Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach

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Abstract

High-resolution x-ray imaging requires the relative motion between the zone-plate optics and sample stages to accurately track a reference trajectory with large temporal bandwidth and high positioning resolution. Recent advances in feedback control designs have enabled large tracking bandwidth, high positioning resolution, disturbance rejection, noise attenuation, and robustness to unmodeled plant dynamics. However, these efforts have been impeded by sensor drifts, which are not adequately addressed by existing designs. Especially since high-resolution x-ray imaging experiments are typically of long duration, the uncompensated effects of drifts result in imaging artifacts and substantial degradation in achievable spatial image resolution. In this entry, a method is presented for countering sensor drift in real-time through drift measurements and incorporating them in an optimal control architecture.

Keywords

Drift measurement · Real-time compensation

Introduction

X-ray microscopes provide critical advantages over optical counterparts since they achieve higher image resolutions on the order of nanometers due to their shorter wavelengths and enable imaging the internal structure of samples since they penetrate matter far easier than visible light. In scanning transmission x-ray microscopy (STXM), x-rays are produced by passing a high-energy electron beam through a periodic array of magnets, where the Lorentz force causes undulations, as shown in Fig. 1. These undulations elicit the production of synchrotron radiation, an intense beam of x-ray light. This beam, after being filtered through a monochromator, which selects a narrow bandwidth around a chosen frequency, is focused on the sample by appropriately positioning the zone-plate optics stage. This focused x-ray spot is then scanned along a predefined trajectory to cover a target region of the sample. The high-energy x-ray photons interact with the sample molecules and are diffracted in various directions as they pass through the sample, which are then detected downstream. A two-/three-dimensional

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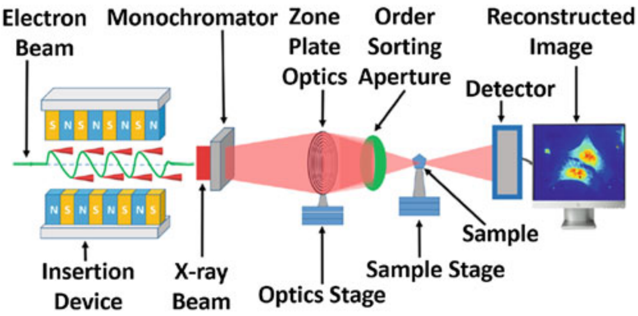
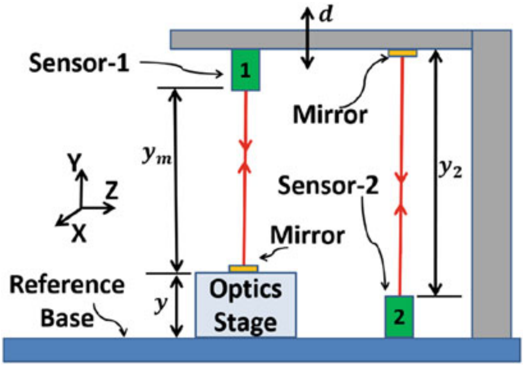


Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 1 A schematic diagram of the scanning transmission x-ray microscopy

image of the scanned sample is reconstructed from the recorded diffraction intensity data.

The image resolution is dependent not only on the quality of the x-ray beam but the precision of the relative motion between optics stage and sample stage. In Mashrafi et al. (2017), authors present a robust optimal control framework for the fine positioning of zone-plate optics stages, which was demonstrated on x-ray microscopes at Advanced Photon Source (APS) at Argonne National Laboratory (ANL). These experiments demonstrated reduction in scanning time by over four orders of magnitude, when compared to existing designs. This control-design framework for high-resolution, high-bandwidth, and robust positioning and tracking is well poised to remove positioning as a bottleneck for achieving high image resolution.

However, this framework relies heavily on how precisely the position of the moving optics stages are known with respect to the global reference frame. The high-resolution laser interferometric sensors are a great choice for implementing the feedback laws, except for one important limitation. The metal alloy fixtures that hold the sensor drift by hundreds of nanometers are due to the cyclic temperature changes, especially in long imaging experiments that can last many hours. For instance, temperature variations of about 0.6° C in a day can lead to a drift over 500 nm. These drifts are significant since the required positioning resolutions are only on the order of few nanometers. Since there is no way to distinguish between the actual motion of the scanning stage and the sensor drift, the control system does not even recognize the drift and fails to compensate for it. This entry presents a method to counteract the sensor drift.



