PRECISION MOTION IN HIGHLY ACCURATE MECHANICAL POSITIONING

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ABSTRACT

Numerous applications for antenna, radome and RCS measurements require a very accurate positioning capability to properly characterize the product being tested. Testing of weapons (missiles), guidance systems, and satellites, among other applications, require multi-axis position accuracies of a few thousandths of an inch or degree. For global positioning, spherical error volumes can be extremely small having diameters of .002 inches to .005 inches. This paper addresses the issues that must be resolved when highly accurate mechanical positioning is required. Many factors such as thermal stability, axis configuration, bearing runout and mechanical alignment can adversely affect the overall system accuracy. Additionally, when examined from a global positioning system perspective, the accuracy of the entire system is further degraded as the number of axes increases. Successful system implementation requires carefully examining and addressing the most dominant error factors. The paper will cover current tools and techniques available to characterize and correct the contributing errors in order to achieve the highest possible system level accuracy. A recently delivered 4 ft radius SNF arch scanner, which achieved ± .0043° global positioning accuracy, will provide insight into these methods and show how the dominant factors were addressed.

Keywords: Precision Motion, Three-dimensional, Near-Field, Tracking Laser, Errors, Accuracy

1. Introduction

Simple comparisons of individual product specifications such as position accuracy, load capacity and bending moment capacity do not guarantee suitability of an individual or multi-axis positioning system for a specific electro-magnetic measurement application.

When a typical statement of work is developed for a specific use or a multi-purpose measurement system, general requirements such as load capacity, speed, accuracy and others are specified to select a suitable mechanical system for the application. This is acceptable for most cases.

However, for demanding measurement applications where global positioning accuracies of a few thousandths of a degree are required, dominant factors contributing to mechanical system error must be determined and addressed.

Global positioning error or volumetric error correction has been used in the machine tool industry for years to compensate for many factors which contribute to positioning errors in a multi-axis system. These methods can be applied to antenna measurement systems to achieve significant improvements in positioning accuracy resulting in better antenna measurement data.

2. What is global positioning error?

In a multi-axis positioning system, each axis of motion must constrain or control its moving interface in six degrees-of-freedom; translation in X, Y and Z and rotation in pitch, roll and yaw. Likewise, any structural component that connects two axes together must constrain their respective interfaces relative to each other in the same six degrees-of-freedom. Geometry errors and structural compliance create errors in each degree-of-freedom for each component in a system. Upon assembly, each of these individual component errors add together to create the global positioning error. These errors may be extremely small for each component, but it is easy to see that as the number of axes increases so does the global positioning error. For this reason, high accuracy antenna measurement systems require close examination of each individual axis as well as a system wide analysis to determine the root cause of an error and how to best address it.

3. What are dominant error factors?

In multi-axis antenna positioning systems, the mechanical errors affecting system measurement accuracy are as follows:

- Mechanical alignment errors between individual axes
- Angular & linear position errors of individual axes
- Load induced deflection or resonance of the foundation, primary structures & bearings
- Thermal deflection

In the design and fabrication of a system to be utilized for high frequencies or extreme fidelity, a few instances of the above error types will usually make the largest contributions to the mechanical system error. These are referred to as “dominant error factors”.

In some cases, dominant error factors are easy to determine. For example, consider a very high accuracy positioner mounted on top of a low stiffness tower with a heavy unbalanced load. In this particular case, the high accuracy positioner is not a major source of system error. Most of the mechanical system error comes from the deflection of the tower as the unbalanced load is rotated.

The following sections will examine the various error types and discuss the means of addressing them when they are the dominant error factors in a high accuracy measurement system.

4. Mechanical Alignment

Proper mechanical alignment of an antenna measurement system is critical when trying to achieve the highest levels of accuracy. Autocollimators offer excellent accuracy, but are time consuming when compared with the latest laser tracking systems. Laser trackers allow for the measurement of individual axes relative to each other to within approximately .002” and .001° at distances up to 10 meters (32.8 ft). When carefully executed in a system designed with the appropriate resolution adjustment capability, axis intersection errors can be minimized to levels approaching the metrology measurement quality. As laser tracking technology continues to improve, the adjustable system alignment error should continue to be an ever decreasing contributor to the global positioning error.

