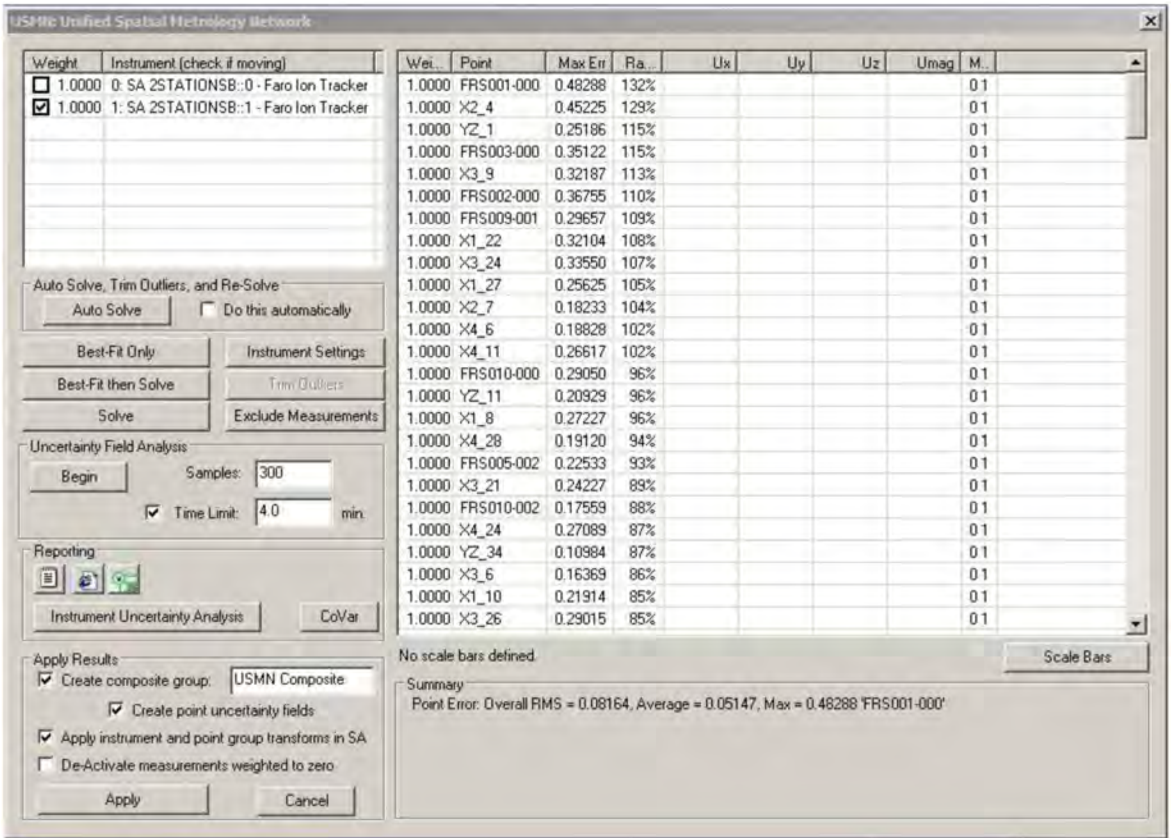

Figure 11. Running USMN Analysis in Spatial Analyzer.

