IMPROVED COORDINATED MOTION CONTROL FOR ANTENNA MEASUREMENT

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ABSTRACT

Some antenna measurement applications require the precise positioning of an antenna along a prescribed path which may be realized by a combination of several, independent physical axes. Coordinated motion allows for emulation of a more complex and/or precise positioning system by utilizing axes which are mechanically less complex or precise and are correspondingly more easily realizable.

An ideal coordinated motion system should 1) Allow for the description of coordinated paths as parametric mathematical functions and/or interpolated look-up tables 2) Support control variable parameters which affect the trajectory 3) Compute a feasible trajectory within given kinematical constraints 4) Generate measurement trigger signals along the trajectory 5) Minimize control-induced vibration 6) Compensate for multivariate positioning errors.

This paper will describe a novel approach to virtual-axis coordinated motion which offers significant improvements over existing motion control systems. This advancement can be applied to many antenna measurement problems such as Helicoidal Near-Field Scanning and Radome Characterization.

Keywords:

Antenna Measurement, Coordinated Motion, Helicoidal Scanning, Motion Planning Algorithms, Positioning Error Compensation, Radome Characterization.

1. Introduction

Coordinated motion is the antenna test system technique of simultaneously moving one or more independent motion axes in concert in order to achieve a desired path of antenna, probe and radome motion. Applications of coordinated motion include: 1) Counter-steering the range antenna with the Antenna Under Test (AUT) to perform Ludwig patterns, 2) Helicoidal Near-Field Scanning, 3) Coordinating the multi-axis motions of a nose radome and a test antenna for radome characterization measurements and 4) Utilizing an Az/El/Az positioner in order to achieve roll/pitch/yaw motions. In addition, coordinated motion can be used to compensate for repeatable positioning errors which depend upon one or more independent variables such as bearing run-out, non-orthogonal axes, and non-linear components. Coordinated motion has been a feature of MI Technologies position controllers for a decade [1]. This paper describes the design goals for improved coordinated motion and discusses how they were implemented and improved in the MI-710 series controllers.

2. Design Goals

There were six key goals for the coordinated motion software design incorporated into the MI-710 Position Controller. This section will discuss each of these goals.

2.1 Efficient Virtual Path Descriptions.

Users must be able to easily and efficiently specify parametric mathematical descriptions of the desired virtual axis path to be achieved during coordinated motion. The virtual axis description relates the users' desired trajectory along a (potentially complex) virtual axis to the vector of required physical axis positions over time. This goal was met in part by integrating a widely-used, high-performance embedded scripting language called Lua [2] into the motion control software. Lua is well-known for its reliability, computing efficiency, extensibility, ease of use and small memory footprint. In most coordinated motion applications, only a very small portion of the Lua language syntax is needed. Lua makes the implementation of the parametric motion equations very straightforward for anyone who is generally familiar with any computer language similar to BASIC.

Figure 1 shows an example Lua script which defines the three physical axis positions (x,y,z) as a function of the virtual coordinate (v) and independent parameters Xc, Yc, w, h, and k.

```
-- Implements an elliptical helix
--   centered at Xc, Yc

function main (v)
    local x,y,z
    x = Xc + w * cos(v)
    y = Yc + h * sin(v)
    z = k * v
    return x,y,z
end
```

Figure 1 – Example Virtual Axis Script

The primary purpose of virtual axis scripts is to perform coordinate transformations between the objective (virtual) coordinate system and the actual, physical axis (joint space) coordinate systems of the antenna measurement positioning system. This transformation can potentially have an arbitrary number of parameters and will often involve complex trigonometric coordinate conversion calculations. Certain parameters (e.g. Xc, Yc, w, h and k in Figure 1) are termed "step" parameters. They will have fixed values during a coordinated move while the virtual coordinate (v) is swept from an initial value to a final value while observing user-specified constraints of maximum velocity, acceleration and jerk (rate of change of acceleration) in the virtual coordinate system.

2.2 Control Variable Parameters

Quite often, the conversion from virtual coordinates to physical (joint) coordinates is required to be a function of more than a single parameter. In such cases, the virtual axis coordinate value (v) serves as one (of possibly many) independent variables which determine the physical path taken.

The "step" parameters are named as such because the usual measurement procedure is to step through a sequence of the possible combinations of their values with a coordinated move being made after each of the uncoordinated steps. The path taken by the AUT (and/or probe) is a function of all of the step parameters, the initial and final virtual coordinates and is subject to various virtual and physical kinematical constraints.