Another source of mechanical alignment error is tolerance stack-up of a multi-axis positioner. Depending on the location of a component within a positioner assembly, a small tolerance may create a large misalignment error. For example, a probe mounting surface that has been improperly toleranced or machined may produce an angular deviation which is relatively small in magnitude, but when magnified over the distance to the antenna-under-test may produce an unacceptable position translation error.

5. Position Accuracy

MI Technologies utilizes various position feedback technologies in its antenna positioners, including synchros, optical encoders and magnetic encoders. Standard accuracy applications typically use synchro assemblies that feature an independent anti-backlash drivetrain to avoid any backlash that may be present in the positioner powertrain. For high accuracy rotary applications, optical encoders are used almost exclusively, and when possible, in an on-axis configuration. This arrangement maximizes the accuracy by eliminating all gearing in the position feedback path. The only source of backlash is the torsional wind-up of a servo class coupling between the encoder grating component and the encoder read head. Linear axes feature magnetic linear encoders that provide a robust, high accuracy solution.

Modern optical encoders offer excellent native angular accuracy (±.005°) and, generally, can be packaged into a given servo positioner with little difficulty. In some cases, due to non-standard slip ring requirements, an on-axis configuration of the encoder is not possible. Off-axis mounting can be utilized, but introduces error contributions from the position feedback geartrain. This increased error can push the positioner accuracy beyond an acceptable level. For this reason, MI Technologies is introducing new error correction methods to address these error sources. One of these methods goes beyond conventional error mapping. It applies correction filters within the servo loop to reduce repeatable errors. The filters are constructed based on spatial frequency analysis of the measured errors such that repeatable errors are corrected without contamination from unrepeatable errors. Three-fold accuracy improvements are regularly achieved with this technology. If bi-directional error mapping is conducted, accuracy improvements of up to 10X have been realized. The reader is directed to Reference [1] for a more complete discussion about this method.

In addition, error correction of a given axis can be performed not only as a function of itself, but also as a function of other axes. MI Technologies calls this a virtual axis [4]. For example, the probe aperture radius of a high accuracy spherical near-field measurement scanner needs to be held to within a very tight tolerance. Depending on the size of the minimum AUT sphere, maintaining that radius can be very difficult due to machining tolerances, bearing runout, gravitational deflection, etc. We will refer to the probe rotational axis about the antenna-under-test (AUT) as the theta axis. With the use of a virtual axis, a linear probe positioner, or radial axis, can be incorporated that automatically moves the probe aperture to the desired radius as the probe is rotated about the theta axis. The desired probe radius is then maintained to within the sum of the laser tracker and radial axis error, instead of the native mechanically constrained theta axis error.

Another aspect of position accuracy depends on how the antenna measurement system will function. Namely, which axes are to be stepped and which axes are to be scanned during a measurement acquisition. A scanned axis in a high accuracy system must have high position readout accuracy. Position readout accuracy is defined as the accuracy of the indicated positioner location at a given point in time. For scanned axis acquisitions, the only mechanical requirements for a proper measurement are an accurate servo axis position and an accurate timestamp that coincides with the measurement. A stepped axis, in contrast, must have high position readout accuracy as well as high positioning accuracy. Positioning accuracy is defined as the ability of a positioner with an inertial load to settle to a commanded position within a given amount of time. The positioning accuracy can only be as good as the position readout accuracy in a given positioner. A positioner with high position readout accuracy may have poor positioning accuracy due to backlash or servo loop instability.

Backlash can be minimized through the use of high quality gearing and low backlash servo class gearboxes and couplings. In cases where extremely low backlash is required, a torque-biased servo axis may be necessary. A torque-biased servo axis incorporates two independent servo drivetrains that are controlled in conjunction with each other. One drivetrain is biased against the other any time the axis is commanded to be at a static position. By doing this, the servo axis is locked at a known position and any drivetrain backlash is effectively eliminated.

Servo instability can also limit the positioning accuracy of an axis. The axis may not be able to settle at the desired location, instead overshooting and crossing over the location indefinitely. The positioning system should be mechanically designed so that the ratio of the reflected load inertia to the motor inertia is no more than 10:1, if possible, for each servo motor of the system. The locked rotor natural frequency of each servo axis of the system should also be maximized to aid in the ability to tune each servo axis. The minimum value a designer should strive for is highly dependent on the function of the given axis, but should generally be 2-3 times the required frequency response of the given axis. These two criteria, along with the backlash, will dictate the ease with which accurate positioning of a servo axis can be achieved.