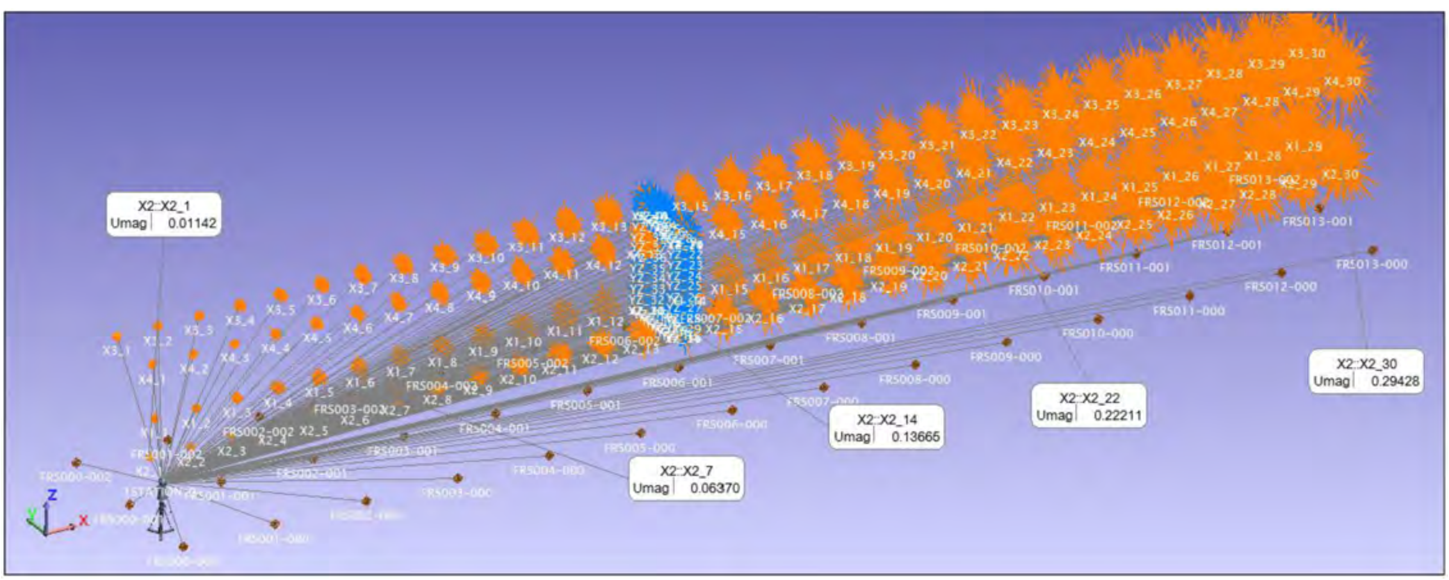

Figure 12. Uncertainty analysis of a single laser tracker station placed at the end of a 40m long cell. The increasing size of the uncertainty cloud reflects the magnitude and shape of the uncertainty measurements for that point.

