Advanced Positioner Control Techniques in Antenna Measurements

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***Abstract*—Antenna, Radome, and RCS measurement systems rely on high-fidelity positioner systems to provide high-precision positioning of measurement articles. The industry currently relies on linear PID control techniques in current, velocity, and position control loops on individual axes to drive the positioners. Recent control advancements have been made in the use of position feedback devices, brushless DC motors, VFD AC motors, and multi-drive torque-biased actuation along with high-speed computing in all digital controllers. Current advanced control techniques including open-loop error correction and multi-axis global error compensation have been implemented to improve positioner accuracy. Here, an assessment is conducted on the viability of advanced control techniques in similar positioner industries to provide insight into the potential future control and capabilities of positioning systems in the RF measurement industry. Candidate advanced techniques include closed-loop error compensation using laser feedback devices to provide superior positioning accuracy. Input-shaping and feedforward model-based techniques could help suppress dynamic vibrations and nonlinear behavior to improve dynamic tracking for improved continuous-measurement scanning accuracy. Gain scheduling and sliding-mode control could provide improved motion over a wider range of conditions to maintain scanning motion fidelity.**

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

I. INTRODUCTION

RF measurement systems utilize complex, highly-engineered positioning systems to facilitate a large array of antenna, radome, RCS, and target simulation measurement scenarios under a variety of stringent specifications. The measurement positioning systems have architectures that vary across an endless combination of linear and rotary axes while managing payloads that vary from a few pounds to several tons.

Positioning goals for these systems carry a common thread of high global positional accuracy and repeatability. However, requirements for static and dynamic positioning capabilities vary according to the measurements being performed driving a need for either stepped-motion or continuous-motion data acquisition. Additionally, RF measurement positioner systems are characterized by years of reliable usage with relatively low duty cycles when compared to other industries such as machine tools and industrial automation.

The control systems utilized for the movement within these systems have traditionally relied on linear control techniques operating around the most common operating point for the measurement application. These control techniques usually include a motor current loop feeding a PWM amplifier, a motor velocity loop based on measured motor speed, and an axis position loop with position feedback measured after the drivetrain. This traditional architecture is shown in Figure 1 where the conventional limiter and filter locations are seen to modify the velocity and current commands.

Early RF measurement systems utilized analog circuitry to close the current and velocity loops with simplified linear proportional gain controls. Tuning of these early systems was done by experienced controls engineers who adjusted analog potentiometers to set the available gains. The first generations of digital control systems utilized logic switches to set various control loop settings along with simplistic digital operating system interfaces that allowed adjustment of a limited number of parameters. Modern digital control systems allow for fine resolution parameter tuning along with overall control structure modification. For example, signal filters can be implemented digitally without the need for hardware adjustments. Improved digital interfaces allow for real-time data monitoring and signal scoping for streamlined performance evaluation. This technological progress of positioner controls over the last 20 years has led to improved positioner performance across all types of RF measurements. The progress leads to a question of what future control methods could be implemented to further improve positioner capabilities.

This paper provides an overview of modern RF measurement positioner controls and what advantages the new techniques provide to RF measurement processes. An outlook for the future of positioner control technologies is presented by examining the advanced nonlinear control techniques utilized in other industries such as machine tools and robotics. A discussion of the advantages and disadvantages of each of these advanced techniques indicates how specific aspects of various RF measurement scenarios can be improved by adopting these methods of positioner control.

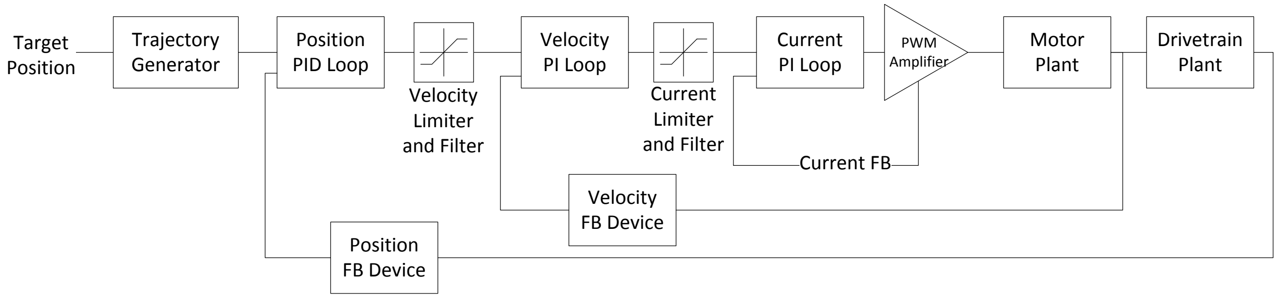

Figure 1. Block diagram of typical positioner control system including linear current, velocity, and position feedback controllers