6. Load Induced Deflection or Resonance

Load induced deflection and/or resonance can severely limit the overall fidelity of a measurement system, even if all other aspects of the system are ideal. A load induced deflection can come from gravitational loads, inertial loads or, what we will call, geometry error loads. Gravitational loads are simply loads on the positioner due to gravity. Inertial loads are loads induced by the acceleration of one or more axes of the positioner. Geometry error loads are those created by out-of-tolerance irregularities in the geometry of the components of the positioner. An example might be a bearing mounting surface that is out-of-tolerance. Depending on the stiffness of the bearing housing and the bearing, both will deform proportionally, pulling both components out of their intended positions. These load induced deflections are frequently dominant error factors. Great care must be exercised in the design and analysis of a high accuracy positioner to control these error sources. Static finite element analyses should be conducted to examine the various gravitational and inertial load conditions that will occur on a given positioner to design in the necessary stiffness. Geometry error loads should be prevented through pre-assembly inspection to capture critical parts that are out of tolerance prior to assembly. When possible, bearing and component stiffness values should be verified through vendor data or load testing. Inability to meet system accuracy requirements based on one out of specification component is not something to find after an extensive alignment effort has already been conducted.

Resonance of a positioning system can occur if the natural frequency of one or more components of the system is low enough to be excited by movement of one of the axes or from vibrations transmitted through the foundation. Modal finite element analyses should be performed to determine what the various modal frequencies are, where they are taking place on the positioner and what the mass participation is at each frequency. Mass participation is the percentage of total mass in which vibration will be induced at the given excitation frequency. If a given modal frequency has very low mass participation and it’s determined to be a non-critical component, it can likely be ignored. If a modal frequency shows that a critical element of the system is going to be excited at a very low frequency, .5 Hz for instance, design modifications should be considered to increase the stiffness if possible.

Many deflection and resonance issues can be avoided by careful selection and stacking of the various required axes of motion. As mentioned previously, minimizing the global positioning error for a positioner requires minimizing the number of axes and carefully configuring each individual axis. Due to continuous improvements in technology and cost reduction efforts, more motorized axes or manual axes can be added at lower cost than ever before. However, adding motorized or manual axes purely for the sake of convenience without careful consideration of the impact to the overall system accuracy will bring undesired results. For applications such as spherical near-field measurement, mechanical alignment between the azimuth and roll axes of the AUT positioner is critical. The acceptable intersection error between the two axes is a function of the quality factor of the measurement frequency wavelength. To minimize the intersection error, effort should be placed on reducing the number of axes added for convenience purposes between the azimuth and roll axes as much as possible. Eliminating these non-essential axes eases the initial alignment and reduces the overall structural compliance of the positioner. An additional reduction in structural compliance could be achieved by simply placing a riser below the azimuth positioner and decreasing the length of the mast between the azimuth positioner and the roll axis. The antenna deflections that occur based on moments applied to the roll axis are a function of the square of the mast length. Simply stated, reducing the mast length to half of its original length decreases the induced deflections by 75%.

Foundation stiffness is also very important. Foundations and the attachment components should be significantly stiffer than the positioner being mounted. Due to simple geometry, a small level of mechanical compliance in foundation and its anchors can be multiplied by a factor of 10 or higher depending on the size of positioner mounted on the foundation. Careful design and load analysis of the foundation is required to minimize measurement errors due to foundation deflection.

In some applications, the dominant error factor can be ground vibration. If not properly addressed, the benefit of purchasing a high accuracy positioning system will not be realized in the fidelity of the measurement. In high frequency or imaging applications, minimizing unwanted random vibration is critical to a high fidelity measurement. The correct site selection for a high fidelity measurement system is crucial. Proximity to vibration sources such as highways or railroads must be taken into account. For some systems, isolation of the antenna measurement system foundation from an external foundation is necessary. This isolation pad can be accomplished through use of an elastomeric barrier between the two foundations. Civil engineers should be consulted for this level of effort to ensure that the foundation will remain sound after initial installation.

MI Technologies follows the well documented foundation vibration requirement, Institute of Environmental Sciences Standard IES-RP-CC012.1 Criterion VC-A. As a point of reference, this standard would ensure a usable vibration environment for a 400X optical microscope used to resolve an 8 micron feature.