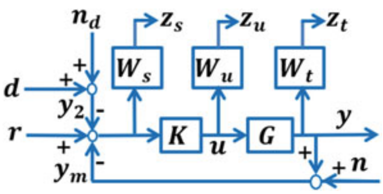
Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 2 Optics-stage measurement system. Primary sensor (sensor-1) drifts due to thermal drift of sensor fixture. Another sensor is added to detect this drift

Figure 2 illustrates the effect of sensor drift on position measurements of an optics stage. Such drift effects are present for the sample stage too; here we do not explicitly discuss its design since the framework presented for the optics stage directly extends to the sample stage. If there were no drift, and sensors were ideal, then the changes in the stage displacement y relative to the reference base are identical to the changes in the sensor measurement y_m; however these are not the same when due to thermal drift of the sensor fixtures, the sensor head itself drifts by a distance d. The existing literature covers primarily image post-processing methods such as using linear and nonlinear drift model to detrend drift effects or filtering and averaging over multiple exposures to increase signal to noise ratio (Beckers et al. 2013). These methods do not address the thermal drift of sensor in real time and result in images where it is not easy to distinguish artifacts from true features in the images.

Drift Compensation Through Feedback Control

In the proposed concept, we add a sensor that measures the relative distance between a reference base and the sensor fixture, which allows for estimating drift of the primary sensor (sensor-1) and compensating for the drift effects. Figure 2 demonstrates the scheme where the optics-stage displacement y_m is measured with sensor-1 and its drift d is measured with sensor-2. Here the sensor-2 measures the motion of the sensor fixture to which sensor-1 is attached with respect to a fixed reference base and therefore gives a measure of the drift d. For nonideal sensors, the differential measurements about operating points are given by $y_m = y + n$ and $y_2 = d + n_d$, where n and n_d are the measurement noises in the two sensors. The measurement y_2 is incorporated in the optimal control design, whose objective is to counter the effects of the drift d.

Figure 3 represents the resulting closed-loop nanopositioning system. In this figure, G represents the transfer function of the scanner which comprises the positioning flexure stage, the actuating, and the sensing components of the positioning system. Here y, u, r, and d represent the stage displacement, the input given to the actuator, the reference to be tracked, and the drift; n and n_d denote sensors' noise, and $y_m = y + n$ and $y_2 = d + n_d$ are the corresponding measurements. The main objective for the design of the feedback control transfer function K is to make the tracking error small (how small is determined by the resolution requirement) over as large a bandwidth as possible while accounting for modeling uncertainties. The tracking error is given by $e = r - y - d = S(r - d) + T(n + n_d)$, where $S = 1/(1 + GK)$ and $T = 1 - S$ are the sensitivity and the complementary sensitivity transfer functions. For good noise attenuation, the controller K needs to be such that $T \approx 1$ within the tracking bandwidth and small in high frequencies where measurement noise n and n_d are predominant. Similarly for drift compensation, S should be small over the desired tracking bandwidth and in low frequencies where drift d is predominant. Also, low values of the peak in the magnitude plot of sensitivity S ensures robustness to modeling uncertainties.



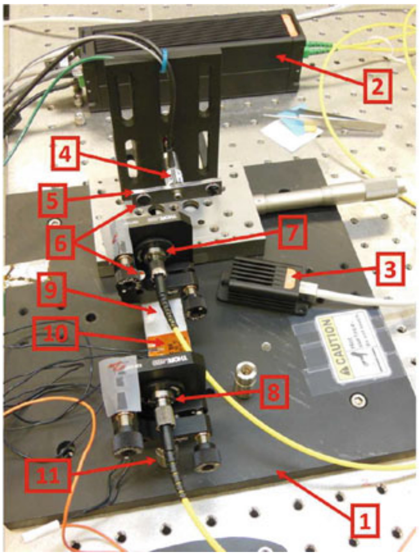
Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 3 Transfer function block diagram for the h-infinity minimization problem