II. State of the Art in Positioner Control Techniques

RF measurement systems have a variety of mechanical positioner architectures and specifications for positioning measurement articles. This wide range of capabilities requires control systems that are highly flexible and possess modular capabilities to add complexity to meet a wide range of applications. The advent of modern digital controls implemented directly in drive amplifiers allows for simplified system tuning with control loop architectures that can be modified digitally without the need to alter hardware.

A. Control Architecture and Tuning

The position controller manufactured by MI Technologies allows custom tuning of the position control loops through a simple digital interface. These controllers implement digital current and velocity loops with tunable proportional and integral gains with customizable filters on the command signals to maximize the response bandwidth and motor plant stiffness while still maintaining adequate closed loop dampening of the motor actuation.

Additionally, the digital position PID controller allows simple fine tuning to achieve a smooth, overdamped position response. This facilitates point-to-point movements with quick responses that do not add excessive vibrational energy through overshoot but still have short settling times and small steady-state errors. This is critical for stepped-motion acquisitions.

Modern controllers also implement linear velocity and acceleration feedforward loops stemming from the trajectory generator as shown in Figure 2 [1, 2]. The instantaneous trajectory velocity is multiplied by the velocity feedforward proportional gain and added to the velocity command signal in an effort to reduce positional following error during periods of constant velocity. Similarly, the instantaneous trajectory acceleration is multiplied by the acceleration feedforward proportional gain and added to the velocity command signal in an effort to reduce positional following error during periods of constant acceleration and deceleration.

This form of tracking control helps ensure consistent trajectory following regardless of commanded positional step sizes, slewing velocities, or accelerations. The smooth and accurate tracking of commanded s-curve or raised cosine motions is critical so that the system benefits from vibration-limited performance [3]. The tracking control also provides accurate positioning during continuous movement data acquisitions by minimizing the settling times for the following error during the constant velocity continuous data acquisition. This reduces the overhead distance needed to reach steady-state velocity.

B. Error Compensation Techniques

Error compensation techniques have become more prevalent in the industry with the advent of new non-contact metrology methods. Compensation techniques are divided into two separate architectures, open-loop and closed-loop. Currently, open-loop compensation is the standard method of error correction offered by most measurement system suppliers.

Open-loop error compensation techniques involve pre-loading a static error map into the controller trajectory generator such that it can alter the commanded profile to remove the positioning error. The static error maps are generated from measurements taken with laser tracker interferometers and single degree-of-freedom planar lasers [4]. The RF measurement industry has used this technique to improve positional accuracy of spherical near-field scanning arches [5] and planar near-field scanners [6, 7]. This method is extremely effective on systems that suffer from geometric straightness errors, axis intersection errors, geometric loading deflections, and gravitational loading deflections. The open-loop compensation technique also does not require dedicated closed-loop metrology hardware thereby limiting the system complexity and cost.

However, the method requires physical or virtual axes that can achieve sufficient movement to compensate the error. Additionally, the method can only correct for errors that are position-dependent. Stochastic time-dependent errors and errors derived from inertial loadings and vibrational excitation cannot be compensated open-loop [3]. Changes to the system such as load alterations, temperature changes, etc. also cannot be compensated without re-measuring the error map or loading a database of error maps for various system states.

