APPLICATION OF INPUT SHAPING® AND HYPERBIT™ CONTROL TO IMPROVE THE DYNAMIC PERFORMANCE OF A SIX-AXIS MEMS NANOPositioner

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SYNOPSIS
In this paper, we demonstrate how Input Shaping® and HyperBit™ control may be used to obtain fine resolution motion and minimize vibration errors in all six axes of a six-axis, MEMS nanopositioner — microHexFlex [1]. We will first review the dynamic characteristics of the nanopositioner, including the natural frequencies and their corresponding mode shapes. We then demonstrate the effect of Input Shaping® and HyperBit™ on the nanopositioner’s resolution and settling time. Using these techniques, it is possible to obtain ms settling times with sub-nanometer resolution. The practical implications of this work are that future small-scale precision devices will be able to use these techniques to provide low-cost, multi-axis positioning at high-speeds and with fine resolution.

INTRODUCTION
Six-axis nanopositioners have the ability to rectify angular misalignment and thereby correct sine/cosine errors. This capability is important to nanopositioners as angular errors may result in tens of nanometers or more position error. The ability to correct these errors enables six-axis devices to obtain levels of accuracy that are out of the reach of other types of nanopositioners. It is also important to note that six-axis positioners are capable of pivoting about an arbitrary point, i.e. a virtual pivot point, in space. This characteristic would be useful for the creation and inspection of free-form surfaces in applications, such as nano-machining, probing, scanning and manipulation.

The improved accuracy and motion capabilities are most significant if the nanopositioner moves at speeds that are required for creating or inspecting large numbers of features in a short period of time. It is therefore beneficial to possess six-axis capability in a micro-scale device that can take advantage of the beneficial scaling of natural frequency with miniaturization.

This is important for instance in high speed positioning devices for endoscopic scanners [2], integrated alignment mechanisms in micro-optic devices [3], nanoinstrumentation and positioners that are used in nano-manufacturing/data storage [4, 5]. Unfortunately, flexure-based micro-scale positioners are often made from single crystalline Silicon which has negligible damping. As a result, it is difficult to incorporate damping into these micro-/meso-scale nano-positioners. The types of dynamic problems, e.g. ringing and overshoot, which are typically addressed by damping in macro-scale machines, must therefore be addressed at the micro-scale via control techniques. In this paper, we present a study on the effect of two technologies, input shaping and Hyperbit, that can improve the dynamic performance of small-scale nanopositioners.

CASE STUDY: µ-HEXFLEX
The focus our experiments is the microHexFlex, a planar six-axis micro-scale nanomanipulator shown in Fig. 1A.

Figure 1: Overview of µ-HexFlex

The device contains teams of micro-actuators [1] that cause the stage to move in one to six axes. Motions are achieved using actuators that deform the device’s compliant structure and thereby cause the stage to move in a controlled manner. Structurally, the microHexFlex consists
of two layers of single crystalline silicon with one layer of silicon dioxide that resides between them. This multi-layer architecture, shown in Fig 1B, may be used in a bi-morph mode of operation to achieve out-of-plane motions, or in a planar mode of operation to achieve in-plane motions [1]. The stage of the microHexFlex is supported by micro-scale flexures that enhance the actuation displacements from the microactuators.

The dynamic characteristics of a 2.5 mm diameter microHexFlex were obtained via a scanning Laser-Doppler Vibrometer. The first resonance mode peaks at 6.4 kHz with a mode shape that is in the z direction (out-of-the-plane in Fig. 1A). The subsequent three modes occur between 10 kHz to 13 kHz and correspond to tip and tilt mode shapes. More mode shapes, including in-plane motions and out-of-phase motions, at higher resonance frequencies were also obtained in the experiment. Given the preceding information, the modal frequencies may be selectively nullified by the Input shaping/HyperBit algorithm to generate desired motion paths.

In our tests, the thermomechanical actuators were driven via a voltage that was preconditioned using an Input shaping controller. The controller [6, 7] is an implementation of a feed-forward technique that acts to remove ringing and overshoot by modifying the input signal to the actuators to obtain the best possible performance from the positioner.

**INPUT SHAPING®**

An Input Shaping controller is an implementation of a deterministic and robust feed forward technique. It is designed specifically to suppress vibration excited by motion transients. The input shaping algorithm requires only knowledge of the modal frequencies of the system, which in this case were collected experimentally. The controller is designed to reside in series between a function generator and an analog position-command input.

We prefer to observe the resultant motion of the microHexFlex driven by a 100Hz square wave that would command positive Z direction. As shown in Fig 2A, the resultant displacement of the microHexFlex without Input Shaping control exhibits a high frequency ringing effect at ~6.4 kHz. The nullification of this resonant behavior can be observed after the resonance characteristics (frequency ~6400 Hz, damping $\zeta \sim 0.005$) are provided to the Input Shaping controller, as shown in Fig 2B. Note that the drift/slope in Fig 2 is attributable to an integration constant that is obtained when the data (velocity) is integrated to obtain position.

**HYPERBIT™ CONTROL**

HyperBit™ is a recently-developed technique [8, 9, 10] for extending the resolution of digital-to-analog converters (DACs), which is otherwise fixed by the number of addressable bits in a DAC’s command input. In its simplest implementation, the technique involves pulse-width modulation (PWM) of the least-significant bits (LSBs) of the DAC. As DAC update rate capabilities are generally significantly faster than the bandwidths of the devices being driven, this
technique allows the idle time-domain capacity of the DAC to be converted into resolution, as shown in Equation (1).

\[
\text{res}_{\text{bits}} \rightarrow \text{res}_{\text{DAC}} + \log_2 \left( \frac{\text{DAC Rate}}{\text{PWM Frequency}} \right)
\]

(1)

HyperBit is of particular interest to MEMS developers as less silicon real-estate or off-die circuitry is required to achieve a target resolution, enabling a cascade of fabrication cost savings and density improvements. As the microHexFlex is a flexure-based device where friction is negligible, its resolution is typically limited by its drive electronics’ DAC granularity. Figure 3A to 3H shows laser Vibrometer results demonstrating resolution enhancement of microHexFlex under waveform actuation using “bitness-limited” DACs.

FIGURE 3. MicroHexFlex actuation vs. HyperBit configuration. Amplitude chosen for 3 bit transitions of 3-bit DAC. No Input Shaping® is seen in these
examples therefore some ringing can be seen after vertical edge of sawtooth.

CONCLUSION:
We have provided an experimental demonstration of the utility of combining a micro-scale six-axis nanopositioner with Input Shaping and HyperBit Control. The end result of this combination is to show that even though small-scale nanopositioners may have high natural frequencies, this characteristic will not be enough to enable nanometer resolution positioning at high speeds. Damping is difficult to add to micro-scale systems and therefore additional technology is required to realize high-speed nanopositioning via micro-scale devices.

Input Shaping has been shown to have a significant effect via our experimental investigation. The software-based HyperBit technology has also demonstrated the ability to enable low-bit DACs emulate high-bit DACs. The implications of the high-bit DAC emulation are the simplification and further miniaturization of future electronic circuits for on-chip nanopositioners. With the combined technologies, we can now achieve ~5nm resolution at 100 Hz.

We envision that in the near future Input Shaping and Hyperbit control technology will be extensively used in micro-scale positioning systems in various fields. microHexFlex with Input Shaping control, for example, can be used in manufacturing processes that require moving/aligning parts with nanometer resolution, as is the case with many fiber optics components. MicroHexFlex can also be embedded directly into a silicon optical bench, containing numerous smaller devices that need to be kept in alignment over the life of the component.

REFERENCES