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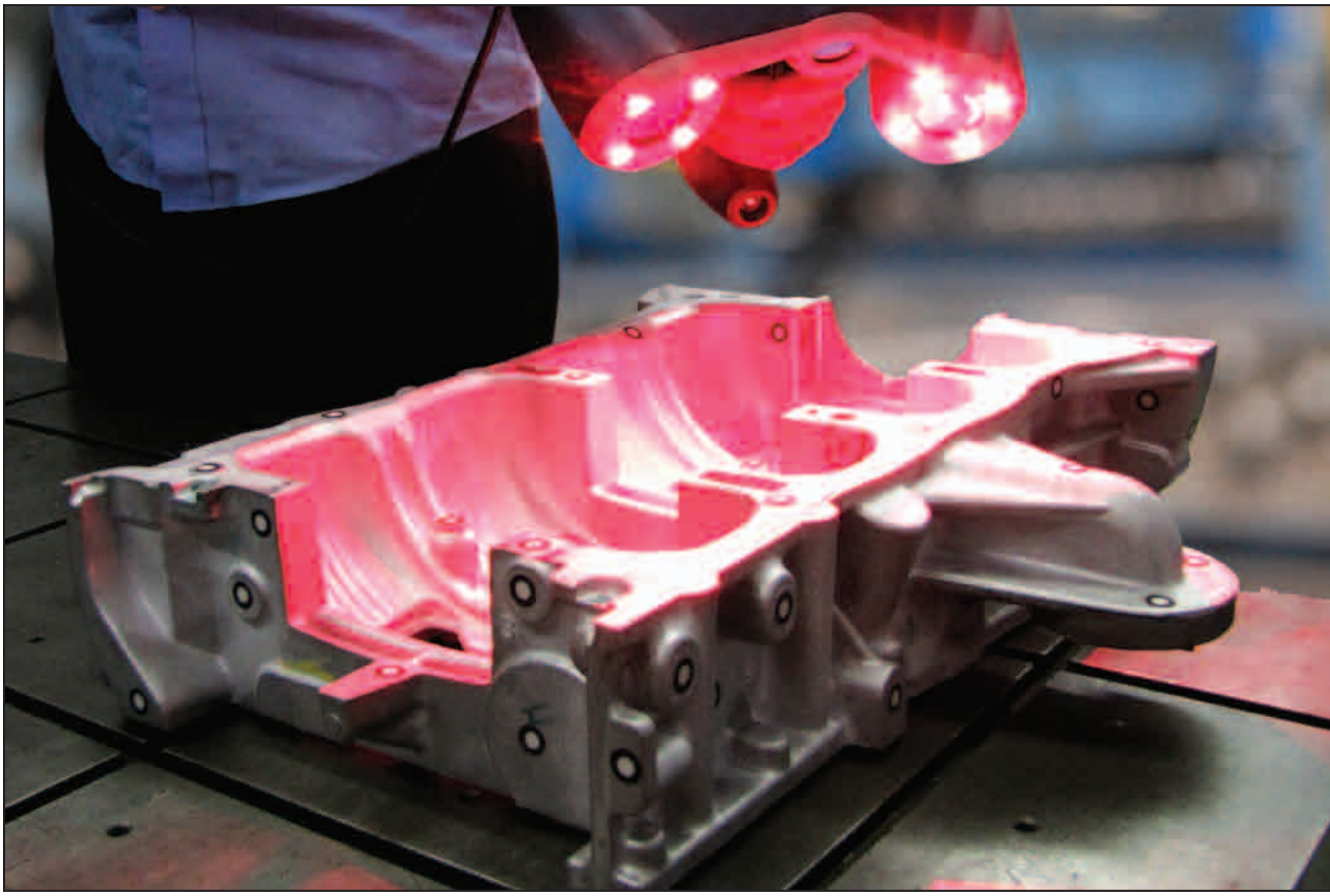

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Reducing Engineering Time for Compensation of Large CNC Machines

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Machine compensation challenges increase with machine size. Increased production of large CNC machines led to the pursuit of improved methods for machine compensation. These methods included the use of volumetric compensation, implementation of a custom software solver tool, the use of API's Active Target, the development of various laser tracker triggering tools, and eventually a custom software solution for communication between the CNC and tracker PC. The resulting process reduces station time for taking measurements, eliminates many blunder points, increases process flexibility, and reduces post-measurement analysis, as well as decreases overall engineering time.

