Proceedings

ASPE Spring Topical Meeting on Control of Precision Systems

April 2004

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Proceedings of:

Control of Precision Systems

2004 Spring Topical Meeting

April 19 and 20, 2004

Tang Center
Massachusetts Institute of Technology
Cambridge, Massachusetts

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Preface

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2004 Spring Topical Meeting

Meeting Schedule

	Monday, April 19		**Tuesday, April 20**
7:45	Registration & Light Breakfast	7:45	Registration & Light Breakfast
8:30 10:00	TECHNICAL SESSION I	8:30 10:00	TECHNICAL SESSION V
	Break		Break
10:30 12:00	TECHNICAL SESSION II	10:30 12:00	TECHNICAL SESSION VI
	Lunch on your own and lab tours		Lunch on your own and lab tours
1:30 3:00	TECHNICAL SESSION III	1:30 3:00	TECHNICAL SESSION VII
	Break		Break
3:30 5:00	TECHNICAL SESSION IV	3:30 5:00	TECHNICAL SESSION VIII
5:30 6:30	Reception		

Foreword

The meeting will focus on new developments in feedback as applied to precision systems. Many presentations will elaborate the principles essential to achieving high performance in precision control systems and provide case studies of their practical implementation.

The control of precision systems encompasses a wide range of applications such as motion generation in semiconductor processing and precision machining, e-beam and optical scanning systems, data storage and transmission devices, microscopy, micro-devices, high-resolution sensors, and low-noise electronics. The performance of such instruments, devices, and processes depends intimately upon the innovative application of feedback principles due to the large dynamic range of controlled variables and the sensitivity to effects which might be ignorable in conventional systems.

This conference is intended to promote a broader understanding of the principles and techniques applicable for precision control, to highlight the challenges and achievements unique to our field, to bring together specialists and practitioners from industry, government, and academia for the exchange of ideas, and to identify topics for further research. The conference schedule will include unstructured time to allow for technical and social interactions.

Contributed papers include the following topics:

- *Precision motion control*
- *Feedback applications in instrumentation and metrology*
- *Novel control systems*
- *Active vibration isolation*
- *Multi-axis motion control*
- *High speed machine tool control*
- *Sensor and actuator selection and integration*
- *Case studies in precision system control*
- *Precision electronic feedback systems*
- *Modeling and uncertainty analyses of systems; noise and disturbances*
- *Effect of nonidealities on feedback systems performance*
- *Advanced control techniques*
- *Command generation and feedforward design*

2004 Spring Topical Meeting Co-Chairmen:

David L. Trumper
Massachusetts Institute of Technology
Jeffrey W. Roblee
Precistech, Inc.

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Contents

Technical Papers

A S P E

Linear Stage System with Subnanometer Resolution and Centimeters Travel Range

D. Shu, J. Maser, B. Lai, Y. Han, S. Vogt, T. S. Toellner, and E. E. Alp
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1. Introduction

The Advanced Photon Source (APS) at the Argonne National Laboratory is a national user facility for synchrotron radiation research. The high-brilliance x-ray beams of this third-generation synchrotron radiation source provide powerful tools for forefront basic and applied research in the fields of materials science; biological science; physics; chemistry; environmental, geophysical, and planetary science; and innovative x-ray instrumentation. Instrument developers at the APS are facing many technical challenges. One of the challenges is to develop a state-of-the-art linear stage system for x-ray instruments with ultrahigh resolution, stability, and a large dynamic range, such as an ultraprecision scanning stage system for an x-ray nanoprobe with pixel repeatability in the nanometer scale [1] and driving mechanism for an ultrahigh-energy-resolution hard x-ray crystal monochromator [2].

There are two major ultraprecision motion-control techniques that have been developed for this challenging task.

- A novel laser Doppler encoder system with multiple-reflection optics.
- A specially designed high-stiffness weak-link mechanism with stacked thin metal sheets having subangstrom driving sensitivity with excellent stability [3,4].

In this paper, we present recent progress towards development of an ultraprecision linear stage system for x-ray instruments. Its test results, as well as its applications for multi-axis motion control, are also discussed.