Before each coordinated move is begun, host software sets the value of each of the step parameters as required and then commands the system to make an uncoordinated move to the starting virtual coordinate. After achieving the starting virtual coordinate, the system is then commanded to plan and execute a coordinated move to a specified final virtual coordinate. It is during the coordinated move that antenna pattern data is actually taken.

2.3 Observe Kinematical & Measurement Constraints

Coordinated motion means that the instantaneous axis states (position, velocity, acceleration, and jerk) must match a planned trajectory at all times during the motion. This requires that the trajectory must be planned such that it is physically realizable given a number of practical positioned limitations (e.g. finite capacity for position, velocity, acceleration, and jerk). Lee et al [3] have formalized a convolution-based approach to this problem.

If the motion plan requires that a physical axis move at a velocity higher than it has the capacity to achieve, the path taken by the AUT will diverge from the desired virtual path and the data taken will be spatially inaccurate. The same is true for violations of other kinematical constraints such as acceleration and jerk. If this occurs, the system would produce erroneous pattern data without any clear indication of a problem. This condition is known as "position over-speed" because the spatial scanning rate is higher than the physical axes can achieve.

There is also a second kind of constraint which must be taken into account during motion planning. When a measurement trigger is issued, a finite amount of time is needed to make the required measurements. These measurements must be completed before the next measurement trigger can be accepted by the test system. When a measurement trigger is generated before the measurements associated with the last trigger have been completed, a condition known as "measurement over-speed" is said to have occurred. Specifically, measurement over-speed occurs when the instantaneous measurement trigger rate exceeds the instantaneous measurement rate. In the past, this was prevented in one of two ways: 1) Reduce the trigger rate by decreasing the virtual axis velocity during measurements or 2) Decrease the measurement time by reducing the number of frequencies, decreasing the time to change frequencies or decreasing processing time at each frequency. Both of these approaches cause significant and undesirable increases in test time.

The MI-710 prevents both types of over-speed conditions by utilizing an improved coordinated motion planning process which minimizes the throughput losses due to kinematical and measurement rate constraints. It does this by pre-planning the virtual axis motion such that all the constraints are minimally met. For example, if an analysis of the user's virtual velocity specifications or allowable measurement rate would cause a constraint violation, the motion plan takes this into account and only slows down just enough to avoid the over-speed and only during the virtual coordinate span in which the slow-down is needed. It does not slow down the entire scan because there is a minor problematic region.

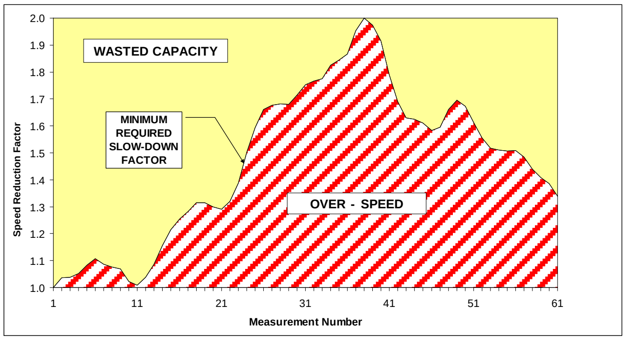

Figure 2 –Example Reduction in Wasted Capacity

Figure 2 charts the speed reduction factor which is required in order to avoid measurement and position over-speed conditions due to constraints in an example system. The upper area represents wasted system capacity due to unnecessary slow-downs. In previous approaches, the entire measurement would have been taken at a speed reduction of the peak value (a slow-down factor of 2.0). However, the MI-710 is able to operate just above the minimum slow-down factor in order to avoid over-speed. The MI-710 would execute this measurement faster by using its adaptive constraint handling capability to eliminate the approximately 27% capacity waste shown in the example.

In an antenna measurement system, the potential limiting resources are the axis capabilities (for position, velocity, acceleration and jerk) and the RF source and measurement equipment (signal sources, receiver(s), switches etc.). For example, if a required resource such as scan axis velocity is performing to its maximum capability, it may limit the utilization of other resources. As an example, at some point, a system cannot take data faster than its scan axis can move, regardless of how quickly a signal source can switch frequencies.

The resource utilization interactions between the various resources in an antenna measurement system can be quite complex and are highly dependent upon the virtual axis equations, desired virtual velocity profile, and the performance capabilities of the axes and RF measurement equipment. The MI-710 automatically generates a trajectory which takes all of the constraints into account and generates motion and triggering plans which meet all of the constraints while minimizing system capacity waste, which also minimizes test time.