INTRODUCTION

Large CNC machines require compensation to achieve improved accuracies. Recent years have seen the development and wider implementation of volumetric compensation, which offers a number of benefits, including improved accuracy and potentially reduced compensation times. Other tools can enhance the advantages of volumetric compensation. CNC software maintenance screen tools simplify the process for new or infrequent users. Improved triggering methods decrease actual measurement time and eliminate many measurement blunders, which in turn reduces engineering analysis time. The use of metrology software featuring uncertainty analysis tools enables the engineer to analyze the benefits of the use of additional instrument stations and make rational trade-offs between the number and location of stations and the desired accuracy. Combining these different technologies can reduce overall compensation time while improving compensation accuracy.

ERROR SOURCES AND COMPENSATION TYPES

There are many sources for machine error in a typical CNC machine. Variable errors, which are errors that cause the tool-point to not repeat when commanded to a point from different initial conditions (i.e., dynamic deflections, gear backlash, or other transient effects) cannot be corrected with the types of compensation schemes discussed here. Transient errors are beyond the scope of this discussion. However, it is usually possible to nearly eliminate these variable errors through good machine design, resulting in a machine with highly repeatable, if inaccurate, tool-point positioning. Given such a (typically) well-designed machine, the machine builder has several choices to improve accuracy, including mechanical compensation, single-axis compensation, and volumetric compensation.

Mechanical compensation can be done for some conditions. For example, if a machine *Y* axis is required to be perpendicular to the *X* axis but is slightly off, this condition might be corrected by careful measurement, and the correction via ground shims. Although this method is sound, it is also very tedious, especially for a large machine, and may take weeks to correct a single axis.

Software compensation is an attractive alternative to mechanical compensation. With traditional single-axis software compensation, a precision instrument—often a stationary-beam laser interferometer—is used to measure an array of point positions, and these are then compared to the commanded position to generate a compensation table for that axis. For example, a CNC machine with a long *X* axis commonly requires multiple gear racks placed end-to-end to provide *X*-axis motion, and single-axis compensation does an excellent job addressing the errors caused by imperfections in the rack segments and their spacing.

However, there are “secondary” errors that might not be addressed by this compensation scheme. For example, as a machine travels in the *X* axis, imperfections in the rails cause both *Y* and *Z* tool-point error, even if the *X* axis is perfectly compensated, as seen in figure 1. With certain CNC controllers some of these “secondary” errors may be addressed through the use of additional tables. However, a limited number of tables, time, and measurement capability may make it difficult or impossible to compensate for all errors with this methodology. Volumetric compensation bypasses these difficulties.

Volumetric compensation is achieved by creating an error map of the tool-point throughout the volume of the machine, including motions for all axes of motion, linear and rotational. The resulting error map is sent to a linear numerical solver, which calculates the optimal kinematic parameters to minimize the error at all the mapped points. Random points are also collected throughout the error map and the post-correction position is checked at these points to yield a predicted error. If a blunder is made during data collection (e.g., the tracker is bumped) then the solver will not be able to generate a good solution and a bad compensation will not be applied. A good solution will immediately be validated by the random point check. It is very important to note that the quality of the solution is directly related to the accuracy of the data. The solver cannot resolve discrepancies due to measurement error.

IMPLEMENTING VOLUMETRIC COMPENSATION

Volumetric compensation of machine tools is a recent methodology. Implementation details will depend on the CNC controller and on the software used to implement it, and these details are outside the scope of this article. (See the “References” section at the end of this article for a list of some of the companies involved with volumetric compensation.) Once the compensation scheme is set up, we arrive at a question of how to best take the required measurements. For volumetric compensation this will typically be done with a laser tracker. Experience has revealed several recurring problems in compensation metrology revolving around targeting, triggering, and accuracy.