2. Laser Doppler encoder with multiple-reflection optics

Since 1998 a prototype laser Doppler linear encoder (LDLE) with multiple reflections has been under development at the APS [5,6,7]. With a customized commercial laser Doppler displacement meter (LDDM) [8], this novel linear encoder achieved subangstrom sensitivity in a 300 mm measuring range. The LDDM is based on the principles of radar, the Doppler effect, and optical heterodyning. We have chosen a LDDM as our basic system, not only because of its high resolution (2 nm typically) and fast object speed (2 m/s) but also because of its unique performance independent of polarization, which provides the convenience to create a novel multiple-reflection-based optical design to attain subangstrom linear resolution.

In the self-aligning multiple-reflection optical design for the LDDM system, the heterodyning detector is housed coaxially inside the frequency-stabilized laser source. Instead of a typical single reflection on the moving target, the laser beam is reflected back and forth twelve times between the fixed base and the moving target as shown in Fig.1 [9,10]. The laser beam, which is reflected back to the heterodyning detector, is frequency-shifted by the movement of the moving target relative to the fixed base. With same LDDM laser source and detector electronics, this optical path provides twelve times greater resolution for the linear displacement measurement and encoding. A 0.03 nm resolution was reached by the prototype LDLE system recently [9].

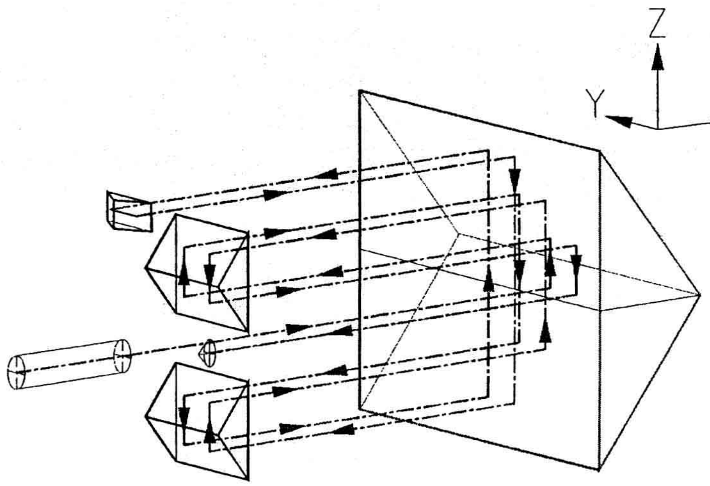

Fig.1. Schematic of the the self-aligning multiple-reflection optical design. With same LDDM laser source and detector electronics, this optical path provides twelve times greater resolution for the linear displacement measurement and encoding.

3. High-stiffness weak-link for linear motion reduction mechanism

To develop a mechanism that allows us to align or adjust an assembly of crystals to achieve the same performance as does a single channel-cut crystal, we have developed a novel high-stiffness weak-link mechanism. In this "artificial channel-cut crystal" design, we have chosen overconstrained mechanisms to optimize the system stiffness. The precision of the modern photochemical machining process using lithography techniques makes it possible to construct a strain-free (or strain-limited) overconstrained mechanism on a thin metal sheet [2]. By stacking these thin metal weak-link sheets with alignment pins, we can construct a solid complex weak-link structure for a reasonable cost. The test results show that the contribution of the angular drift of two crystals attached to each other with the high-stiffness weak-link mechanism is less than 25 nrad per hour [2].

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With the same technique, we have developed a novel stage using a high-stiffness weak-link mechanism to perform linear motion closed-loop control at the subangstrom level with microns travel range. The structure consists of four groups of overconstrained weak-link parallelogram mechanisms made with lithography techniques as shown in Fig. 2.

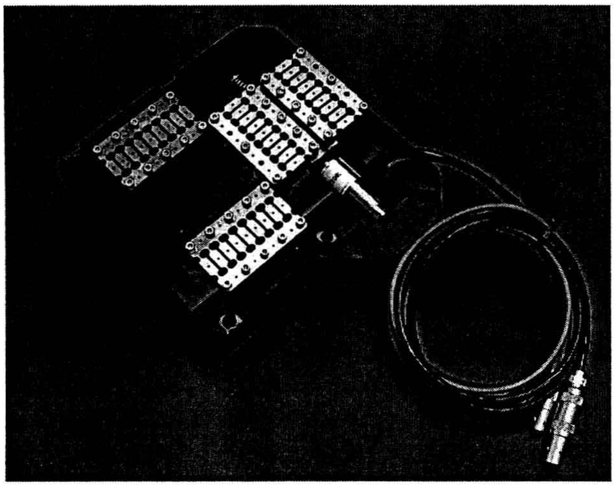

Fig. 2. Photogragh of the high-stiffness weak-link linear motion reduction mechanism.

