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

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**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 $s^{-1}$

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- 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

known nor a designed-in feature. Alternatively viewed, there will be a finite elastic response prior to macroscopic sliding.

4. In our particular design, being a stacked system, the motion axes will contain a finite coupling again in some or all of the above characteristics.

For the fine motion controller, dynamic characterization is somewhat simpler due to the fact that this flexure-based system can, at limited precisions, be adequately modeled as a linear system. While this enables the application of conventional control laws extensively developed over the last 150 years or so, it is probably the differences between the two systems that will present the challenging problems associated with their integration. Some of the major differences are postulated to include

1. The flexure system is considered to incorporate considerably less energy dissipation.
2. The coarse stage will have control in 2 freedoms while the fine stage is a full 6 degree of freedom mechanism.
3. There will be a coupling between the two systems across a wide range of frequencies and this may be amplitude dependent.

Because of the above considerations, in a first step to investigate the relative magnitude of these interactions and the efficacy of controller strategies, we will be constructing a considerably less complex dual stage system. This will comprise both a single-axis slideway with a single-axis fine motion stage mounted onto its moving carriage, see figure 3. In brief, the key attributes of this system include;

- Five adjustable bearings for alignment of linear slideway
- Two Zerodur optical flats to provide smooth repeatable sliding
- Normal and side preload mechanisms to stabilize slideway
- Drive mechanism consist of Rohlix or feed-screw nut driven by Brushless DC motor

For the purpose of controller testing, a single axis piezoelectric actuator with cube corner reflector will be mounted onto the moving carriage. Details of the system components as well as manufacture and assembly will be presented.

## System control architecture

The stage controller block diagram is shown below. As shown in the diagram, at the highest level the controller is responsible for coordinating fine and coarse motion along with taking images from probe systems associated with the stage. The fine motion stage will be implemented with a six-axis piezoelectrically actuated stage with a range of 10 μm and 0.2 mrad in each axis. Motion of this fine stage will be measured with a six-axis interferometer system. The coarse stage system provides x- and y-motion over long travel (about 50 mm) via two Rohlix/feed-screws driven with brushless DC motors with integral encoders. The controller will coordinate the motion of these two stage systems so as to remain within the limited travel of the fine stage while achieving nanometer-scale resolution over the full travel of the coarse stage.

In support of the high-resolution motion requirements of the stage system, we have developed novel interfaces for the A/D, D/A, and laser interferometer channels. These are described in more detail below.

## High resolution A/D and D/A system

A high resolution analog to digital converter system has been designed and built to take advantage of the benefits of averaging many samples from an A/D converter to produce a low noise digital representation of the analog signal. The system is specifically designed to interface with the DS1103 controller board from dSPACE which we have selected as the main controller for the system. The board is based upon a high speed 18-bit A/D converter from Analog Devices (AD7678) coupled with a 16-bit fixed point DSP from Texas Instruments (TMS320LF2406A). The A/D converter operates at its maximum rate of 100k samples per second. The DSP sums the samples and formats the data for serial transmission to the DS1103. The DS1103 has a PowerPC 604e running at 400 MHz and a slave TMS320F240 running at 20 MHz. The high resolution A/D interfaces with the slave DSP to take advantage of its processing power. A serial interface is used to facilitate galvanic isolation with high speed digital isolators from Agilent (HCPL-092J).

The software in the slave DSP of the DS1103 is configured to serially shift the data from up to 8 A/D converter systems into the controller while also shifting out data to up to 8 D/A converters. 32 bits are shifted from the A/D converters consisting of 25 bits of data and 7 bits representing the number of samples taken. The system sends the sum of all the samples to the DS1103 to prevent round-off errors. Every time the DS1103 requests data, the current sum is transferred into the serial interface hardware and a new sum is started. In this way the system averages as much data as possible for a given controller sample rate.

The A/D converter is provided with a full differential input front end that can accept +/- 10 volt signals. It is built on a small printed circuit board (2.5” x 2.6”) that can be located close to the source of the signal to increase signal fidelity. The isolated interface to the DS1103 is intended to eliminate problems with ground loops. Results of some initial tests on the system are presented below.

**Sample Results from High Resolution A/D**

| Sample Rate | 8 kHz | 5 kHz | 2 kHz | 1 kHz |
|---|---|---|---|---|
| Averaged Samples | 12 - 13 | 20 | 50 | 100 |
| Peak – Peak Error | 2.72 | 2.25 | 1.43 | 1.18 |
| Equivalent Bits | 16.56 | 16.83 | 17.48 | 17.76 |
| RMS Error | 0.405 | 0.324 | 0.238 | 0.184 |
| Equivalent Bits | 19.30 | 19.63 | 20.07 | 20.44 |

As a companion to the high resolution A/D, a high resolution D/A was also designed and built. A 16-bit low glitch voltage output D/A from Linear Technology (LTC1650) was used. It is also built on a small printed circuit board (2.5” x 1.7”) that can be located close to the destination of the signal. It also utilizes an isolated interface to the DS1103 to eliminate ground loop problems. As mentioned previously, the data for the D/A is serially shifted out at the same time the A/D data is shifted in. This overlap makes good use of the available time for transmitting signals to and from the DS1103 and allows for high system sample rates without extremely high serial clock frequencies to the individual components.