7. Thermal Deflection

It can be easy to overlook the potential effect of environmental variation when creating the specifications for a high accuracy measurement system. For outdoor applications, the environmental factors such as wind, solar loading, ground vibration and rain inhibit the ability to make high accuracy measurements of the fidelity this paper is addressing. Therefore, we will concentrate strictly on the factors which affect indoor measurement applications.

HVAC (heating ventilation and air conditioning) systems must be installed to tightly control temperature and humidity for high accuracy antenna measurements. A standard HVAC system properly sized for a chamber will provide adequate temperature control for standard measurement applications to within approximately ± 5.0° F. High accuracy measurement systems, however, require temperature control to within ± 2.0° F, and ideally ± 1.0° F. It is important to understand the effects of temperature variation and why strict temperature control is crucial. Most conventional positioner structures are fabricated using aluminum or steel primary structures. They are manufactured by welding, stress relieving and post machining the structure to achieve the necessary accuracies for critical interface surfaces. Positioner structures should be analyzed and designed to maintain acceptable alignment accuracy within the thermal variation limits of the chamber. Careful material selection is required to limit expansion and contraction of the various components across the temperature range. The behavior of engineering materials undergoing temperature variation is described by a property referred to as the coefficient of thermal expansion (CTE). The CTE indicates the linear change in length a material will undergo for a given change in temperature. Below are some typical CTE values of various engineering materials [2]:

- Concrete: 5.6 – 7.6 μin/in °F
- Steel: 5.5 – 6.5 μin/in °F
- Aluminum: 11 – 13.5 μin/in °F
- Stainless Steel: 5.6 – 9.5 μin/in °F
- Carbon Composite: 1.0 – 2.0 μin/in °F

Steel is the most economical structural material which offers a good combination of thermal stability, strength, stiffness and cost efficiency. For many components, such as gearbox housings, probes and probe attachment components, aluminum is the optimal material based on its lower density when compared to steel. But, as can be seen from the values above, care must be exercised when combining aluminum components with those of steel in a high fidelity measurement system. For a given temperature change, the expansion of aluminum components will be twice that of their steel counterparts. However, with proper engineering analysis and design, the balance of temperature control and material selection can be optimized for maximum system accuracy.

8. Methods to address global positioning errors

A recently delivered high accuracy spherical near-field system, as seen in Figure 1, will serve as an example of what level of precision mechanical alignment and accuracy can be achieved by following the techniques and practices given in this paper. The system consists of a

3-axis scanner carrying the probe and an azimuth axis under the AUT.

Based on the desired system measurement accuracy, an error budget was derived that yielded the mechanical accuracy and alignment specifications that are summarized below with each associated test result [3].

Axis Description	Accuracy Specification	Achieved Values
Azimuth	± 0.0025° RMS	± 0.002° RMS
Theta	± 0.0025° RMS	± 0.002° RMS
Polarization	± 0.01° RMS	± 0.002° RMS
Radial	± 0.001 "	+0/-0.0015"
Non-Intersection of Phi and Theta Axes	<= 0.005"	.0012"
Orthogonality of Phi and Theta Axes	90 ± 0.003°	90 ± 0.009°
Great Circle Error (Goal)	.0035° RMS	0.0043° RMS

Table 1 – System Alignment Specification & Results

In addition to the more common accuracy specifications, a great circle error goal is also listed. The great circle error is, essentially, the angular misalignment of the probe aperture location on the measurement sphere relative to its theoretically ideal location [3]. This error value encompasses the entire system due to the fact that the measurement sphere coordinate system is created from the best fit azimuth and theta rotation axes. Any error source that creates angular error in either of these measurements will contribute to great circle error. These could be as simple as position feedback errors or more complex sources such load induced deflections on the probe assembly.

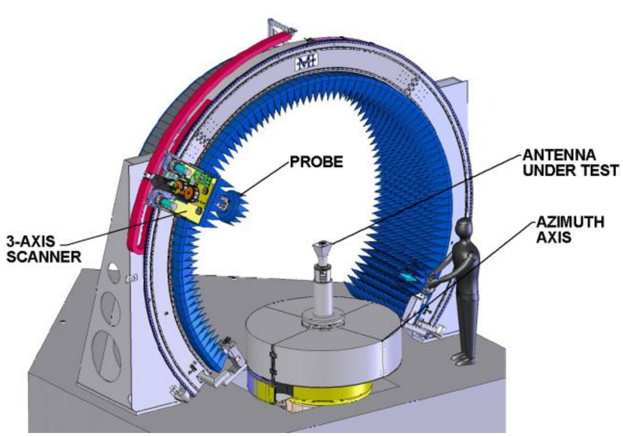

Figure 1 – SNF Isometric View

The chamber incorporates a single isolation pad on which the scanner and azimuth positioner are mounted. This design minimizes any relative movement of one positioner relative to the other. Seismic measurements were taken prior to installation to confirm that no unwanted vibrations reach the system. In addition to the special foundation, the HVAC system tightly controls the temperature to within ± 1° F. This controls any expansion and contraction movements of the system as well as temperature induced drift of the tracking laser during initial and recurring calibrations.