2.4 Generate Measurement Trigger Signals

The positioning system must signal external equipment when it has reached a series of specified positions along the trajectory. These signals are termed, "measurement triggers". Each of the measurement triggers can cause the test system to make antenna pattern measurements at many frequencies, receiver channels and/or antenna beam states. High positional accuracy of these signals is therefore essential for accurately measuring the antenna pattern data.

The ideal system needs an ability to generate triggers that are a function of the distance traveled along the virtual path rather than only along the distance traveled along the path of a constituent physical axis.

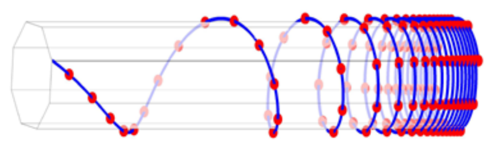

Figure 3 – Helicoidal Scan with virtual path triggering

Figure 3 illustrates the 3-D antenna measurement path of an example helicoidal scan [4]. The measurement triggers are depicted as points along the virtual path with equal space curve path lengths between them.

In principle, the system could simply wait until it had achieved a certain virtual position, and then generate a measurement trigger signal at the required virtual positions. In practice, this is infeasible because the motion control software cannot compute where the system actually is positioned, as measured in virtual coordinates. It only has information about how to calculate a physical position vector which corresponds to a given virtual coordinate and the associated step parameters. In the general case, the reverse transformation is not computable. The control software only has information on where the physical axes are commanded to be and where they actually are; it does not have knowledge of the achieved virtual positions.

The solution to this is based on the fact that if each of the axis servo systems has a following error with known (small) bounds, we can establish bounds on what the virtual position uncertainty might be. With hardware-based triggering, servo following error has no effect on the spatial accuracy of trigger signals. In contrast, software-based triggering requires greater attention to the control system tuning procedure to ensure low servo following error on all axes. This can be readily achieved by incorporating the proper values for the velocity feed-forward and acceleration feed-forward terms of the control algorithm.

During coordinated motion path planning, a triggering plan is created whenever triggering along the virtual axis is required. The triggering plan is a list of wall-clock times relative to the start of the coordinated motion at which measurement triggers are required. A properly working implementation of this technique requires both very high precision timing and very low interrupt latency in the motion control software. In the MI-710, this is achieved by the use of a very efficient, embedded real-time operating system with high-precision hardware-based timers. The software-based approach is able to generate spatially accurate triggers at rates of more than 5 KHz with positional errors that are comparable to a hardware approach when the physical axes are properly tuned for low servo following error.

When generating the trigger plan, it is desirable to generate triggers at either fixed or variable intervals along the virtual axis. Users may specify either a fixed triggering interval, or they may provide a Lua script function which returns the trigger interval value as a function of the virtual coordinate. This allows for antenna data to be taken at a spatial rate which is position dependent. The variable interval triggering technique has potential for significant increases in antenna pattern measurement throughput and corresponding reductions in in test time.

2.5 Minimize Control Induced Vibration

For maximum efficiency, an antenna measurement system must position both dynamically and statically to precise positions as quickly as possible within the system's physical limitations. As the motion control system moves the AUT through a series of paths during measurement, it obviously must accelerate and decelerate the various constituent physical axes to achieve the required virtual path positions over time.

When one or more axes are commanded at high jerk values, additional stresses are placed on the antenna and the AUT positioning equipment. For fragile AUT's and/or massive positioners, these stresses may result in excessive mechanical wear or perhaps permanent damage. In addition, the driving forces may energize multiple modes of mechanical vibration which result in either antenna measurement errors or increased measurement time if the system must wait until these vibrations have subsided before measurements can be made. By minimizing control-induced vibration, the system will have both improved AUT positioning performance and greater accuracy and reliability [5] [6].

Vibration is the result of adding energy to the positioning system at the frequencies of the mechanical resonance modes. Band-limiting the spectrum of driving accelerations has the effect of also band-limiting the spectrum of forces acting on the system. By doing so, we reduce the drive energy at frequencies which excite resonances and in turn, cause undesirable vibrations. The control strategy chosen is to prevent mechanical vibration by an optimal choice of the motion trajectory parameters. Thus, we can improve measurement efficiency by directly reducing the source of vibrational energy, rather than the simplistic, indirect method of only allowing the system to move at very low speeds.