The robust optimal control theory provides an apt framework for incorporating these objectives. In this framework, it is possible to determine if a set of design specifications are feasible, and when feasible the control law K is obtained by posing and solving an optimization problem using easily accessible software routines (e.g., hinfsyn in Matlab). The main advantage of using this optimization framework is that it incorporates performance objectives directly into its cost function. This eliminates the tedious task of tuning gains (in trial-and-hit manner) as in the proportional-integral-derivative (PID) control designs, where even the exhaustively tuned gains may fail to yield acceptable performance. In our context, the optimal control algorithm K is obtained by solving the following minimization problem, $\min_{stab.\,K} \|T_{wz}\|_\infty$, where, T_{wz} is the closed-loop matrix transfer function from exogenous inputs $w = [r - d \; n \; n_d]$ to regulated outputs $z = [z_s \; z_u \; z_t]$. Here the weighted tracking error $z_s = W_s(r - y - d)$, weighted stage displacement $z_t = W_t \, y$, and weighted control effort $z_u = W_u \, u$ are the output signals that need to be made small; accordingly W_s is designed to be high over the desired tracking bandwidth, W_t is high over the frequency range where sensor noise is dominant, and W_u is made high in those frequency ranges where the control effort needs to be small.

Experimental Setup and Results

Figure 4 illustrates the experimental setup. Here laser interferometric sensor is used to measure the displacements, where mirrors are fitted on the target surfaces and on the back of each sensor for reflecting the laser beam coming from the sensors. Such sensor shown as $\boxed{7}$ with corresponding mirror $\boxed{6}$ is used to measure the position of the piezo actuated $\boxed{4}$ Al-alloy target $\boxed{5}$, and sensor $\boxed{8}$ measures the drift of the sensor $\boxed{7}$. Sensor $\boxed{7}$ is positioned at one end of Al-alloy bar $\boxed{9}$ (sensor fixture), which is attached on an Al-alloy post $\boxed{11}$. Sensor $\boxed{8}$ is attached on another Al-alloy post. To replicate the sensor thermal drift, two heat sheets $\boxed{10}$ were attached on both surfaces of the Al-alloy bar $\boxed{9}$ and were turned on/off for certain time periods. The sensor measurements were used for the feedback which were implemented on a field-programmable gate array-based digital signal processor running at 40 MHz.

To determine the piezo actuator and stage dynamics, a band-limited uniform white noise with amplitude 1500 nm was given as input to the actuator, and the corresponding displacement was measured. A 18th order model G was fit to the nonparametric frequency response function, which was estimated from the time-domain input-output data (Fig. 5a). The first resonance peak of the actuator is around 800 Hz. Accordingly, the optimal control problem presented in the previous section was solved to obtain K shown in Fig. 5a; the resulting sensitivity S and complementary sensitivity T transfer functions are shown in Fig. 5b, c.