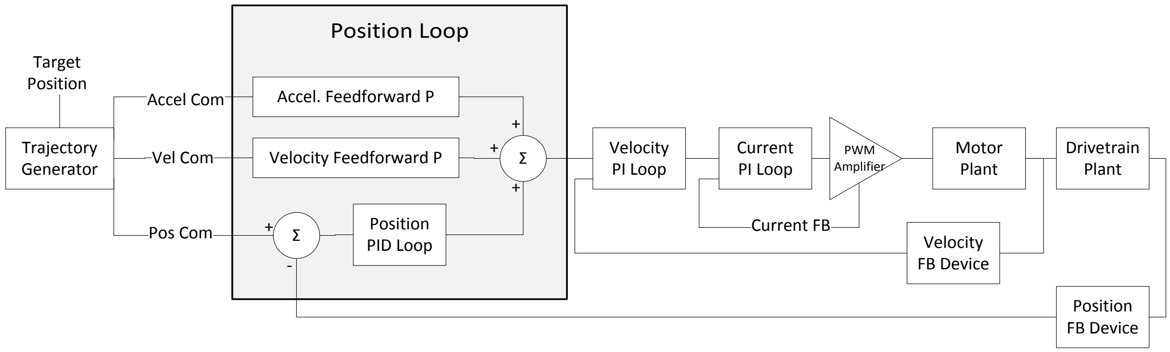

Figure 2. Block diagram of advanced linear trajectory feedforward control in the MI-710C Position Controller

III. FUTURE METHODS FOR ADVANCED CONTROL OF RF MEASUREMENT POSITIONERS

The advent of digital control platforms and ever-increasing computing power has facilitated the possibility of implementing advanced control architectures with extensive flexibility and complexity. This lends the notion that RF measurement positioners can leverage advanced control techniques utilized in other industries with little hardware cost. These new techniques can allow for control systems to be customized to specific measurement scenarios with differing specification requirements, movement profiles, and operation ranges.

A. Active Closed-Loop Error Compensation

Closed-loop error compensation techniques involve utilizing a secondary position feedback sensor to measure either single-axis or global position. This measurement, after being compared to the primary position feedback, provides a positional error signal that is then used in an active feedback control algorithm to correct for position error.

Limited sampling rates for planar lasers and laser trackers have limited their use in the past either to provide simple periodic positional error corrections or to generate static error maps, similar to the open-loop technique, which are generated during each scanning traverse of the positioner. However, advances in laser interferometers capable of providing highly-accurate, real-time 3D position measurement can facilitate closed-loop error correction in PNF scanners, SNF arches, gantries and AUT positioners. An example of such a concept for a gantry positioner is shown in Figure 3 where a dedicated 3D laser tracker on the tower establishes a stationary reference frame using targets on the floor. During RF measurement movements, the laser measures the probe position with respect to the stationary frame providing a real-time, 3D positional error signal. The 3D error signal is then decomposed such that closed-loop compensation can be executed on the gantry elevation axis and the orthogonal compensation axes on which the probe is mounted.

Various potential control architectures could be used to incorporate the position error signal in the control loop. One method would use the position error signal as the primary position feedback for a compensation axis that would constantly strive to maintain zero positional error. This would be used for the orthogonal compensation axes in the gantry example. The real-time position error could also be used as a correction signal in either a simple or weighted Kalman filter scheme. This would be used on the elevation axis in the gantry example. This method could compensate for errors in on-axis feedback devices and time-independent errors generated from static deflection, geometric deflection, and assembly misalignment. The use of global position error feedback can also allow for compensation of low frequency, time-dependent errors such as those generated from inertial loading, lower frequency vibrations, and thermal deflection.

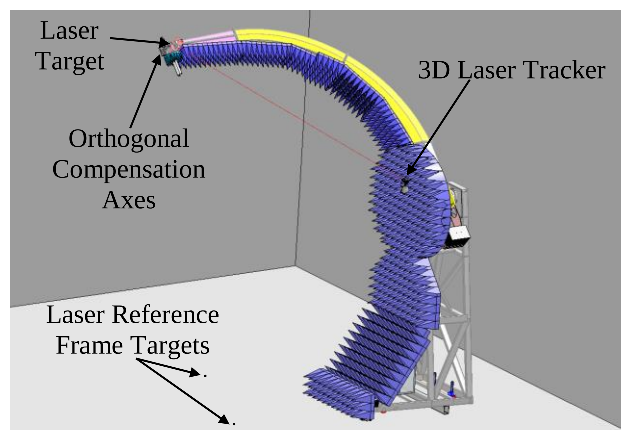

Figure 3. Gantry measurement positioner with conceptual 3D closed-loop error compensation

B. Feedforward and Shaping Control to Eliminate Unwanted Dynamics and Nonlinearities

Positioners that are characterized by low stiffness or excessive excitation due to large accelerations traditionally require large settling times or overhead movements to allow for excessive dynamic excitation to dampen out. Advanced control techniques targeting model-based compensation can help reduce measurement times and improve tracking accuracy while minimizing dynamic excitation.