## ZMI 4004 Interferometer Interface

The interface for the laser interferometer consists of the following:

- 2 individually isolated 4 channel boards can be connected to dSPACE (8 channels total)
- all channels can be sampled together by dSPACE
- 40-bit position information for each channel (0.1 nm resolution + 3 guard bits)
- 32 bit velocity information for each channel
- 32 bit time information for each channel (50 nsec resolution)

- data transferred to dSPACE as a sequence of parallel bytes (8 bits)
- transfer managed by main processor in 1103 board
- Agilent HCPL-092J isolator

It is expected that the first tests of this system will use the single-axis stage of the preceding section. Early results will be presented at the conference of these proceedings.

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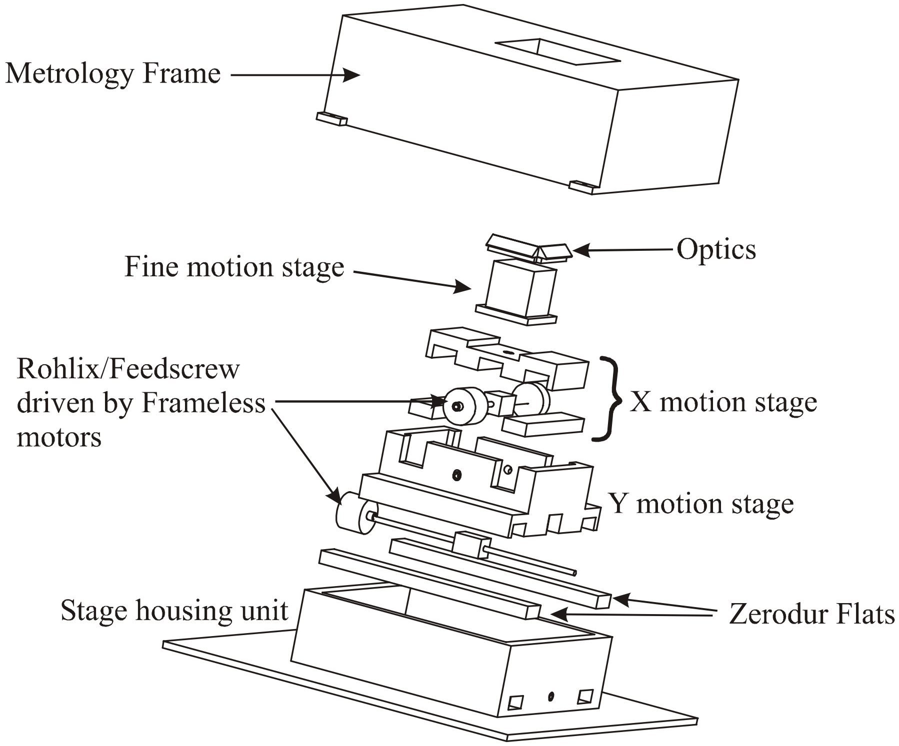

**Figure 1:** Line diagram indicating major components of the complete motion control stage

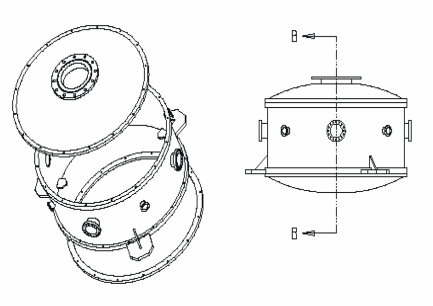

**Figure 2:** Vacuum system

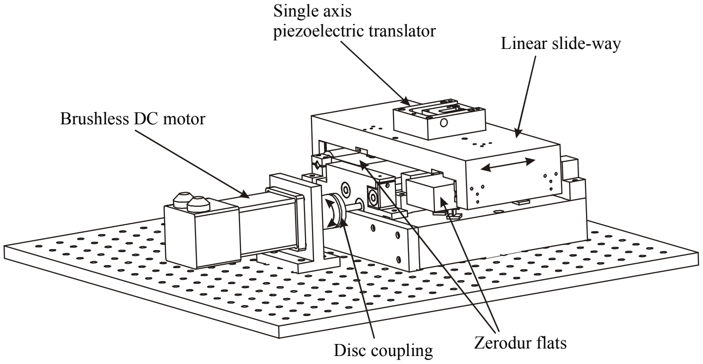

**Figure 3:** Single-axis stage assembly

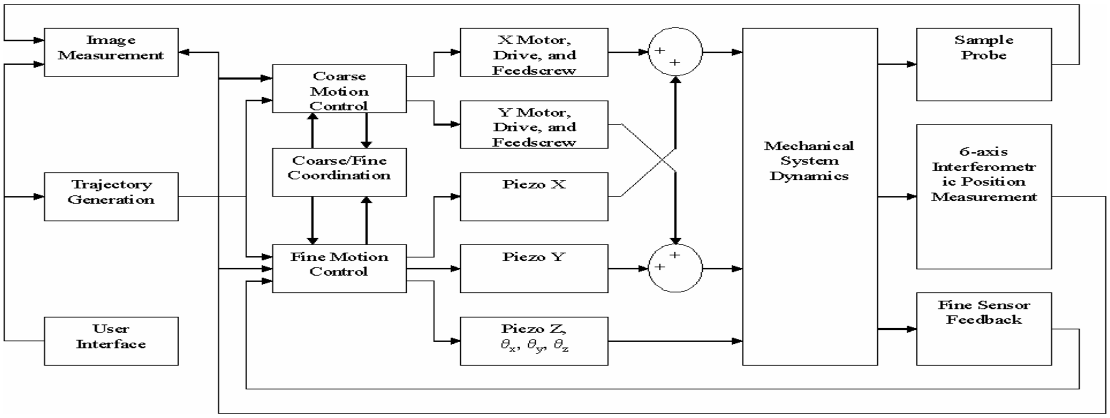

**Figure 4:** Block diagram of system control architecture

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