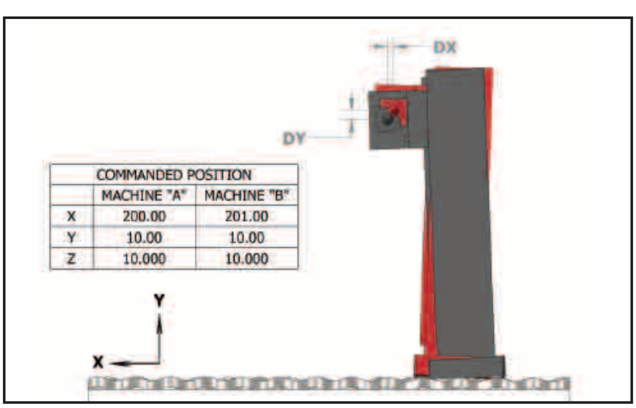

Figure 1. Slight variations in machine rail cause X, Y, and Z axis errors when moving in X (Illustrated by Ben Todd)

Figure 2. Large machines make it difficult to aim targeting throughout elevated parts of the work envelope

TARGETING

Tool-point targeting is a challenge for large machine tools. Often the system will require that the machine move past the laser tracker station, resulting in large angular changes in the pointing of the target. These angular changes are made manually, and with large machines this may require the use of a boom lift or ladder to reach the tool-point, as seen in figure 2.

This slows down the process, increases blunders, and adds to the time on station. An alternative is to use an Active Target, a self-powered, two-axis retroreflector device that automatically orients itself towards the laser tracker, as seen in figure 3. The Active Target was designed for use with an API tracker but is successfully in use on FARO trackers, also. The metrology software must support the use of the Active Target to implement a

Figure 3. The Active Target replaces a conventional SMR and automatically adjusts to keep pointing at the tracker

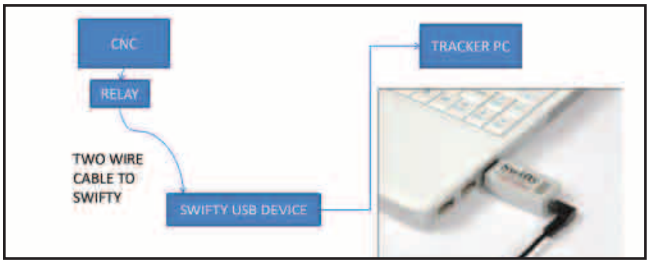

Figure 4. Swifty configuration

target offset. SpatialAnalyzer supports this target offset, and other software may as well.

TRIGGERING

Measurement triggering is another issue to resolve for large machine compensations. Typically many hundreds of measurements are required for compensation. Although it is possible to have an operator push the "measure" button for each of these, this approach is time-consuming, error-prone, and tedious. Automated triggering methods are much preferred. Automated triggering is possible through off-the-shelf software, off-the-shelf hardware, or custom software solutions.

Stable-point triggering

An easy method for automated triggering is to trigger a measurement as soon as the tracker detects that the target is stable. SpatialAnalyzer has the feature built-in in the form of a measurement method (Measure Stable Point). For this method, the CNC is programmed to make a move every so many seconds, hopefully allowing enough time for the measurement to complete for each move. The tracker detects each move to a new position and measures as soon as the target is stable. The disadvantage of this method stems from the fact that it is open loop and there is no communication between the CNC and the tracker PC. In practice there is extensive variation in actual measurement time with some trackers, so the programmed dwell time is much longer than the typical measure time. Also, with no feedback the operator must manually halt the tracker measurement sequence before making any machine move which is not to be measured.

