AN INNOVATIVE TECHNIQUE FOR POSITIONER ERROR CORRECTION

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ABSTRACT

Antenna measurement systems employ mechanical positioners to spatially orient antennas, vehicles, and a variety of other test articles. These mechanical devices exhibit native positioning accuracy in varying degrees based on their design and position feedback technology. Even the most precise positioning systems have insufficient native accuracy for some specific applications.

As the limits of economical positioning accuracy are approached, a new error correction technique developed by MI Technologies satisfies these higher accuracy requirements without resorting to extreme measures in positioner design. The new technique allows real-time correction of repeatable positioning errors. This is accomplished by (1) performing a finely grained measurement of positioner accuracy, (2) creating a map of the errors in both spatial and spatial frequency domains, (3) separating the errors into their various components, and (4) applying correction filters to algorithmically perform error correction within the positioner control system.

The technique may be used to achieve extreme positioning accuracy with positioners of high native accuracy. It may also be applied to conventional (synchro feedback) positioners to achieve impressive results with no modifications at all to the positioner. The following paper discusses the new error correction technique in detail.

Keywords: Kinematic error, Positioning accuracy, Position error correction, Position feedback, Spatial frequency analysis

1. Introduction

Positioning error correction techniques have been used and applied in antenna measurement systems successfully for some time [1] [2]. By accurately measuring errors, a portion of the largest systematic errors can easily be removed. With relatively coarse measurements and simple linear interpolation, some good accuracy improvements can be obtained.

However, in the pursuit of even better accuracy and lower cost, a more sophisticated approach is needed. Since the measured error data is the consolidation of many sources of error, including repeatable and non-repeatable errors, simply using the error data as-is may not produce adequate results.

By applying digital signal processing (DSP) techniques to the measured error data to develop correction tables, better results can be achieved. These techniques include analyzing the error data in the spatial frequency domain, applying filtering, resampling or enhancing the resolution of measured errors, and either correcting or eliminating aliased components [3].

2. Positioning System Basics

A meaningful discussion of this error correction technique must begin with an introduction to some basic principles of mechanical positioning. All further discussion is limited to rotational axes, but applies equally to linear axes in most cases.

An antenna measurement positioning system is an electro-mechanical device that is capable of placing a test article in space at a known location and orientation. The positioning system may have only one axis of rotation, or may employ several axes, some rotational, and some linear. Complex positioning systems are typically composed of a variety of artfully assembled single-axis positioners.

Positioning errors attendant to these systems result in undesirable errors in the recorded RF data. For this reason, designers and manufacturers of positioners routinely pursue high positioning accuracy. High accuracy is of course achievable, but at considerable cost. The limits of affordable intrinsic accuracy in rotary positioner axes have not been challenged for some years. It is now possible, with MI Technologies' new positioner error correction technique, to significantly improve the native readout accuracy of a given positioner, and to do so at modest cost.

Accuracy – This quantity, *accuracy*, often dominates discussions of positioning systems. A primary distinction is made between *readout accuracy* and *positioning accuracy*. Most published accuracy values relating to antenna measurement positioners are of the readout accuracy type.

Readout accuracy is defined as the difference between the actual angular position and the displayed angular position of a single positioner axis at rest. The dominant errors are kinematic, resulting from mechanical inaccuracies within gears, couplings, and bearings. Reducing these inaccuracies by design requires tighter tolerances on mechanical components, resulting in higher cost.

Positioning accuracy is defined as the difference between the actual angular position and the commanded angular position of a single positioner axis at rest. Several factors affect positioning accuracy, including readout accuracy and control loop performance.

Repeatability – This quantity is a key element in native positioner accuracy and establishes the theoretical limit to the error correction function. *Repeatability* is the variation in a set of position error measurements, all of which are taken under the same conditions with the same test instrument. Bidirectional rotation of the positioner should be incorporated in the both repeatability and accuracy measurements to ensure detection of certain types of mechanical uncertainties, such as backlash.

Native accuracy – In this paper, *native accuracy* refers to the readout accuracy intrinsic to a positioner without application of any form of error correction. Values range from ±0.05° for conventional positioners to ±0.005° for high-accuracy models. Occasionally, even higher accuracies are achievable.