The input-shaping control technique is a fairly simple model-based technique that targets minimizing excitation of specific flexible modes in the positioner [8]. This is achieved by "shaping" the commanded motion from the trajectory generator to eliminated targeted vibrational frequencies. The block diagram in Figure 4 shows that the input shaper does not require additional hardware or feedback devices but instead operates open-loop. The generation of the input shaper profile requires system identification to obtain the targeted frequencies for elimination but this could be executed in either the system mechanical design phase or using metrology methods after system assembly.

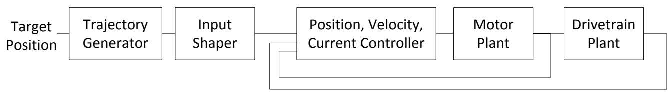

Figure 4. Block diagram for input shaping

Input shaping has been used in many industries to eliminate unwanted vibration during both point-to-point movements and during dynamic tracking motions. These industries include commercial cranes, machine tools, aerospace, and robotics [8, 9]. An example result of this method is shown in Figure 5 for an application to a coordinate measuring machine (CMM) which moves a measurement probe using Cartesian axes.

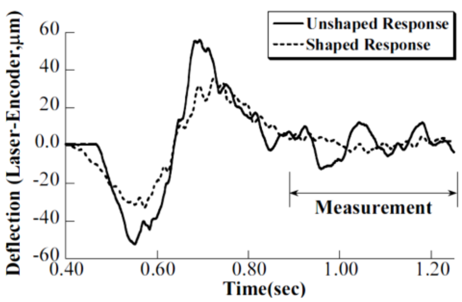

Figure 5. Input shaping results show a significant reduction in unwanted dynamic excitation in a Coordinate Measuring Machine[8]

However, input shaping is limited as the initial acceleration period does not follow the desired trajectory profile. However, the readout error between the on-axis feedback device and the actual position of the measurement article is drastically improved overall as un-measured dynamic vibration is limited. This method could have drastic implications in positional accuracy and movement speed of gantry style RF measurement positioners. Gantry positioners, such as that shown in Figure 3, suffer from decreased positioner stiffness and large amplitude vibrational modes. These could be effectively minimized with the input shaping technique.

Feedforward model-based control is a technique that compensates for system behavior by multiplying the reference signal by the inverse of the unwanted system dynamics. This technique can be implemented in both a simple local linear manner or in a more global nonlinear control scheme. Feedforward control is most effective when used in conjunction with a traditional feedback controller as shown in Figure 6. Feedback controllers provide desired responses and robustness in the face of disturbances introduced to the motor plant, drivetrain, or positioner load. However, they do not take advantage of knowledge about the known system behavior and its dynamics. The feedforward model-based controller, however, accomplishes the opposite by using the known plant dynamics to eliminate unwanted behavior before it is ever introduced into the system. The feedforward controller itself does not have the ability to compensate for disturbances or un-modeled behavior, but the combination with a feedback controller provides a system that is robust to both known and unknown disturbances and dynamics.

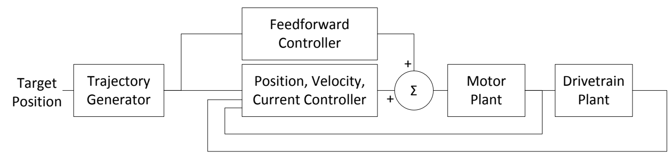

Figure 6. Block diagram for model-based feedforward control

The most widely used application of feedforward model-based control in positioner technologies is compensation for friction and backlash in the machine tool industry [10, 11]. Types of model-based control are also used in actual antenna and telescope pointing positioners in conjunction with linear-quadratic-Gaussian and H_∞ optimized feedback controllers to reject rigid and flexible body vibrations as well as wind-gust disturbances [12]. Model-based feedforward compensation is also prevalent in the commercial robotics industry in minimize tracking errors due to friction and vibrational excitation. Example results of the use of a feedforward model-based controller in addition to traditional PID feedback controls in a Siemens Manutec r15 industrial robot are shown in Figure 7 [13]. The nonlinear model of the closed-loop system captured the dynamics of axis friction and rigid-body modes allowing for their precorrection for a drastically improved tracking performance.