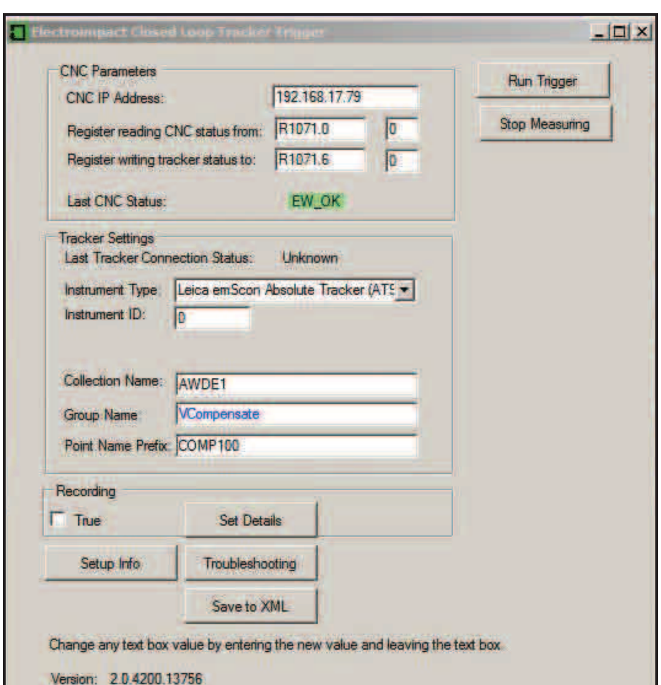

Figure 5. Closed Loop Tracker Trigger interface

CNC relay triggering

It is also possible to trigger the measurement via a relay output from the CNC. The relay output is converted to a PC USB input via a Swifty input device, as seen in figure 4. Software converts the input to a "measure" command. This method is adequate but suffers from some of the same disadvantages as stable-point triggering.

Closed Loop Tracker Trigger

Custom software offers a more complete triggering solution. For this application, a custom C# program—Closed Loop Tracker Trigger (CLTT), as seen in figure 5—was written to communicate from the tracker PC to the CNC via Ethernet cable. The software enables full two-way communication between the two systems so that a measurement is triggered by a CNC command and the machine move is triggered by a command from the tracker PC. Tracker commands are issued by the CLTT and implemented via the Measure Plan scripting language feature of Spatial Analyzer. The CLTT also can record the commanded and measured positions and write to a single line in an ASCII text file. Although requiring development time and some additional setup steps, the CLTT has been the most satisfactory triggering method implemented by Electroimpact to date.

IMPROVING ACCURACY

Having addressed triggering methods and targets, accuracy must be examined. How can measurement accuracy be improved? Aside from using best metrology practices—e.g., high-quality targets, fully calibrated trackers, appropriate number of samples/point, etc.—the most likely way to improve accuracy will be to measure each target from multiple stations. The use of multiple stations has as a prerequisite the establishment of a control network so that the different stations can be tied together.

Foundation reference system (control network)

A control network is needed when using multiple stations so that each station shares a mutual reference. The control network should be permanent (to minimize future machine compensations), it should be of adequate density for the best accuracy, and it should be very accurately valued. We have had good success with a foundation reference system (FRS), that is, monuments epoxyed into holes cored into the floor. These are placed at approximately 10-foot intervals and encompass the area of interest. The FRS should be measured from multiple tracker stations and independent datasets compared to validate them.

Station location

The first requirement for tracker station location is that it be stable and not subject to movement. Extremely large CNC machines often have a mass sufficient to cause measurable local foundation deflections, and if a station is to be placed where a foundation is subject to such loads the stability of the station

Figure 6. Large gantry automated fiber placement machine undergoing volumetric compensation—note tracker directly underneath machine. A 1.5-m-thick foundation poured on compact fill ensures a stable instrument station even under this heavy load.

must be verified. Stations should also be located to minimize shot lengths and to give good lines of sight to targets.