Native positioner accuracy is primarily driven by the type of feedback device and its method of coupling to the axis of rotation, either geared or coaxial. Coaxially mounted devices generally offer much higher native accuracy by eliminating the inherent errors of the geared approach.

Corrected accuracy - Regardless of the type of feedback device and mounting arrangement, error correction techniques can be applied to any axis having systematic, repeatable errors. *Corrected accuracy* is the resulting readout accuracy after error correction has been applied.

3. Repeatability: The Basis for Error Correction

By examining measured native accuracy data over many positioners, it became apparent that much of the readout error is systematic and repeatable. Lack of concentricity due to gears or translations in coaxial mounted devices are one of the primary sources of error, and these errors are quite consistent.

The large scale performance of an elevation axis is shown in Figure 1. Observe that there is a cyclical error that repeats every 60 degrees, or 6 times per revolution. This correlates with a 6:1 gear used to couple the axis to the synchro feedback device, and is a large portion of the overall readout error.

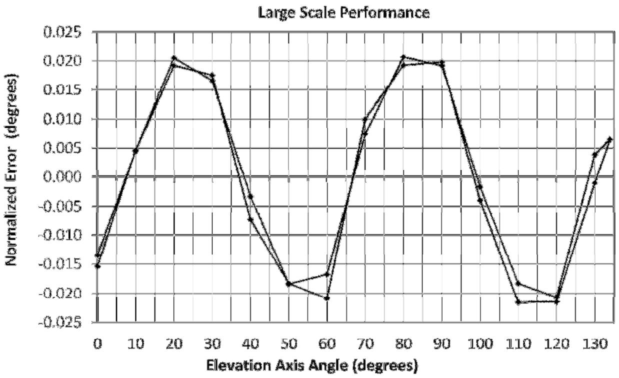

Figure 1

The two lines on the plot indicate results for measurements in both the forward and reverse directions. A small hysteresis effect, peaking at nearly 0.005 degrees, is observed due to residual backlash in the anti-backlash gear used to couple the synchro package to the axis. The hysteresis effect cannot be removed by the error correction process described in this paper, and it becomes the primary limiting factor in both repeatability and corrected accuracy.

By making accuracy measurements with finer resolution, systematic errors within the synchro package can be observed. The solid line in Figure 2shows the error for a 36:1 dual speed synchro over a 20 degree range of motion, and the dashed line shows the calculated error pattern due to a slight eccentricity in the gear on the shaft of the 36:1 synchro.

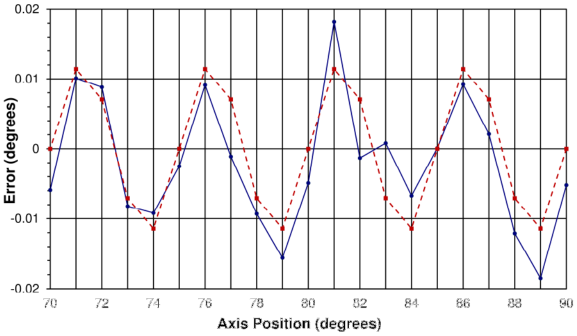

Figure 2

Note that there are 2 positive peaks and 2 negative peaks for every 10 degrees of motion, corresponding with a 36:1 dual speed synchro system. Also note that there are other errors in the system that cause the 80 – 90 degree range to produce a slightly different pattern than the 70 – 80 degree range.

The total error for this Elevation axis may be estimated by adding these two error plots together, yielding approximately +/-0.04 degrees of error. (The specification for this axis is +/-0.05 degrees.) This illustration indicates that there are at least 2 sources of error, and both of them may be due to mechanical components that are repeatable. But there are also other errors of unknown source that may not be repeatable. Using the non-repeatable elements of the measured errors may limit the degree of accuracy that can be achieved.

4. Error Correction Process

The error correction process consists of the following steps:

- Measure native accuracy
- Data processing using DSP techniques
- Apply error correction in real-time hardware
- Measure corrected accuracy

Each one of these steps must be performed with the care appropriate to the level of accuracy that must be achieved. Extreme accuracy requires extreme care in the test setup, processing of the data, and implementation in hardware.