We have tested the sensitivity of the weak-link linear motion reduction mechanism with a laser Doppler linear encoder. During the test, a Physik Instrumente PI-841 PZT actuator with E-501.10 amplifier [11] was used for input motion control. Driving sensitivity better than 0.03 nm was demonstrated with this weak-link linear-motion-reduction mechanism with a 1 micron travel range.

4. A linear actuator system with subnanometer closed-loop control resolution and centimeters travel range

A one-dimensional linear actuator system based on the above high-stiffness weak-link technique and LDDM with multiple-reflection optics has been tested. Figure 3 shows a photograph of the one-dimensional laser Doppler linear actuator (LDLA) system for an atomic force microscope. In this coarse/fine closed-loop control setup, a PZT-driven motion-reduction mechanism was mounted on the top of a DC-motor-driven stage to drive the motion object (for this example, a sample holder for atomic force microscope). A laser Doppler displacement meter with an optical resolution extension assembly is used to measure the sample holder motion in a 25 mm range with subangstrom resolution. The LDDM position signal is fed back through a system-control computer to control the PZT. The PZT drives the motion-reduction mechanism with subangstrom resolution to stabilize the motion. The system control computer also synchronizes the stage position and PZT feedback lock-in point with the LDDM position signal.

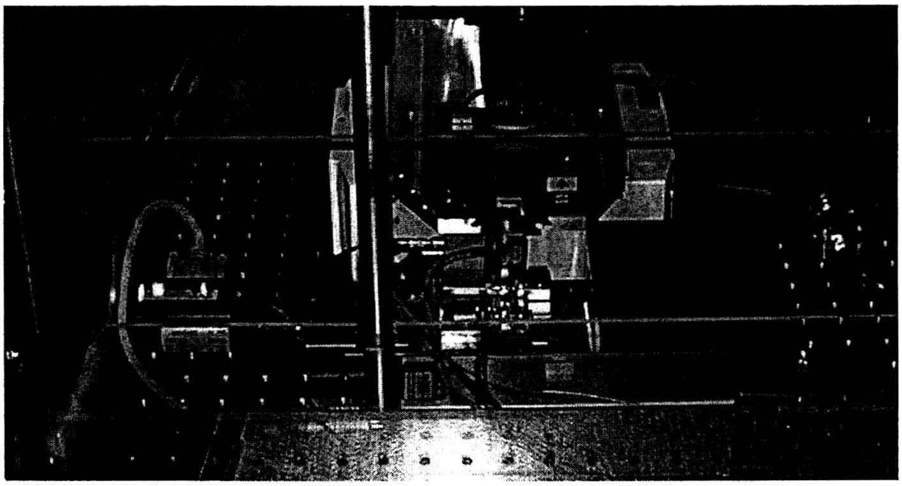

Fig. 3. Photograph of the one-dimensional laser Doppler linear actuator system for an atomic force microscope.

We have measured the closed-loop control resolution for a one-dimensional laser Doppler linear actuator system. A series of three 0.3 nm steps and three 0.1 nm steps have been demonstrated as shown in Fig. 4.

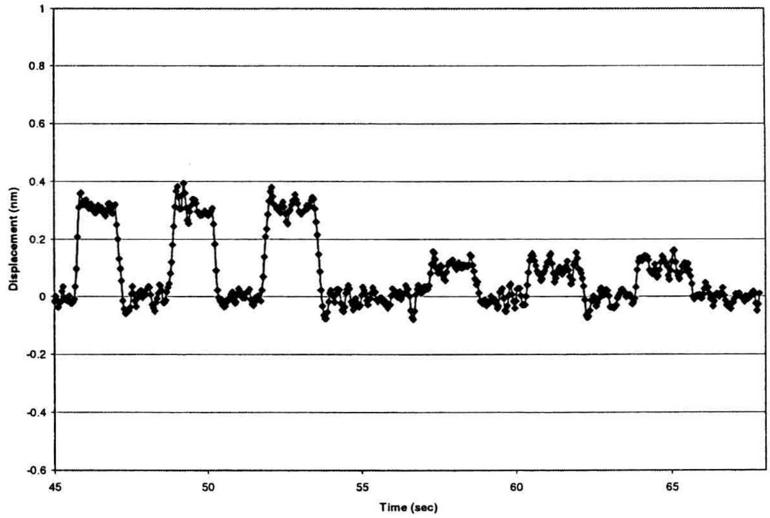

Fig. 4. Resolution test of the one-dimensional laser Doppler linear actuator closed-loop control system. A series of three 0.3 nm steps (left side) and three 0.1 nm steps (right side) have been demonstrated.