Traditionally, motion control systems have produced a trapezoidal velocity profile by commanding two rectangular pulses of acceleration with opposite signs. Although this approach is easily implemented, it suffers from an important drawback: It requires an instantaneous changes of acceleration (i.e. unbounded impulses of jerk), which are not physically realizable. Because the spectrum of an acceleration step is unlimited, many vibration modes are strongly energized, which results in undesirable vibration, mechanical wear and increased drive energy. This causes undesirable energy to be dissipated within machine structures (due to friction and flexure) as well as within drive motor windings in the form of ohmic heating.

The cause of high jerk levels is primarily due to discontinuities in the acceleration profile. Figure 4 shows a typical motion control profile which implements a trapezoidal velocity profile. Such a profile is characterized by a linearly increasing velocity from zero up to some maximum level (the slew rate), a period of constant velocity, and finally a linearly decreasing velocity back down to zero. The equations of motion require that in order to perform such a profile, there must be four instantaneous changes in acceleration during the motion as shown.

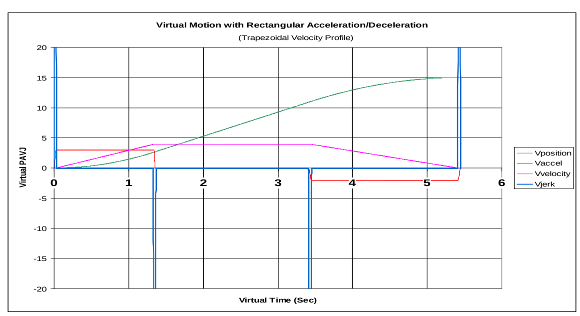

Figure 4 – Trapezoidal Motion Profile

At each of the discontinuities of acceleration there will be impulses of jerk. A jerk impulse has energy at all frequencies, including all of the mechanical resonance frequencies of the system. This causes undesirable oscillations in the various mechanical resonance modes. Another way to view this problem is that since the bandwidth of the rectangular acceleration spectrum is very wide, the bandwidth of applied forces is also very wide. When a wide spectrum of forces is applied to a mechanical system with resonances, some energy is transferred and stored in the oscillation modes. When the energy source is removed, this stored energy will dissipate over time via loss mechanisms. However, this can substantially increase the time needed in order to reach a goal position.

In order to avoid these effects, a smoother motion profile is needed. Rather than using a trapezoidal velocity profile which results in constant accelerations with very large jerk impulses, the improved motion planning process produces an acceleration profile which is a "raised cosine" function as shown in Figure 5. The raised cosine trajectory generation procedure allows for a family of acceleration profiles which are selected by two "smoothness" factors: starting phase and stopping phase smoothness. These two parameters control the fractions of the starting and stopping phases which are not at a constant acceleration. Zero smoothness produces the conventional trapezoidal velocity (constant acceleration) profile. For unity smoothness, the acceleration profile is proportional to $\sin^2(t)$.

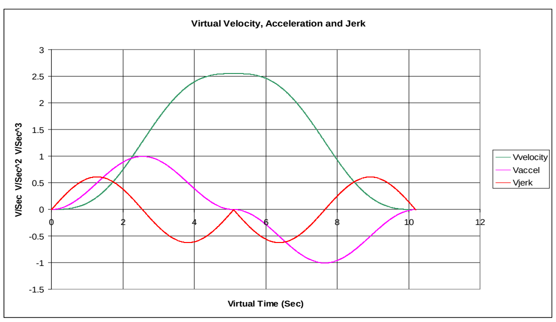

Figure 5 – Raised Cosine Acceleration Profile

The beneficial effect of sinusoidal acceleration in reducing mechanical vibrations and improving positioning performance has been demonstrated [7] in applications of low-vibration control algorithms for linear motion positioners.

2.6 Compensation for Multivariate Positioning Errors

Calculation of the vector of physical axis positions needed in order to achieve a given virtual coordinate assumes an ideal geometrical arrangement of the physical axes. It also assumes that the physical axes have a fixed, linear relationship between the physical (joint) coordinate space and physical distance or angle achieved. Due to the limitations of the achievable tolerances in a given manufacturing process, components can never be manufactured to their perfect, ideal shapes and sizes. In addition, when mechanical components are assembled, it is progressively more difficult (and expensive) to align them to their ideal relationships (e.g. parallel or orthogonal) to within extremely tight tolerances.

One could simply improve the quality of the component manufacturing process and the quality of the assembly process by reducing allowable tolerances. However, there is always a point where even small mechanical tolerance reductions result in disproportionate increases in the cost to achieve them.