Measure Native Accuracy

The native accuracy is measured by stepping a positioner in small increments through its full range of motion and comparing the control system readout value with the value obtained by an independent measuring instrument, such as an autocollimator or a precision laser measurement instrument. The results are stored in an error map.

The primary requirements of such an error map are:

1) The data must be sufficiently fine-grained to support the error correction algorithms and to capture the significant kinematic errors within the positioner.
2) The positioner readout errors must be sufficiently repeatable to support the error correction algorithms. Simply stated, hysteresis and random errors cannot be nulled by processing the data in an error map; only repeatable errors can be nulled.

The independent measuring instrument used for determining the actual angular position may be either an *autocollimator* or a *tracking laser*. The autocollimator has the advantage of accuracy (±0.00015° accuracy), but is very slow to operate and gather data. The tracking laser is much faster, and can be automated. Its accuracy is about ±0.001° in a typical measurement setup. The limitation on the tracking laser accuracy introduces a minor uncertainty in the collected data.

Data collection with a tracking laser instrument is achieved with the test setup similar to that shown in Figure 3. In this test, an error map is being developed for an azimuth positioner with a coaxial encoder instead of synchros. A test arm is attached to the positioner turntable to improve laser accuracy. At the end of the arm is affixed a mount for a S*pherically Mounted Retroreflector* (SMR). The tracking laser automatically tracks the SMR as it moves throughout the positioner's range of motion.

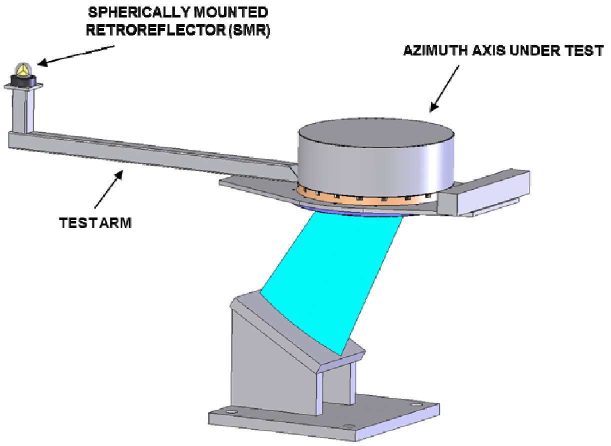

Figure 3

The positioner is moved in small increments, and both readout and actual position values are recorded. The process is repeated in the reverse direction. The difference between the recorded values is stored as the error map.

Data Processing

To properly take into account the sources of errors and reduce or eliminate the impact of random errors, some signal processing techniques are applied to the error data. This approach aspires to:

- Identify the sources of error
- Quantify the contribution of error sources
- Filter out non-repeatable and random errors
- Determine whether sufficient sample spacing was used in the measurement process
- Frequency shift or filter out significant aliased components
- Generate an appropriate error correction table
- Simulate anticipated resulting accuracy

A data processing tool was developed that displays the error map in both the spatial and spatial frequency domains for further analysis. By examining the spatial frequency plots and comparing significant error sources to known positioner design parameters, some assessments about the mechanical system can be made. Some sources of mechanical error can be isolated from each other and independently quantified. This enables the engineer to determine the magnitude of errors due to a pinion gear, ring gear, eccentricity, or bearing noise. Viewing error data in the spatial domain also allows one to see pinch points, backlash, and repeatability.

It also allows the operator to view whether the data has been sampled with sufficiently fine resolution to prevent aliasing and suggests which components are actually aliased. If it is determined that certain components have aliased, they can be removed or repositioned in the frequency domain to the appropriate location.

The operator is allowed to select which components are repeatable and which are non-repeatable and specify filtering, deletion, and other parameters as appropriate for processing of the data. These parameters are stored in a separate file to be used again on similar positioners.

Viewing the data in the frequency domain - Figure 4 shows error data for a positioner in the spatial frequency domain. The spectrum is shown as the number of cycles per full revolution of the axis. Viewing the data this way shows error sources that are not readily identifiable in the spatial domain. By comparing spectral frequency components to the mechanical design, error sources can usually be identified.