5. Design of multiaxis stages with differential measurement capability for a x-ray scanning nanoprobe

A hard x-ray nanoprobe has been proposed as the centerpiece of the x-ray characterization facilities at the APS for the proposed Center for Nanoscale Materials (CNM) to be established at Argonne National Laboratory. This new probe will cover a photon energy range of 3-30 keV. The working distance between the nanofocusing optics and the sample will typically be in the range of 10-30 mm [12]. A dedicated set of source, beamline, and optics will be used to avoid compromising the capabilities of the nanoprobe [13]. This unique instrument will offer diverse capabilities in studying nanomaterials and nanostructures.

We have developed a prototype instrument with a novel LDDM-based scanning stage system. The system consists of nine DC-motor-driven stages, four picomotor-driven stages [14], and two PZT-driven stages. An APS-designed custom-built laser Doppler displacement meter system provides two-dimensional differential displacement measurement with subnanometer resolution between the zone-plate x-ray optics and the sample holder. Also included is the alignment and stable positioning of two stacked zone plates for increasing the focusing efficiency. The entire scanning system was designed with high stiffness, high repeatability, low drift, flexible scanning schemes, and possibility of fast feedback for differential motion. Fig. 5 is a photograph of the prototype scanning stage system for x-ray nanoprobe development. The test of this prototype is in progress.

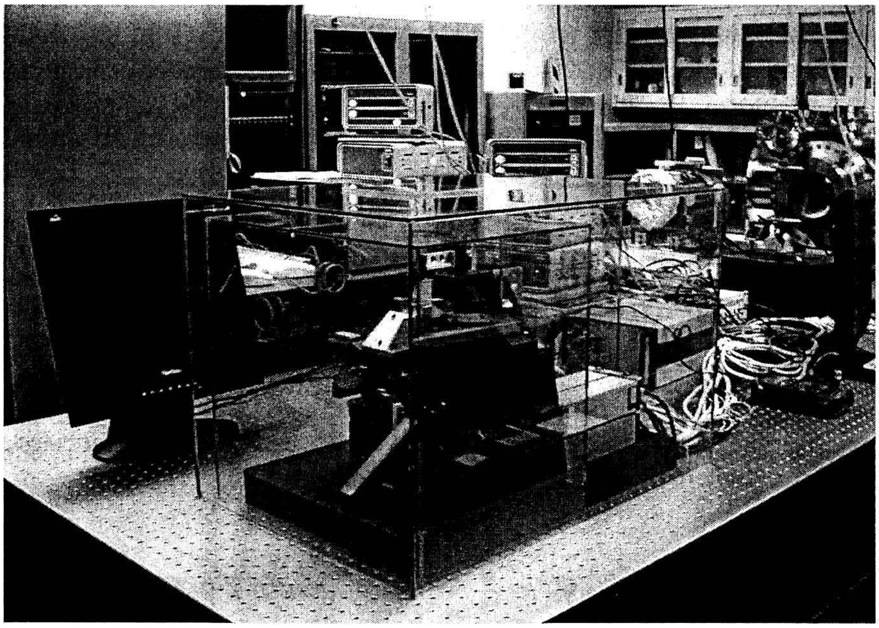

Fig. 5, Photograph of the prototype of multidimensional stages with differential measurement capability for x-ray nanoprobe development.

6. Conclusion

Over the last few years, progress has been made in the development of novel mechanisms with high positioning resolution and high stability at the APS. Applications include: high-energy-resolution x-ray crystal monochromator and x-ray nanoprobe scanning stages. Further development will be focused on the techniques of differential positioning measurement and structural dynamics optimization for multiaxis ultra-high-precision positioning devices.

7. Acknowledgments

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[14] Picomotor is a trademark of Newfocus Co. California.