The azimuth axis utilizes a torque-biased servo drive with a preloaded, high precision bearing to control backlash and features an on-axis optical encoder for position feedback. The positioner is based on a standard unit rated for 30,000 lbs. The positioner was purposely over-sized to minimize deflection under the actual payload of approximately 1,200 lbs. The resulting accuracy plot for the azimuth axis is shown below in Figure 2.

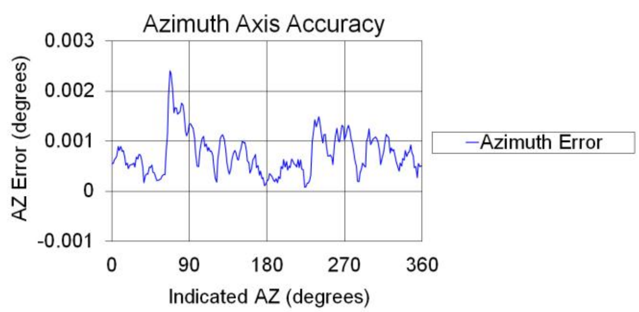

Figure 2 – Azimuth Accuracy

The probe scanner, as shown in Figure 3, incorporates a curved rack and pinion servo axis (theta) for travel along the arch, a radial axis and a polarization axis. All three axes incorporate encoder position feedback and preloaded bearing systems throughout. The theta axis also incorporates a torque-biased drive to address the rack and pinion backlash.

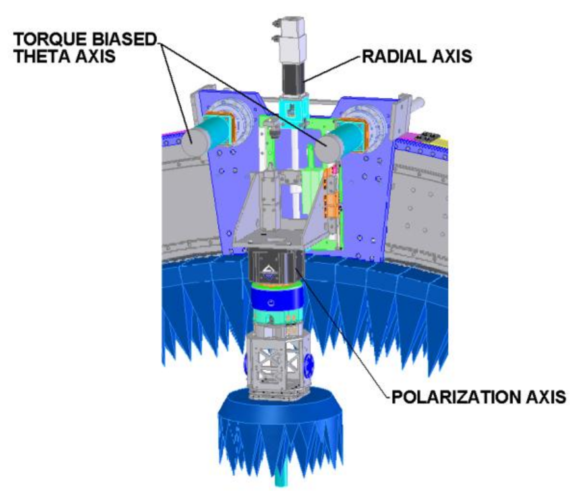

Figure 3 – Probe Scanner Components

Each positioning system was carefully designed to maximize its accuracy within the context of the overall system. For example, the weight of the 3-axis probe assembly was balanced against the stiffness requirements of each component in an effort to produce an optimized design that minimized local probe deflections as well as deflections in the arch structure. Error correction, as described in Section 5, was utilized on the individual axes of the system to maximize accuracy. A virtual axis was also established to correct the radial position as a function of the probe theta position.

The scanner positioning system structure was initially installed and aligned to its desired location in the chamber. To start, a tracking laser was used to measure the required shim thickness at each mounting hole for the curvilinear rail system used for the theta axis. The machined surface for the rails had a surface flatness of ± .006”. After shimming, the theta carriage plate axial deviation was recorded at +.001/-.0017” over the 100° required travel range. This was very important, because there is no cross range axis to correct for any out-of–plane (lateral) error in the probe position. The radial and polarization axes were then aligned to each other. The tracking laser was used to measure and install shims to obtain the desired alignment. The entire probe assembly was then rotated to point to the coordinate system created at the center of rotation of the theta axis.

Upon completion of the system alignment, excessive probe deflection was discovered when the probe was positioned at the 90° theta position as shown in Figure 4 below.

