A closed-loop approach to reducing scan errors in nanopositioning platforms

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Abstract: Piezoelectric stack-actuated parallel-kinematic nanopositioning platforms have their first resonant mode at relatively low frequencies and also suffer from nonlinearities such as hysteresis and creep, resulting in a typically low-grade positioning performance. Closed-loop control algorithms have shown the potential to eliminate these problems and achieve robust, repeatable nanopositioning. In this work, the performance of three commonly used damping controllers is compared based on their closed-loop noise characteristics. The best one is combined with an integrator to produce accurate raster scans of large areas while imparting substantial damping to the system and minimizing inherent nonlinearities. A scanning resolution of approximately 8nm, over a 100μm × 100μm area is achieved.

Keywords: Nanopositioning, resonance damping, tracking, feedback control

1. INTRODUCTION

Advances in nanopositioning directly affect a range of important fields including nanomachining, scanning probe microscopy, microlithography and nanometrology, Fuji-masa (1996); Desai et al. (1998); Bhushan (2004). Nano-platforms have desirable properties such as larger range of motion, greater mechanical robustness, lower cross-coupling between the axes and ease of integration.

The two main factors that limit the performance of nanopositioning platforms are: (i) Resonance and (ii) Nonlinearities. Researchers, Kang and Mills (2005), have proposed techniques to damp the resonant modes of highly resonant systems such as piezoelectric tube nanopositioners. Passive techniques such as shunt damping have been reported by earlier researchers, Fleming and Moheimani (2006). Although, such techniques can deliver acceptable performance, they may need frequent tuning, Niederberger et al. (2004). Resonant control has been applied to damp resonant systems, Pota et al. (2002). These controllers have attractive robustness properties. However, they also have a high-pass profile that may worsen the measurement noise, a main consideration in precise nanopositioning applications. Polynomial-based pole placement control, Goodwin et al. (2001), and Positive Position Feedback (PPF) control, Fanson and Caughey (1990), are some other popular techniques and have been applied to damp the resonant modes of nanopositioning systems such as the piezoelectric tube nanopositioners, Bhikkaji et al. (2007) as well as cantilever beams, Moheimani et al. (2006). These controllers provide robust damping performance under variations in resonance frequencies. They also have a high-frequency roll-off and thus do not excite the unmodeled high-frequency dynamics.

In nanopositioning platforms actuated by piezoelectric stacks, nonlinearities such as hysteresis and creep result in degraded scan performance. Closed-loop compensation of hysteresis and creep is desirable and simple tracking controllers such as an integrator, have shown potential in eliminating the errors due to these nonlinearities, Jung et al. (2001).

Closed-loop nanopositioning schemes are less common than the open-loop architectures due to the low resolution resulting from the feed back sensor noise, see Sebastian and Salapaka (2005). Croft et al. (2001) have proposed open-loop compensation for the vibration as well as nonlinearities in piezoelectric actuators. Researchers have also proposed feedforward techniques to address hysteresis as well as simple filter based compensation techniques to deal with creep in piezoelectrically actuated scanning devices, El-Rifai and Youcef-Toumi (2002). Most techniques are used to obtain scans either for very small ranges (<10 μm) or at low speeds (<1 Hz). We propose a simple yet well-performing closed-loop nanopositioning scheme that results in high-resolution scans of large areas (100μm × 100μm) at high speeds (4 Hz).

1.1 Objectives

The main objective of this work is to obtain high-resolution closed-loop raster scans using a piezoelectric stack-actuated nanopositioning platform. Section 2 describes the experimental setup and Section 3 gives the details of the system identification and the design algorithms for the three controllers. Based on the noise analysis given in Section 4, the Polynomial-based pole placement controller is deemed most suitable for this specific application. Experimental results are given in Section 5 and Section 6 concludes the paper.

2. EXPERIMENTAL SETUP

The PI-734 nanopositioning platform, used in this work, is a two-axis piezoelectric stack-actuated platform based on
Fig. 1. Working principle of the monolithic XY piezoelectric-stack actuated nanopositioning platform.