Key words: precision motion control, encoder, linear stage

Towards a coarse/fine approach to multi-degree-of-freedom ultra-precision motion control systems

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David Otten, David L. Trumper, MIT Cambridge

Abstract. This abstract presents some of the controller issues that are being addressed in the development of an accurate nanometer level positioning system for scanning specimens of an area measuring 50 x 50 mm using a combined coarse and fine motion control stage. It is envisaged that the final system design will comprise a long-range, two-axis *XY* coarse positioning system with a short-range, 6 degree of freedom fine motion platform (10 μm, 40 μrad), to achieve nanometer resolution positioning. Motion of this platform relative to a measurement frame will be achieved using a laser interferometer. The complete system will be housed in a vacuum chamber in a temperature-controlled laboratory. Prior to manufacture of this complete system, a number of concerns such as, vacuum system design, nanometer precision bearings, controller strategy and interferometer configuration must be addressed. Currently, we are developing controller algorithm and implementation strategies. As a first step to assess a cascade controller implantations, a considerably simpler, single-axis, coarse/fine stage has been design and manufactured. This system will be interfaced with a custom-built, DSP-based controller based around a dSPACE™ architecture described herein. As well as some controller implementation strategies and considerations, results from preliminary tests on this system will be presented.

Introduction

The primary motivation for this project is to help facilitate the transition from nano-science to productive nanotechnology. The current system will provide the ability to "pick and place" at nanometer levels and compare system performance with other comparable designs at international locations such as, National Physical Laboratory (NPL) in the UK, Technical University of Eindhoven (TUE) in the Netherlands and Physikalisch-Technische Bundesanstalt (PTB) in Germany.

Major objectives of this project include;

- Development of integrated position measurement system with nanometer uncertainties traceable to national standards[i].
- Translation mechanism for multi degree-of-freedom motion control.
- Integration of fine motion controllers into long-range instrumentation for nano-scale manipulation in centimeter-sized workspaces.
- Integration of combined uncertainty analyses for determination of system error budget.
- Integration of cascaded multi degree-of-freedom control systems.

Critical requirements of the completed system are as follows

- Vacuum Compatibility of better than 10^{-3} to 10^{-4} Torr
- Range of 50 mm × 50 mm × 10 μm
- Maximum translation velocity of 5 mm s^{-1}

[1] Now at National Institute of Standards and Technology, Gaithersburg, MD, 20899-08221, USA

- Resolution of better than 1 nm
- Accuracy of 10 nm.

The final stage will incorporate mechanical, optical and controller developments.

Mechanical system design

While many design configurations are possible, each having particular pro's and cons, it has been decided that the coarse *XY* positioning stage will be in the form of a stacked pair of linear slides with guide ways being in an 'H' configuration. A 6 degree of freedom fine positioning stage[ii] will be attached to the upper moving carriage to compensate parasitic motion errors, thereby providing *XY* scanning over a large area with local, limited-range, 3 dimensional control at any location, see figure 1. Key components of this design are;

- Rigid metrology frame
- Optical prism configuration for laser feedback
- Stacked *X-Y* motion stage
- Zerodur flats for sliding polymer bearings
- Rohlix/Feed screw nut driven by frameless motor

In the development of this design it became apparent that it would be necessary to develop and assess a number of subsystem elements to obtain a more complete knowledge of expected dynamic performance. One of the key components of this system is the slideway for long-range translation of the *X*- and *Y*-axis carriage. It was decided to base the bearing system on a previous design using PTFE thin film bearings that were successfully implemented in both the Nanostep™ profilometer and the Tetraform™ grinding machine[iii]. However, it was decided to use an alternative UHMWPE design to produce a low-cost, robust, vacuum compatible and modular dry rubbing bearing with sub-nanometer performance[iv]. As of writing, these bearings appear to be relatively robust and appear to be capable of nanometer level repeatable motions with relatively low wear rates[v]. While further tests are being undertaken, current results are favorable for this bearing design.

The vacuum system for housing the complete motion control platform is shown in figure 2. Key parameters of this 304 stainless steel chamber include an of ID 44 inches, a working height of greater than 24 inches, two stage isolation (external and internal isolation) and a maglev turbo pump with roughing pump. This system is currently under construction.

Controller implementation considerations

In this particular design, when trying to simultaneously control two combined mechanical systems having very different performance characteristics. A number of matching issues must be addressed. For a rubbing bearing slideway-based coarse stage, it is known that it may exhibit some, or all, of the following characteristics

1. The frictional component of the bearing is variable during motion, while it may be repeatable the value of the friction coefficient may vary with position.
2. There will be a finite, hysteretic characteristic between the motor torque and carriage displacement.
3. It has been observed[vi] that there is also a micro displacement region that has its own linear dynamic characteristic. This is probably due to the combined compliances of all components of the system in the force loop. In practice this does provide a pseudo fine motion control but only in a single freedom and the vector of this freedom is neither

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