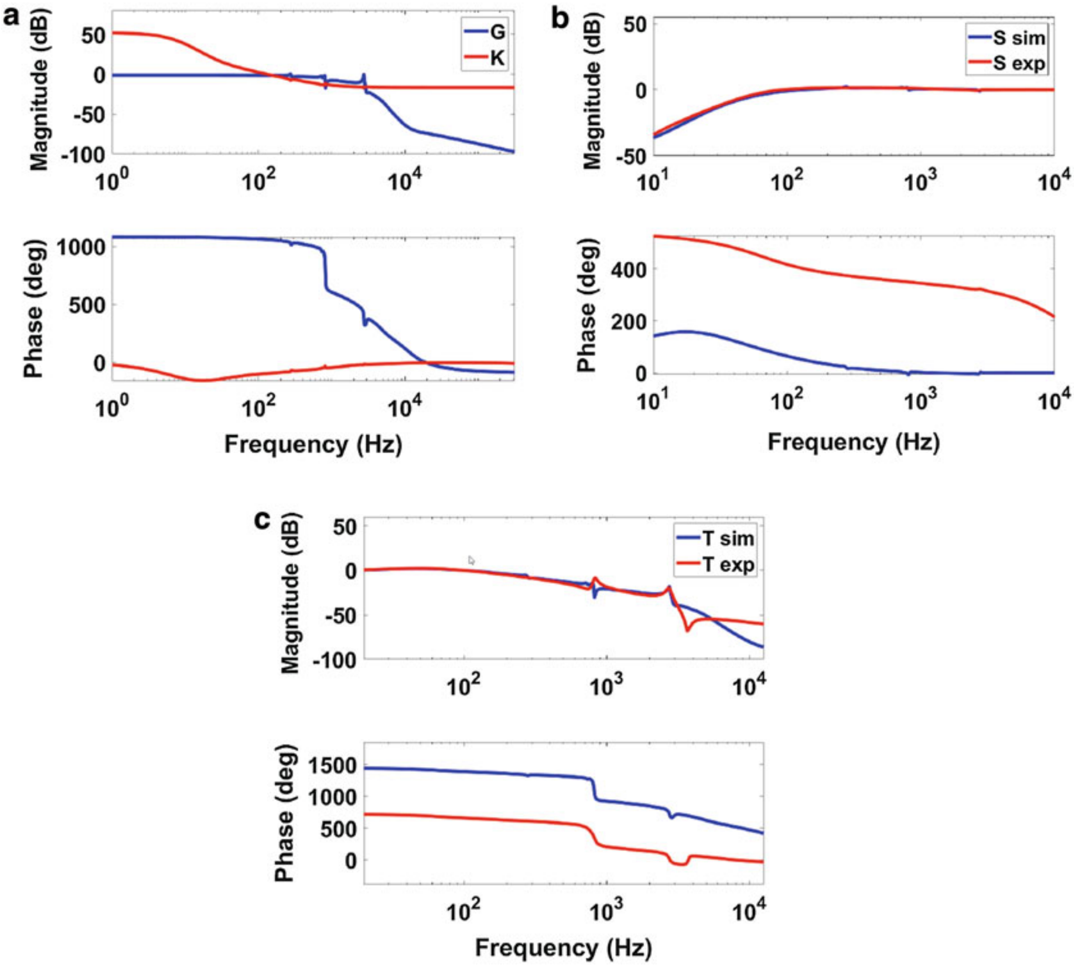
Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 4 Setup for sensor drift rejection

To replicate a 24-h thermal cycle of the APS beamline at ANL, the heat sheets were turned on for 10 min. Data was collected for 30 min to let the setup cool down to ambient temperature. The open-loop (OL) response of a sinusoidal signal with amplitude 1000 nm and frequency 8 Hz is shown in Fig. 6a. It does not distinguish sensor drift ($d \; OL$, (Fig. 6c)) from the actuator motion, and, consequently, the tracking error $e = r - y$ (Fig. 6b) is quite large and mimics the sensor drift. The closed-loop tracking error on the other hand is only about 2% of the input amplitude, of which 1% is due to the sensor noise.