3. SYSTEM IDENTIFICATION AND CONTROL
The nanopositioning platform is treated as a two-input two-output linear system with inputs $u_x$ and $u_y$ being the voltage signals applied to the piezoelectric stacks in the X and Y directions, respectively, and the outputs $d_x$ and $d_y$ being the corresponding displacements in $\mu$m, measured by the capacitive sensor. Here, we set

$$Y(s) \triangleq G(s)U(s), \quad (1)$$

where $U(s)$ is the Laplace transform of $[u_x, u_y]^T$, $Y(s)$ denotes the Laplace transform of $[d_x, d_y]^T$, and

$$G(s) = \begin{bmatrix} G_{xx}(s) & G_{xy}(s) \\ G_{yx}(s) & G_{yy}(s) \end{bmatrix} \quad (2)$$

is $2 \times 2$ matrix of transfer functions.

It is evident from the plots (Figure 5) that the magnitude of the cross coupling terms $G_{xy}(i\omega)$ and $G_{yx}(i\omega)$, at any $\omega > 0$, are less than the direct terms $G_{xx}(i\omega)$ and $G_{yy}(i\omega)$, respectively, by about 40 dB. Therefore the two resonant modes seen in each of the cross-coupling FRFs are due to the mechanical resonant peaks of each individual axis. Therefore, they occur at exactly the same frequencies, i.e. at 410 Hz and 415 Hz, in both the $G_{xy}$ and $G_{yx}$.

 cross coupling terms can be neglected and the system is assumed to be decoupled.

$$G_{xx}(s) = \frac{k_x}{s^2 + 2\sigma_x\omega_x s + \omega_x^2} + D_x, \quad (3)$$

and

$$G_{yy}(s) = \frac{k_y}{s^2 + 2\sigma_y\omega_y s + \omega_y^2} + D_y, \quad (4)$$

accurately capture the dynamics of the measured FRFs. The parameters of these models are tabulated in Table 1. As the models are of second order their estimation is not difficult, and the details on parameter estimation are omitted.

| $k_x$ | $8.1532 \times 10^4$ |
| $2\sigma_x\omega_x$ | $6.05 \times 10^4$ |
| $\omega_x^2$ | $6.65 \times 10^9$ |
| $D_x$ | $-0.13$ |
| $k_y$ | $8.6023 \times 10^9$ |
| $2\sigma_y\omega_y$ | $5.64 \times 10^4$ |
| $\omega_y^2$ | $6.8 \times 10^9$ |
| $D_y$ | $-0.13$ |

Table 1. Parameter values of the FRFs $G_{xx}(s), G_{yy}(s), G_{cx}, (s)$ and $G_{cy}, (s)$

3.1 Control Design
As the axes are considered to be decoupled, controllers are designed independently for each axis and the implemented strategy is shown in Figure 2. Here, controller $C_1(s)$ is aimed at damping the resonant mode of $G_{xx}(s)$ (or $G_{yy}(s)$), while $C_2(s)$ is incorporated for tracking the reference signal. In the following, three different control techniques, (i) Polynomial-based pole placement control (will be referred to as Polynomial-based control, from now on) (ii) PPF control and (iii) Resonant control, will be used for obtaining $C_1(s)$. The controllers will be chosen such that all the three damp the resonant peak by approximately the same level. In Section 4, one of the three will be chosen based on their response to sensor noise $n(t)$, see Figure 2.

**Polynomial-based controller**: In the current context, a Polynomial-based controller is defined by the second order transfer-function

$$G_{xx}(s)G_{yy}(s)G_{cx}, (s)$$

Note that both PPF and Polynomial-based controllers are implemented in positive feedback while the resonant controller is implemented in negative feedback.
where \( \xi, \omega, \Gamma_1 \) and \( \Gamma_2 \) are the design parameters. Since the feedback is positive, the transfer-function connecting the output \( d_x \) and the input \( u_x \) is given by

\[
G_{xx}^{(c)}(s) = \frac{G_{xx}(s)}{1 - G_{xx}(s)K_{poly}(s)}.
\]  

For the closed loop system to be well damped it is desirable that its poles are well inside the left half plane. The poles of \( G_{xx}(s) \), computed from (3), are \( p_{\pm} = -30.23 \pm i2578.5 \). Here, the desired closed-loop poles are set to

\[
P_1 = P_2 = -1030.23 \pm i2578.5,
\]

which amounts to placing the closed-loop poles of the system further into the left half plane by 1000 units.

It can be checked that the controller

\[
K_{poly}(s) \triangleq -499.9s + 3.249 \times 10^6
\]

would render a closed-loop system having poles at \( P_{1+}, P_{2+}, P_{1-}, \) and \( P_{2-} \). This controller damps the resonant mode of the x-axis by 23 dB.