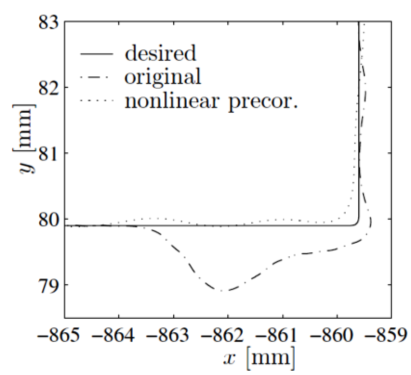

Figure 7. Impact of a model-based feedforward controller compensating for friction and rigid-body dynamics in a Siemens manutec-r15 robot during a 2-axis traverse[13]

Potential applications for feedforward model-based control in RF measurement positioners are vast. All positioners suffer from movement quality inhibitors such as friction, stiction, and backlash along with degraded performance stemming from dynamic excitation. The applications that could benefit the most from such improvements include RF tracking positioners and axes that continuously compensate error through the use of pre-mapped error correction. The continuous tracking motion of an error correction axis requires maintaining small command following errors throughout repeated back-and-forth motions during continuous RF scanning scenarios. Feedforward compensation for friction and backlash could drastically improve the ability of the correctional axis to follow the error map. Additional applications include compensation for thermal expansion-induced errors as is commonly compensated for in the machine tool industry [14]. Temperature changes in the RF measurement positioner can cause positional errors due to thermal expansion differences in various components. Accurate modeling and measurement of these errors could allow them to be compensated in a feedforward control scheme that utilizes separate temperature measurement inputs.

C. Gain Scheduling and Sliding-Mode Control for Improved Performance over a Wider Range of Operating Conditions

RF measurement positioners are designed and customized to facilitate specific measurement scenarios. The increasing prevalence of wide frequency range, reversible near-field and far-field measurement ranges has led to a need for positioners that can position with a wide range of measurement article sizes, weights, movement speeds, and movement profiles. These general purpose positioners need to maintain performance over a broad range of operating points. Current methods of accommodating a wide range of measurement article sizes include high gearing ratios and large capacity positioners. However, these design approaches limit the available measurement speeds and require larger measurement ranges. Gain scheduling and sliding-mode control allow for a system to be tuned at various operating points and transition between those tuned controller modes as the system state changes.

Gain scheduling is a relatively simple control technique that is currently being used on a limited basis in RF measurement positioners. Most current applications implement scheduling of feedback control loop gains based on changes in positioner dynamics caused by differing measurement article loads and sizes. However, this is more akin to having separate control systems altogether since the actual system plant changes drastically. True gain scheduling, as shown in the block diagram in Figure 8, modifies the feedback control gains in the position or velocity loop based on current system states.

An example of the capabilities of gain scheduling can be seen in a study of the control of an XYZ pick-and-place positioner shown in Figure 9 [15]. The study examined the settling time of movements of the x-axis while the z-axis actuated to provide varying overhung beam lengths.

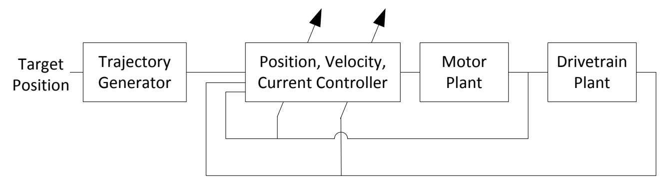

Figure 8. Block diagram for state-based gain scheduling of a traditional positioner feedback loop

The results, shown in Figure 10, showed that a single set of position loop PID gains would not maintain stability and adequate settling time. However, using smooth, differential functions to calculate ideal gains based on the overhung z-axis beam length provided improved performance over the entire range of system states.