A gear tooth having machining imperfections will produce a spectrum that is different from a bent shaft or a bad bearing. If all gear passes that contribute position error rotate an integer number of times per rotation of the turntable, then all repeatable errors will be periodic over one rotation of measurements. As shown in Figure 4, these periodic errors tend to be restricted to a few discrete frequencies. Unrepeatable errors will also appear in the spectrum, though their amplitude and/or phase distributions will be different over multiple measurement sets. Multiple sets can be compared to isolate the repeatable portion of the error from the random portion.

A side benefit of this process is that it can be used as a diagnostic tool. Once the error source is identified, the engineer can determine whether the error is an anticipated effect from tolerances on mechanical components or is due to a defective mechanical component that needs to be replaced.

Two position-sensing encoders for the system in Figure 4 were each driven off a ring gear using a pinion gear with a 12:1 ratio. This is clearly seen in the error spectrum. The 12 cycles-per-revolution fundamental and its harmonics are major contributors to the error function. The error contributed by the pinion gear is significant out to the 5th harmonic, although it will be shown that other error sources also contribute at 72 cycles. Viewing this error source from successive scans in the spectral amplitude and phase domain will allow the engineer to determine if the components of this error source are repeatable. In this case they were. The error was from slight imperfections in the pinion, such as eccentricity and gear-tooth surface. As the gear ratio is an integer, the same teeth will always mesh with the ring gear at the same position yielding the same error, making it repeatable and therefore correctable.

This positioner used a dual encoder system to help remove eccentricity effects. This suppressed contributions that otherwise would have been present at odd frequencies. The two-cycle error in Figure 4 was repeatable and may be due to an elliptical distortion of the encoder scale or ring gear.

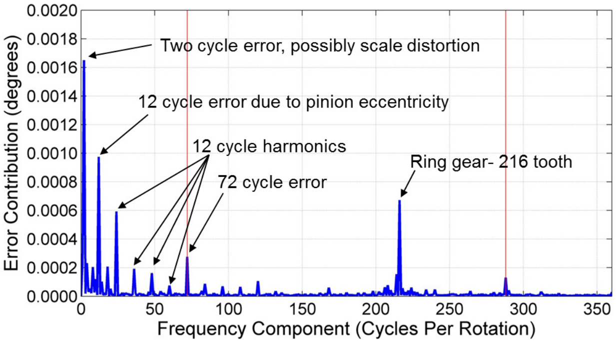

Figure 4 - Source of Errors

In the higher frequency components of the spectral plot, the error contributed by the machining of the teeth in the ring gear can be seen as a 216 cycle error. There are 216 teeth in the gear, and the error shows up at this spatial frequency. Most of the error is contained in the fundamental, with the harmonics being much smaller. The tooth-to-tooth error is fairly consistent, as the modulation of the 216 cycle error is small as seen by the spectral sideband amplitudes.

The fundamental component of the 12:1 pinion gear is larger than the 216 cycle ring gear error, indicating that it is a larger contributor to the error function.

Since 720 measurements per revolution were made, the harmonics of the 216 cycle error are aliased in Figure 4, with the 2nd and 3rd harmonics appearing at 288 cycles and 72 cycles respectively [3]. If interpolation is done without either moving them to the correct frequency or removing them, the error will be multiplied by two when the real error is 180 degrees out of phase with the aliased error, which will occur at some points in the interpolation.

These two aliased ring gear harmonics are shown at their proper location in Figure 5 (432 and 648 cycles). To move the harmonic, the data was resampled to a higher sample rate and then the harmonic deleted from where it was and moved to the new location. Resampling increases the spectral bandwidth, allowing room for the aliased components to be located at their true frequencies.

