SOMETHING FOR (ALMOST) NOTHING: X-ray Microscope Performance Enhancement Through Control Architecture Change

Sheikh T. Mashrafi[1], Curt Preissner[2], Srinivasa Salapaka[1], and Huyue Zhao[2]
[1]Mechanical Science and Engineering
University of Illinois at Urbana-Champaign
Urbana, IL, USA
[2]Advanced Photon Source
Argonne National Laboratory
Argonne, IL, USA

INTRODUCTION

In this abstract we demonstrate that simply by changing the controller architecture the performance of an X-ray microscope can be drastically improved. For instance, we have demonstrated a bandwidth improvement of over 400%. Current microscopes such as the Hard X-ray Nanoprobe (HXN) at the Advanced Photon Source (APS) can focus the X-rays to a 30 nm spot size (1). Thus, nanopositioning is an important enabling technology for X-ray microscopes at synchrotrons like the APS. The performance of the current controllers limits the resolution, bandwidth, and disturbance rejection of the microscope system. The limited performance may not be sufficient for the next generation of X-ray microscopes.

Advanced controls that improve the precision, accuracy, and bandwidth of nanopositioning systems have seen significant development in the realm of scanning probe microscopes (SPMs). In fact, the area of scanning probe control engineering is extremely active with thousands of papers published in the last two years alone, including well cited review articles (2-4). This is significant because no comparable body of work exists in the similar yet much smaller field of X-ray optics nanopositioning. We have leveraged the SPM developments to transform the capabilities of one example X-ray nanopositioning device.

The X-ray microscopes in use around the United States and the world are room-sized devices meeting many constraints and incorporating many components, a small portion of which is the nanopositioning system. With such a complex and integrated system any physical change to the nanopositioning mechanics requires a significant investment in effort and money and may have a cascade effect on other systems.

Rather than change the mechanics we have applied the bandwidth-, robustness-, and precision-expanding control algorithms found in the SPM community. Improving performance in this way costs less effort and money as compared to that required to physically modify the system. Hence our approach does offer something for, when compared to the cost of a X-ray microscope, almost nothing.

The X-ray Nanopositioning Test Bed

We have built a nanopositioning test bed around the Early User Instrument (EUI), prototype for the HXN. We replaced the original controller with a FPGA based system, allowing for implementation of various control algorithms.

The basic layout of the system is shown in figure 1. The fine motion stage is a flexure-based stage with a 15:1 motion reduction driven by four Physik Instrumente piezo stack actuators.

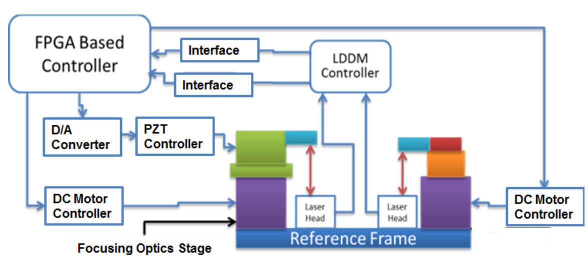

FIGURE 1. A schematic showing the system components. The fine motion stage is part of the focusing optics stack.

<u>Control System Design</u>

A model for the the x-ray optics nanopositioner model was obtained from the frequency response of the system. At each operating point, the system was actuated with pseudo white noise and the corresponding displacement measurement was recorded. A single-input single-output transfer function was fit to this data using identification tools from control systems theory. The system is identified at different operating points covering the range of operation. The system is linear in this range; the natural frequency of the system is around 200 Hz (see Figure 2(a)). The identified plant model was used to design the control laws. The goals of these designs were to achieve high bandwidth, high-resolution (on the order of nm), and high reliability. These objectives are quantified in terms of the closed loop-system transfer functions- the sensitivity transfer function *S(s)* (that models the dynamics from the reference signal to the tracking error, and the complementary sensitivity function *T(s)* that represents the dynamics from the reference signal to the displacement output. The peak-value of the |S(jω)| gives a measure of sensitivity of the closed-loop device and was used to quantify device reliability.

First, we implemented the Proportional-Integral-Derivative (PID) feedback law. We augmented (and implemented) these designs with Glover-McFarlane (GM) feedback laws [4] to guarantee better reliability. We have also designed H_∞ feedback laws, where the above control objectives are cast as an optimization problem and an optimal control law is derived. We designed for low actuator effort, high resolution (noise attenuation), high tracking bandwidth, and reliability as the control objectives.

Results

<u>Baseline system: PI controller</u>: A PID controller with bandwidth 41 Hz meeting the robustly stability criteria is implemented with control law rates up to 200 kHz. PID controllers do not account for uncertainty in plant model and hence fail to guarantee robustness.

<u>GM based robustification of a PI controller:</u> To address this drawback of existing PID control laws GM design is introduced. The GM control law robustifies an existing control law with a small (quantifiable) compromise in performance. This control design accounts for modeling uncertainties and guarantees robust performance by designing for the worst case uncertainty model. We designed and implemented a GM with bandwidth 48 Hz. (Figure 2).

<u>H_∞ Controller with Large Bandwidth:</u> On the other hand, H_∞ control law simultaneously achieves performance and robustness. The bandwidth requirement is based on *S(s)* and the high resolution requirement is achieved from rolling-off of *T(s)* at high frequencies. Simulation results with this feedback law shows a bandwidth of 150 Hz. (in figure 2), which demonstrate the potential for a large bandwidth (over 15 times) improvement.

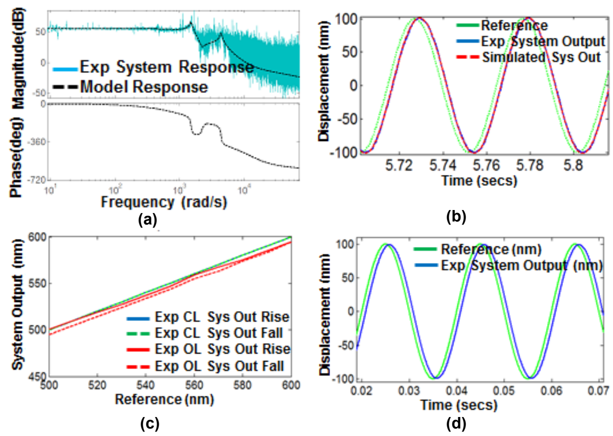

FIGURE 2. (a)Bode plot of experimental system response & the identified model response; (b) Tracking of 20 Hz sine wave with 4rth order Glover-McFarlane control law having bandwidth of 48 Hz; (c) Hysteresis in open loop and its elimination in close loop; (d)Tracking of 50 Hz sine wave with a 4rth order h-infinity control law having 150 Hz bandwidth showed in simulation.

Discussion and Conclusion

We have demonstrated that huge benefits in bandwidth and reliability are obtained by changing the control architecture. The bandwidth was improved by about 4 times (from <10 to 41 Hz). We expect this to improve even more, with our ongoing work on implementing H_∞ control designs.

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