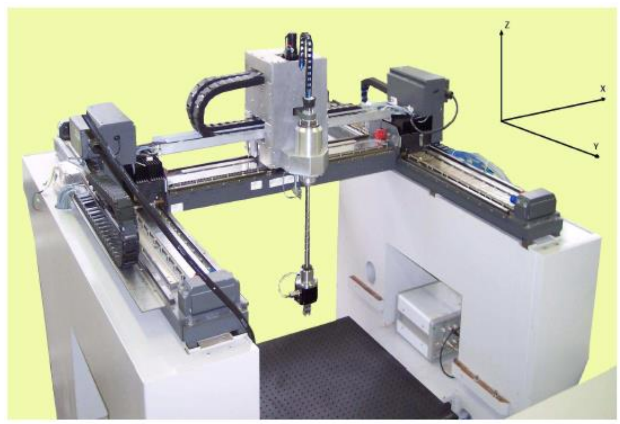

Figure 9. Gantry XYZ pick-and-place positioner studied for the capabilities of gain scheduling[15]

True gain scheduling based on system states can drastically improve response characteristics of a system that has varying dynamics at differing operating points. RF measurement positioners that exhibit this type of behavior include unbalanced loadings or positioners that operate in varying positions with respect to gravity. Such systems include larch arch scanners and gantry scanners. For these systems, the position loop parameters can be scheduled based on the relative direction of the gravity vector to maintain fast settling times without causing instability during stepped-scan acquisitions across a full hemisphere. Other applications include improving worn or faulty positioners where state-dependent dynamic changes result from zones of increased friction or binding after years of use which can be tuned for the local nonlinear behavior.

Sliding-mode control, similar to gain scheduling, alters the feedback controller based on current system states. The difference arises in that the sliding-mode controller changes the actual control architecture and not just its tunable parameters. This method is more drastic and complicated than gain scheduling and is reserved for the compensation of complex system nonlinearities. However, it has been shown to result in high fidelity performance without being sensitive to variations in plant parameters and being able to reject disturbances to a large degree [16]. This method is most prevalently used on linear-motor axes as issues with boundary chattering phenomena are not amplified by backlash and the lack of gearing results in little wear caused by chatter [17]. This technique would most benefit target simulation applications where linear motors are often used for their high-speed motion capabilities.

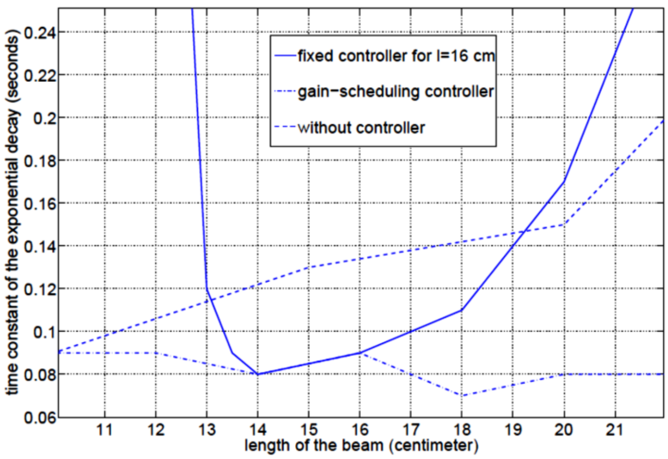

Figure 10. Gain scheduling of PID parameters of the x-axis for a gantry XYZ positioner based on the overhung length of the z-axis beam shows large improvements in position settling time over fixed gains[15]

IV. Summary

Advancements in modern computing technologies have shifted the control of RF measurement positioners into the digital domain with increased system flexibility. These advancements provide the opportunity to improve measurement capabilities and accuracies through the use of advanced secondary feedback devices with true error compensation control loops. Additionally, increased computing power allows for complex model-based controllers such as input shapers and model-based feedforward controllers to flourish in other industries with their capabilities to limit unwanted dynamic excitations, reject known disturbances, and compensate system nonlinearities. Gain scheduling and sliding-mode techniques allow for broadening of potential operating conditions while maintaining require performance. The benefit of these control techniques to the RF measurement industry can be summarized in the promise that they can improve overall positional accuracy readout and facilitate improved continuous motion tracking allowing for improved throughput, increased hardware flexibility, and increased RF measurement accuracy.

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