Multiple stations offer an opportunity for improving measurement accuracy, especially for very large volumes. But how many stations should be used? Where should they be placed? What will be the resulting accuracy? Fortunately, metrology software is available that can evaluate the uncertainty of a given point measured from multiple stations (as seen in the "References" section at the end of this article). It is a practical exercise to construct a nominal set of points representing the FRS, another representing the machine tool-point positions, and to simulate measurements to these from multiple instrument stations. Once this simulation is complete, we can now easily obtain an estimated uncertainty for any measured point in the system. These uncertainty values can quantitatively evaluate the performance of the same tracker at multiple locations. The usefulness of adding another station can be realistically evaluated. Some examples will provide clarity.

UNCERTAINTY ANALYSIS CASE STUDIES

By way of example we offer two case studies. The first is a large automated fiber placement (AFP) machine, as seen in figure 6; the second is a drilling machine with a much smaller envelope.

Case 1: AFP machine

- Moving-column AFP machine
- 19.5 m × 6.4 m × 4.2 m (64 ft × 21 ft × 14 ft) work envelope
- 1,000 points used in compensation
- One station

How much would we benefit from the use of additional stations? The average uncertainty for a single station, as seen in figure 7, is 0.064 mm (0.0025 in.), with the maximum at 0.1 mm (0.004 in.). Adding a second station, as seen in figure 8, has some effect on the average uncertainty, reducing it to 0.051 mm (0.002 in.). In this case the new station forms a large angle between itself, any measured point, and the first station, which is desirable. However, the new station is further away than it must be.

Figure 7. Single-station uncertainty for Case 1

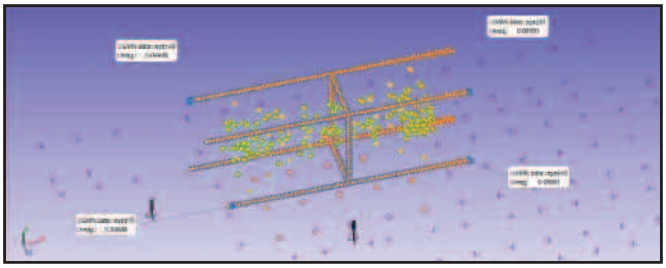

Figure 8. Two-station uncertainty for Case 1

Moving the new station in towards the centerline of the cell improves the accuracy significantly, with average uncertainty at 0.031 mm (0.0012 in.), as seen in figure 9.

Going to three stations in poor locations does not improve uncertainty significantly, coming in at 0.03 mm, as seen in figure 10.

Pulling the two new stations in closer together very mildly improves the uncertainty to 0.026 mm. It is thus difficult to improve much beyond two well-placed stations, the second station yielding a 52-percent reduction in uncertainty, while three stations reduce only to 59 percent of single-station uncertainty, as seen in figure 11.