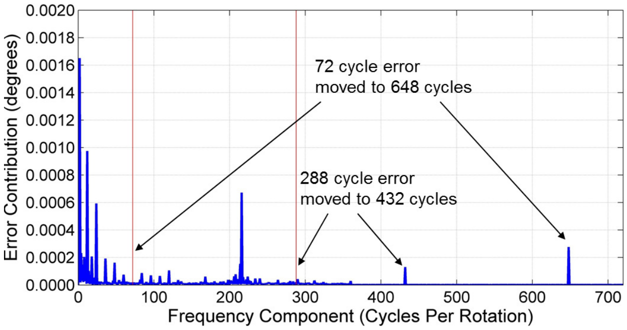

Figure 5 - Aliased Ring Gear Harmonic

Note that it may not always be appropriate to relocate aliased spectral components. If there are multiple sources that contribute to a spectral component, it may be desirable to relocate one portion of the component and not another portion. Since these are not easily separable, one must judge whether a better result would be achieved by relocating or excluding the combined spectral component. Where an aliased spur is identified but cannot be relocated with confidence, it would be better to null (filter) that spectral component in the errors being corrected.

Interpolation of the data – Since the measured data are typically sampled more coarsely than the resolution of the encoder, some form of interpolation is required to estimate what the corrected position should be between measured points. Some techniques to estimate the interpolated value are better than others. Several techniques were explored:

1) Use a fixed value between points
2) Linear interpolation
3) Quadratic interpolation
4) Spectral resampling

The appropriate technique to use is determined by several factors. If the data in the table is very dense, on the order of 16,000 points, then using a fixed value from a table is usually adequate. For 8,000 points, linear interpolation can be used. If the data is sampled to a frequency 20x higher than the highest frequency component in the error function, then quadratic interpolation can be used. In the above case, quadratic interpolation would need 432 cycles * 20 = 8640 points, which also fits the criteria for linear interpolation. The two techniques usually produce similar results for many error functions that are rapidly changing.

Measuring native accuracy at the large number of points required for the first 3 techniques is time consuming. To substantially reduce the number of measurement points required, the resampling technique can be used. For example, an axis could be measured using 1800 points. This is likely high enough to capture all the significant error frequencies, but not dense enough for a simple interpolation. The error data can be expanded to 128,000 points using a resampling technique from digital signal processing [3]. The resampled data can be filtered and the uncorrectable frequency components removed. Aliased data can be deleted or frequency shifted to the appropriate location in the spatial spectrum. The results can then be decimated to the density required by the hardware.

Figure 6 illustrates the comparison between interpolation techniques. Here a data set is decimated by 2 and a 4 K interpolation is performed using linear and quadratic methods. It can be seen that the quadratic case performs better than the linear, but is still short of true data. Resampling is shown to produce the best result.

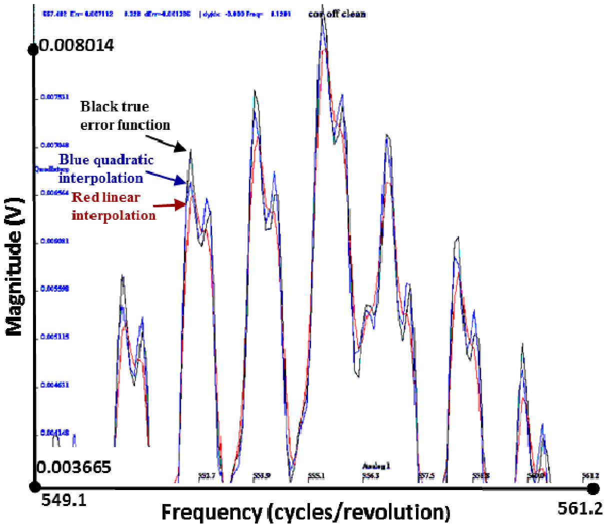

Figure 6 - 4K Interpolation

Final processing of the data - The final step in processing the data is to put it in a format compatible with the hardware. The very high resolution data is decimated to the density required for the specific hardware to use.

The data processing tool also generates an estimate of the predicted accuracy of the positioner after application of the error correction technique.

Recalibration – If and when the system needs recalibration, new survey data is collected using an automated system. To process the new survey data, the steps used by the engineer are recovered from the parameter file and processing occurs in the same way the factory calibration was performed, but using the new survey data.