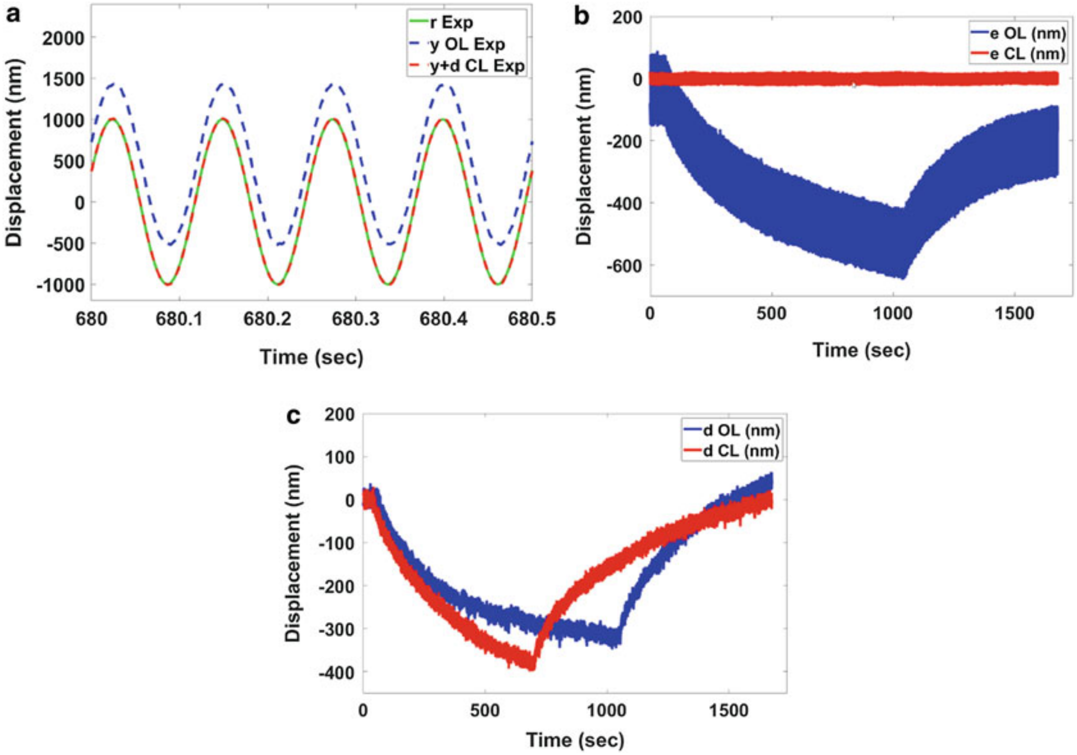
The positioning resolution of the actuator in open-loop (no knowledge of sensor drift) and in closed-loop (with knowledge of sensor drift) was calculated by giving a zero reference signal, where the actuator is solely driven by external disturbance and noise. Respective noise histograms of the measured displacements in Fig. 7 demonstrate an improvement of over 180% in 3σ-resolution – from 35.6 nm in open-loop to 3.8 nm in the closed-loop.

Summary

To counter sensor drift, a key limitation of x-ray imaging resolution, an optimal control scheme is presented, which designs a feedback law that uses drift measurements to compensate for the drift effects. The experimental tracking results demonstrate practical elimination of the drift effects with the design and substantial reduction of over 180% in positioning resolution. This design will significantly improve x-ray microscopy in terms of spatial resolution and quality of images.

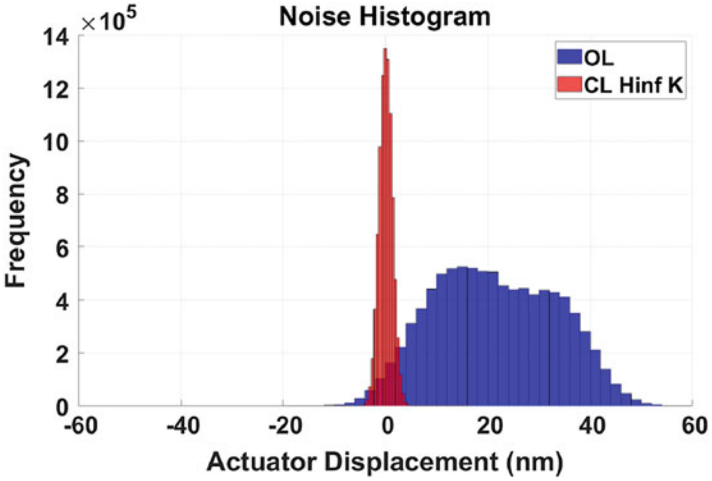


Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 5 Bode plots of (**a**) the positioning system G and the designed controller K; (**b**), (**c**) simulated and experimental sensitivity (S) and complementary sensitivity (T) maps



Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 6 Open- (OL) and closed-loop (CL) tracking results. The control design achieves much better tracking as seen in (**a**), (**b**); the sensor drift is seen in (**c**)

Sensor Drift Rejection in X-Ray Microscopy: A Robust Optimal Control Approach, Fig. 7 Resolution experimental results. Histograms of open-loop and closed-loop responses to external disturbances and noise



Cross-References

- ▶ Control Systems for Nanopositioning
- ▶ Control for Precision Mechatronics
- ▶ Mechanical Design and Control for Speed and Precision
- ▶ Scanning Probe Microscopy Imaging Control

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