**PPF Controller:** A PPF controller is defined by the second order transfer function

\[
K_{PPF}(s) = \frac{\gamma_p}{s^2 + 2\eta \omega_n s + \omega_n^2}.
\]  

It is similar to Polynomial-based controller, (5), but without the velocity term \( \Gamma_1 \). As the feedback is positive, the transfer-function connecting the output \( d_x \) and the input \( u_x \) is as in (6) but with \( K_{poly}(s) \) replaced by \( K_{PPF} \). Here, we aspire for a PPF controller, \( K_{PPF} \), which gives the same level of damping as the controller, \( K_{poly} \), (7). Since, in (7) \( |\Gamma_1| << |\Gamma_2| \), the effect of \( \Gamma_1 \) is negligible near the low frequency regions. Thus, a PPF controller with \( \Gamma_1 \) set zero in (7) would behave the same way as (7) near the low frequency regions. Thus, \( \Gamma_1 \) is set to zero. The resulting PPF controller given by

\[
K_{PPF}(s) \triangleq \frac{3.249 \times 10^6}{s^2 + 4121s + 1.247 \times 10^7},
\]  

is stable in closed-loop and delivers the same level of damping as (7).

**Resonant Controller:** In the current context, resonant controllers can be parametrized as

\[
K_{Res}(s) = \frac{\alpha s^2}{s^2 + 2\delta \omega_x s + \omega_x^2}.
\]  

As \( K_{Res}(s) \) is targeted to damp the resonant mode of the nanopositioning platform, \( \omega \) is set to the first resonance frequency of the platform. The values of \( \alpha \) and \( \delta \) are chosen graphically such that the absolute value of the difference \( h \), between the real parts of the corresponding open- and closed-loop poles is minimized. The resultant Resonant controller that imparts the same amount of damping as the Polynomial-based controller is

\[
Y(s) = \frac{G(s)C_2(s)}{1 + G(s)(C_2(s) - C_1(s))R(s)} - \frac{G(s)(C_2(s) - C_1(s))}{1 + G(s)(C_2(s) - C_1(s)))}N(s)
\]

\[
\triangleq G_y(s)R(s) - G_y(s)N(s),
\]  

where \( G(s) \) denotes the plant dynamics, \( C_1(s) \) and \( C_2(s) \) denote the Polynomial-based controller and the integral controller respectively, while \( R(s) \) and \( N(s) \) are Laplace transforms of the reference signal \( r(t) \) and noise \( n(t) \) respectively. When operating in open loop, where \( Y(s) = G(s)R(s) \), the sensor noise does not disturb the actuation of the plant. However, in closed loop, the sensor noise is fed back into the system, leading to an additional term \( Y_n(s) \triangleq G_y(s)N(s) \); the noise response.

The sensor noise \( n(t) \) is assumed to be both stationary and ergodic. Thus, its mean, variance and covariances can be
approximated by the corresponding sample mean, sample variance and sample covariances. The sample mean, $\bar{m}_n$, was approximately 0 and the sample variance, $\sigma_n^2$, was approximately $6.2287 \times 10^{-5} \mu m^2$. Since the mean of $n(t)$ is approximately zero, due to linearity, the mean $\bar{m}_{y_n}$ of the noise response $y_n(t)$ (the inverse Laplace transform of $Y_n(s)$) must also be close to zero, Brown and Hwang (2002).

To determine the variance of $y_n(t)$, the following relationship is used:

$$S_{y_n}(i\omega) = |G_n(i\omega)|^2 S_n(i\omega),$$

where $S_n(i\omega)$ and $S_{y_n}(i\omega)$ are the spectral densities of $n(t)$ and $y_n(t)$ respectively and $G_n(i\omega)$ is as in (12). The details on how to calculate $S_n(i\omega)$ and eventually the variance $\sigma_{y_n}^2$ from $S_{y_n}(i\omega)$ are given Brown and Hwang (2002). They are not presented here due to the constraints on the number of pages.

5. EXPERIMENTAL RESULTS USING THE POLYNOMIAL-BASED CONTROLLER

The Polynomial-based controllers for the $x$ and $y$ axes are given by:

$$K_{Poly}(s) \triangleq \frac{-499.9s + 3.249 \times 10^6}{s^2 + 4121s + 1.247 \times 10^6},$$

and

$$K_{Poly}(s) \triangleq \frac{-490.6s + 3.124 \times 10^6}{s^2 + 4124s + 1.237 \times 10^7},$$

respectively.