A better approach, Path Correction, is incorporated into the MI-710, which allows for small mechanical variations in the components and their assembly, but compensates for these variations with an improved motion control algorithm. Clearly, any mechanical variations which are stochastically time-dependent cannot be compensated. Variations which are repeatable can be accurately compensated during motion planning.

Path Correction compensates for repeatable errors by adjusting the vector of ideal commanded positions. It does this by adding a correction vector which compensates for the non-ideal physical properties of the AUT positioner. The correction vector values are computed from an efficient third-order, spline interpolation of a multi-dimensional array of measured errors. For each physical axis, there is an array of correction values which may have from one to four dimensions. That is, the correction value for each axis, (the components of the correction vector) can depend upon one to four independent variables.

For example, in a two axis X-Y scanner, the correction value for the X-axis can depend upon both of the commanded positions for X and Y. Likewise, the Y-axis correction value can also depend upon both of the commanded positions for X and Y. Figure 6 illustrates the variation in the X-axis correction (vertical) as a function of the commanded X and Y axis values. The 2-D inputs (x, y) are the horizontal plane. The 1-D output is shown in the vertical and is color coded to show the magnitude of the correction values.

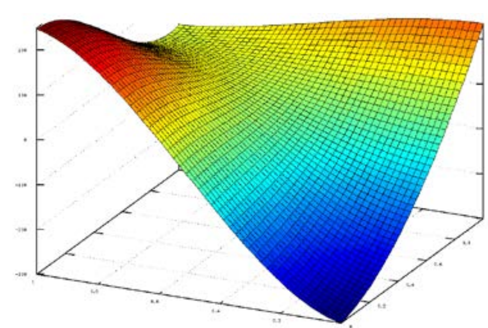

Figure 6 – Example X-Y Scanner Path Correction

Figures 7 and 8 depict an example spherical arch scanner [8]. Path corrections on the Theta (arch), probe radial, Polarization and Phi (azimuth) axes can be employed to significantly improve scanning data positioning accuracy and, if desired, the global positioning accuracy relative to the test article.

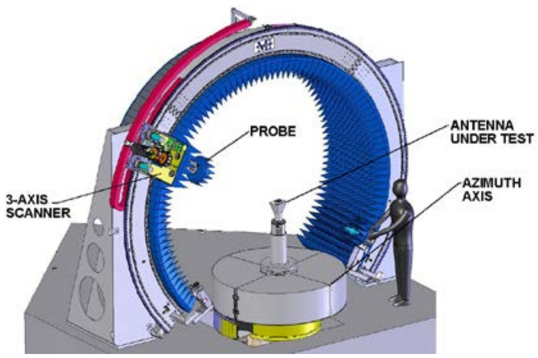

Figure 7 –Example Spherical Arch Scanner

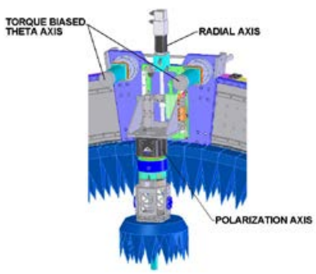

Figure 8 – Spherical Arch Scanner Detail View

In many applications, the correction input variables are the commanded positions of one or more axes, but they may also be arbitrary user-defined parameters. By using user-defined parameters, an even more sophisticated compensation method is possible. Since there are a total of four correction inputs, the corrections could also depend on the values of additional user-defined parameters, such as AUT mass or temperature. The MI-710 Position Controller allows for up to eight axes to be compensated with the correction depending upon up to four independent variables.

Path Correction data is obtained by a calibration process which consists of commanding the system to a series of known position vectors and measuring the true, global position using an independent, calibrated measurement system such as a laser coordinate tracker. Precise laser measurements are taken in a global (X, Y, Z) coordinate system and then transformed to their machine geometry dependent, joint coordinate values. The difference between the laser-measured joint coordinates and the system-measured joint coordinates are the raw correction values. These raw measurements are then analyzed, digitally processed onto a uniform, multi-dimensional grid of correction values, and then stored in the MI-710.

3. Summary

A virtual-axis coordinated motion controller for antenna measurement has been developed which incorporates a number of major improvements over previous approaches. By combining real-time control software, near time-optimal path planning, multivariate path correction, advanced triggering and other features, the MI-710 Position Controller presents new opportunities for higher levels of antenna measurement system accuracy and significantly reduced test time.

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5. Acknowledgments

The authors wish to thank Mr. Scott McBride of MI Technologies for his helpful insights and suggestions in support of this research.