5. Real Time Error Correction

It is important to distinguish between two methods of implementing error correction, one which is applied to the feedback path in real time and one which is not. The latter method simply applies a position offset to the commands given to the positioning system so that the target actual position is correct, but the readout position from the feedback path is uncorrected. Uncorrected feedback results in uncorrected position displays, position triggering, and position information collected as part of the data acquisition system. While this method has been used successfully, it is more desirable to apply correction to the feedback in real time.

Figure 7 illustrates the implementation of the real-time error correction process. The position data stream from a moving positioner is fed to the *encoder interface*. Here it is converted to the native format of the position controller. In this system, error correction is performed in hardware to provide very accurate and fast triggering, as well as to provide real-time corrected feedback to the servo control loop for more precise control.

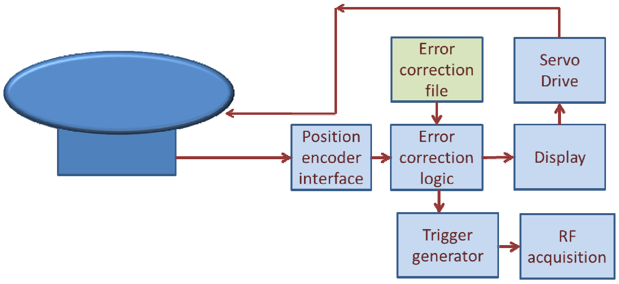

Figure 7 – Real Time Error Correction

Any delay in the error correction logic induces an error in the generation of triggers as well as affecting following error in the servo control loop. At 6 degrees/second, an error of 0.0003 degrees is incurred if a delay of 50 us occurs, which is generally less than 10% of the error budget. By using a position update rate of 20 KHz or higher and performing the correction in hardware, this tight timing budget can be met.

6. Example Results

An azimuth positioner having an integral encoder was evaluated and performance enhancements were achieved using the methodology previously described in this paper. Figure 8 depicts the error curve for the native readout accuracy, with the nominal positioner angle shown on the horizontal axis. Note that the peak-to-peak readout accuracy is approximately ±.015°. A repeating pattern is observed every 18 degrees which suggests a 20:1 gear pass between the axis and the encoder. Encoders and synchros will generate different characteristic curve shapes based upon the kinematic errors inherent to their design and mounting.

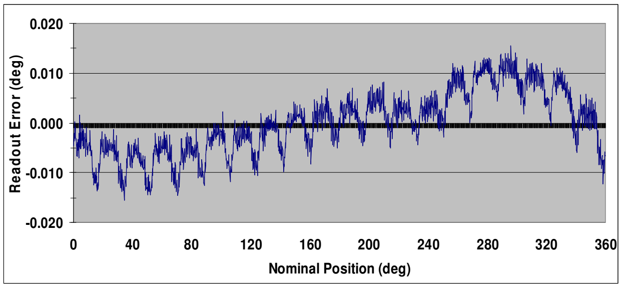

Figure 8 - Measured Native Accuracy

The process described in this paper was used to analyze the error and the signal processing techniques were applied. The resulting error correction was implemented using the real-time hardware described.

Figure 9 depicts the error curve obtained by measuring the corrected accuracy on the same positioner after error correction was implemented. The graphs are plotted to the same vertical scale. The new error correction technique results in a significant improvement in readout accuracy from ±.015° to ±.005°, a factor of 3.

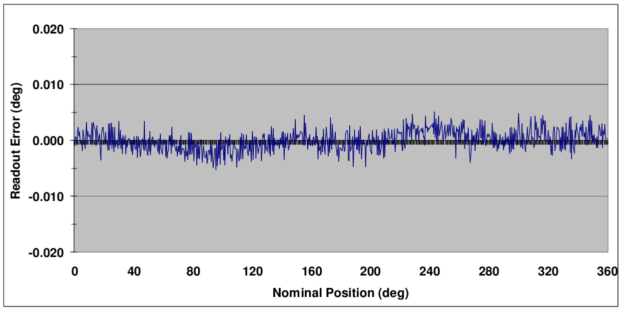

Figure 9 – Measured Corrected Accuracy

7. Summary

The application of digital signal processing techniques to positioner error correction has been described. The ability to identify sources of mechanical error and to include or exclude various components has been demonstrated. These techniques were applied to a high precision axis and excellent results were achieved.

8. References

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