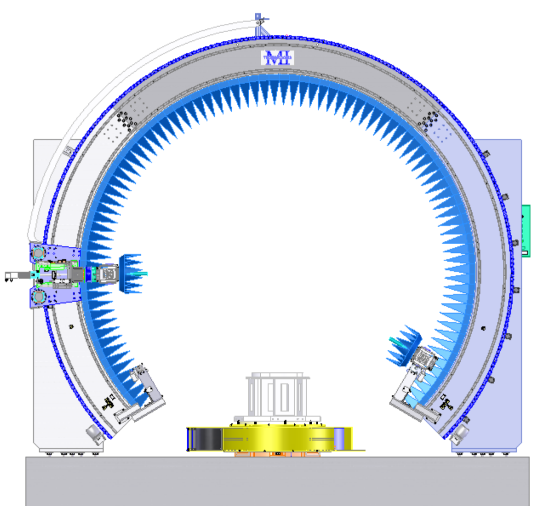

Figure 4 – Probe at 90° Theta Position

The deflection produced a corresponding probe pointing error. In an attempt to compensate for the probe deflection, it was decided to artificially lower the intersection point of the theta and azimuth axes by approximately .030”. This reduced the probe pointing error to an acceptable level. The radial error introduced by the axis intersection translation was compensated for by the virtual axis that was already in place to address any probe aperture radial position variation. Figure 5 shows preliminary radial position measurement results, both uncorrected and corrected.

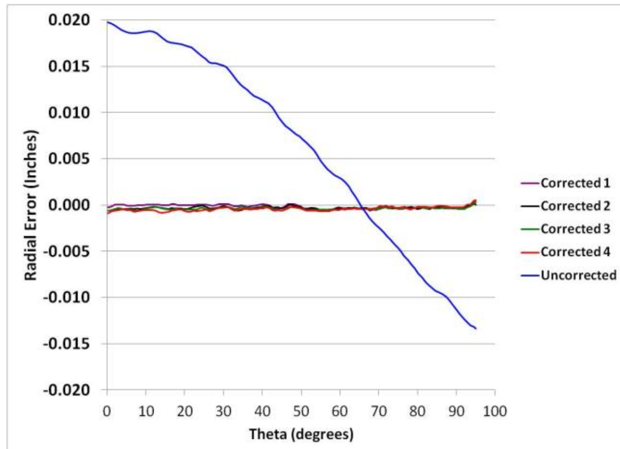

Figure 5 – Radial Error

The uncorrected plot shows the native radial position error, including the contribution incurred by the translation of the intersection. The corrected plots show the radial position error when actively correcting the error with the virtual radial axis. This correction would not have been possible without the use of a virtual axis. The alternative corrective action would have been a costly mechanical re-design and re-alignment of the probe assembly. Figure 6 shows the final accuracy and alignment plots for the system.

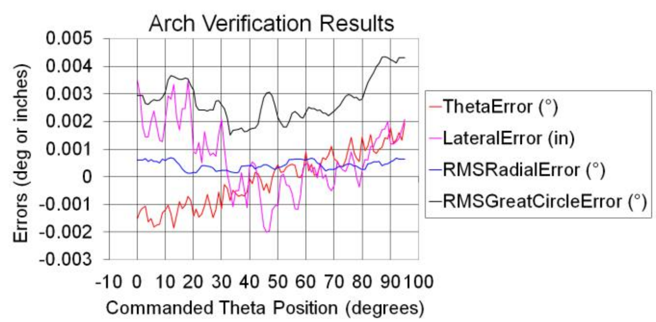

Figure 6 – System Verification Plot

9. Summary

As antenna measurement frequencies continue to increase, higher mechanical positioning accuracy requirements follow. Many of the items discussed in this paper must be accounted for in the earliest stages of system design such as foundation stability and HVAC requirements. Other suggestions are implemented during the detailed design and system integration stages of a program. The intent of this paper is to help users identify what factors may limit their overall system accuracy and to offer some guidance on how to address them.

10. References

[1] Roger Dygert, Mark Hudgens, "An Innovative Technique for Positioner Error Correction", AMTA 2012 Proceedings

[2] ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, ''Composite Structures and Technologies,'' tutorial notes, 1989; and manufacturers' technical data sheets.

[3] Jeffrey Fordham, Tim Schwartz et al., "A Highly Accurate Spherical Near-field Arch Positioning System", AMTA 2011 Proceedings, Atlanta, GA

[4] Charles Pinson, John Wilber et al., "4. Coordinated Motion and the use of Virtual Axis", AMTA 2012 Proceedings