The effectiveness of the Polynomial-based controller in damping the resonance of $G_{xx}(s)$ is evaluated both numerically and experimentally. The experimental results agree favourably with the numerical predictions. Figure 5 shows the measured frequency responses of the undamped and damped nanopositioning platform.

To eliminate the problems associated with nonlinearities such as hysteresis and creep, a suitable tracking controller is necessary Croft et al. (1999). An integral controller with a gain of 400 was implemented along with the Polynomial-based damping controller, as shown in Figure 2, to result in a well-damped, accurately tracking nanopositioning platform. This resulted in a stable closed-loop system with adequate gain and phase margins. The closed-loop plots are shown in Figure 6.

As mentioned in Subsection 4.1, due to the feedback of the sensor noise, the system output $y(t)$, (12), is not deterministic but random. Having fixed $C_1(s)$ and $C_2(s)$ for both the axes, the variance of the respective outputs can...
be empirically determined using the scheme presented in Subsection 4.1. Avoiding the details involved in calculating $S_n(i\omega_k)$, $G_n(i\omega_k)$, and $S_{yn}(i\omega_k)$, the empirical values of the variances along the $x$ and $y$ axes are directly presented. The variances are

$$\sigma_{x,y_n}^2 \approx 1.6355 \times 10^{-5} \mu m^2, \quad (16)$$

and

$$\sigma_{y,yn}^2 \approx 1.6230 \times 10^{-5} \mu m^2 \quad (17)$$

along the $x$ and $y$ axis respectively.

5.1 Open- and closed-loop hysteresis and creep evaluation
The platform was excited by a 4 Hz 80 V sine wave and the resultant displacement was measured to give the total deviation from the desired trajectory; the hysteresis loop of the system. Figure 7 (a) shows the open-loop hysteresis plot. Figure 7 (b) shows that the closed-loop control scheme eliminates the nonlinear hysteresis effects almost totally.

The effect of creep on scanning performance is that at two different scan speeds, it produces scans of different magnifications. To test the performance of the open-loop and closed-loop systems for creep, the system is commanded to move instantaneously by 20 $\mu m$ from its zero initial position at $t = 10$ s. Figure 8 shows the output displacement response of the open-loop and closed-loop nanopositioning platform from 0 s to 100 s. As seen clearly from Figure 8, our control scheme has eliminated creep for all practical purposes.

5.2 Raster scan results
A synchronized 4 Hz triangle wave and a staircase waveform were generated to produce the desired raster scan. As shown in Figure 9 (b), this input excites the axis resonance and the output displacement is nonlinear due to hysteresis as seen in Figure 9 (c). The Polynomial-based controller damps the resonant mode and the integrator effectively tracks the 4 Hz input triangle to result in a perfect triangle trace given in Figure 9 (d).

The second axis is given a staircase input and the same performance improvements are observed in closed-loop. The plots presented in Figures 9 and 10 are essentially measurements of the output $y(t)$, (12), along the $x$ and $y$ axes respectively. The measured scan lines of the traced raster pattern are presented in Figure 11. The lines are 62.5 nm apart. The empirical variances given in (16) and (17), imply that the standard deviations $\sigma_{x,y_n}$ and $\sigma_{y,yn}$ are about 4 nm along both the $x$ and $y$ axes. Thus, the
adjacent scan lines in the raster pattern have to be at least 8 nm (twice the standard deviation) apart, to avoid overlap. With this resolution of 8 nm, 12500 scan lines can be produced in a 100 µm scan. In Figure 11, the scan lines are 62.5 nm apart, which is about 15 times the standard deviation. A Kalman estimate of the output y(t) is also plotted to show how accurate the obtained scan is, with respect to the desired scan.

6. CONCLUSIONS
The Polynomial-based controller was identified as the most suitable option for this nanopositioning application. The implemented Polynomial-based controller damps the dominant first resonant mode of the nanopositioning platform by 23 dB. It was further shown that by combining this damping technique with an integral controller, nonlinear effects due to hysteresis and creep are minimized and superior tracking performance is achieved. This was demonstrated by tracing a 4 Hz 80µm × 80µm raster scan with a resolution of 62.5 nm. Noise analysis suggests a resolution of 8 nm is achievable. A more complete noise model, for the covariance data presented Section 4, using the innovations approach would give a better insight into the noise response and eventually would help in achieving a better resolution.

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REFERENCES