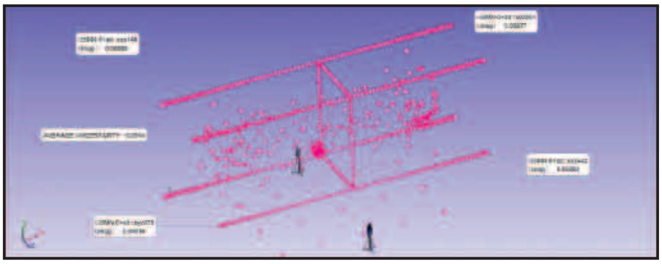

Figure 9. Alternate two-station uncertainty for Case 1

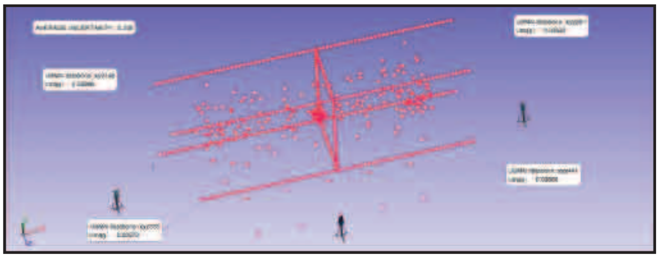

Figure 10. Uncertainties for three instruments for Case 1

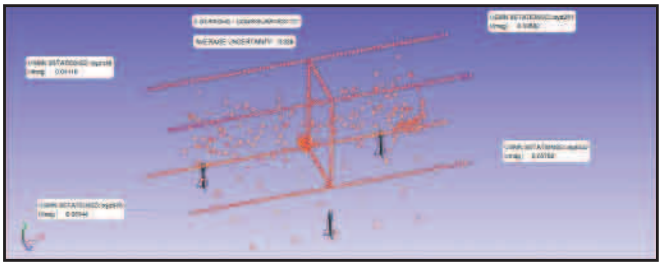

Figure 11. Uncertainty for alternate three stations for Case 1

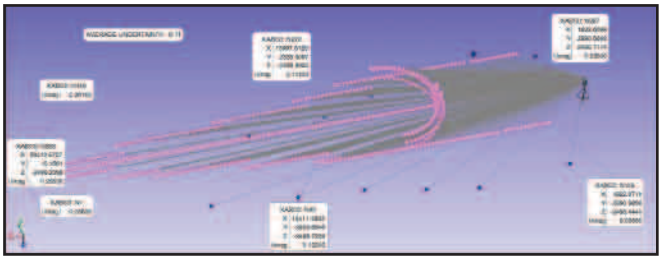

Figure 12. Uncertainty for single instrument, Case 2

Case 1 uncertainty results can be summarized on the following chart:

Point	148	254	375	442	AVERAGE
Single station	.100	.083	.064	.075	.064
2 STATIONS "A"	.044	.084	.037	.070	.051
2 STATIONS "B"	.063	.059	.048	.054	.031
3 STATIONS "C"	.029	.035	.023	.027	.030
3 STATIONS "D"	.041	.047	.031	.038	.026

This (case 1) AFP machine was compensated with a single station. The result was a predicted maximum radial error of < 0.2 mm (0.008 in.) within the work envelope of 19.5 m × 6.4 m × 4.2 m (64 ft × 21 ft × 14 ft). A second station will be considered for the next calibration, though it is necessary to do a stability check to verify that the tracker does not move when the machine passes nearby.

Case 2: Drilling machine

- Vertical drilling/fastening machine
- 34 m × 6 m × 1 m work envelope
- 700 points used in compensation
- Two stations

For this case, a single station has an average uncertainty of 0.11 mm (0.004 in.), as seen in figure 12.

Adding a second station yields an average uncertainty of 0.047 mm (0.0019 in.), as seen in figure 13.

Adding a second station yields a 55-percent drop in uncertainty, or a delta of 0.06 mm (0.002 in.).

Uncertainty analysis benefits

From these two case studies it can be seen that uncertainty analysis tools provide us a method for evaluating the quality of our compensation data, determining the value of additional sta-

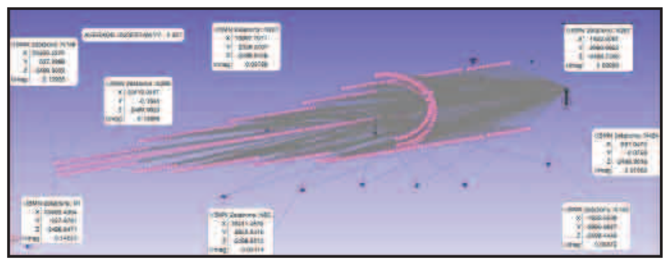

Figure 13. Uncertainty for two instruments, Case 2

tions, and reducing the measured uncertainty with a minimum amount of work. Reducing the uncertainty reduces the average point error, which in turn reduces the solution error generated by the volumetric compensation-solver program.

CONCLUSION

Volumetric compensation routines offer both an opportunity to improve the accuracy of large machine tools and a challenge in how to more quickly and accurately implement such compensation routines. The use of an Active Target, of more developed triggering techniques, and of a foundation reference system can speed the compensation process. Measured accuracy can be improved at the same time, through the use of uncertainty analysis and the selection of additional instrument stations to be used for compensation measurement. Those responsible for implementation of volumetric compensation schemes may find some of these techniques useful for their compensation tasks.

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