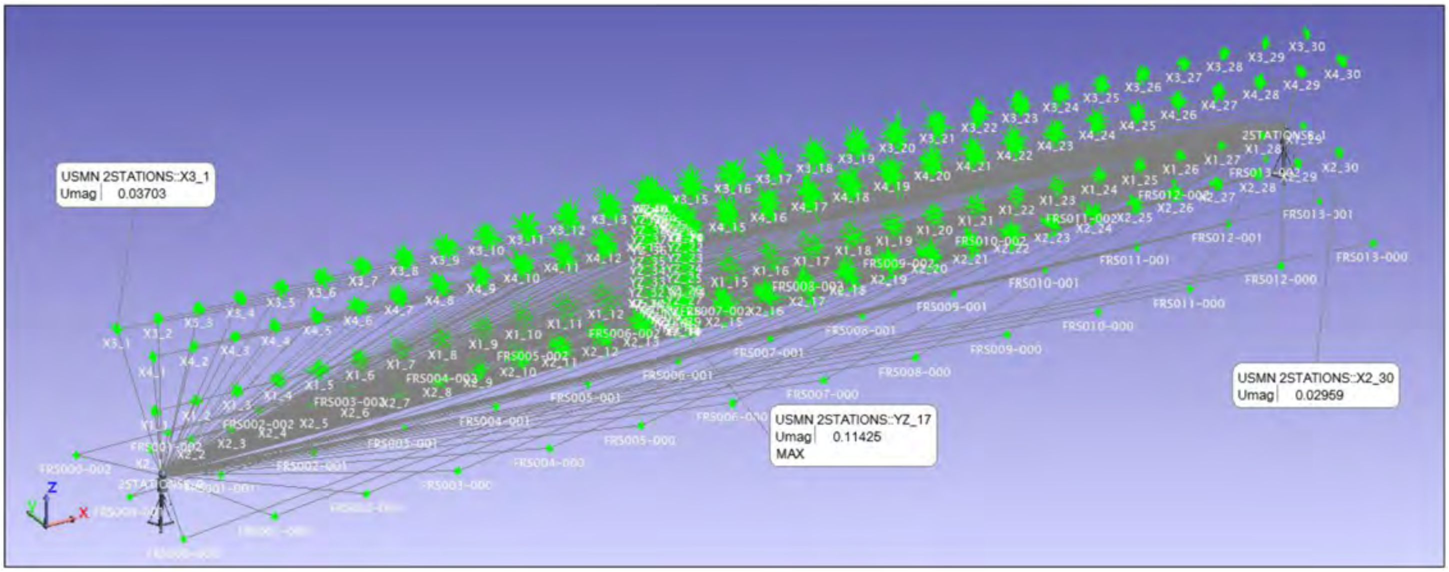

Figure 13. Uncertainty analysis of the previous cell, using a tracker station at each end of the cell. Error is now reasonable at both ends but unacceptable in the center.

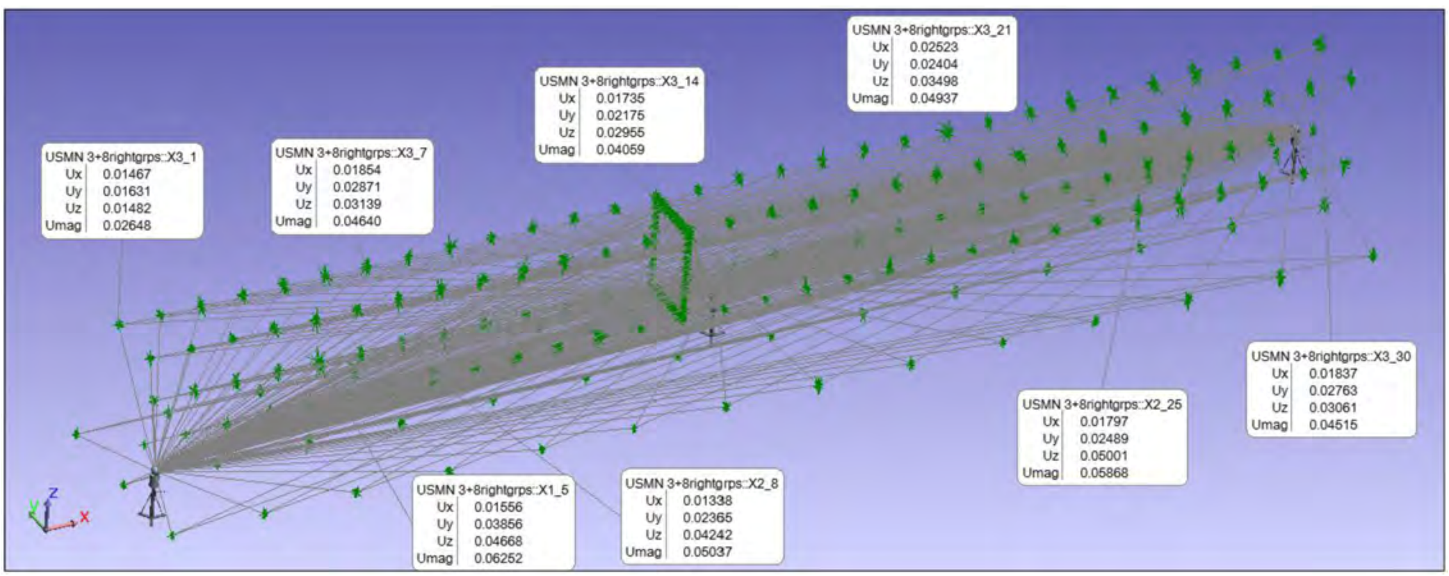

Figure 14. Uncertainty analysis of the previous cell, using 3 tracker stations. Uncertainty is now limited to about 0.07mm (. 0028") throughout the working envelope.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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