Performance Enhancements of a High Precision Scanning Stage

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***Abstract*—Recently, a two dimensional high precision scanning stage was developed at the Department of Automation Engineering, National Formosa University, Taiwan. This stage is composed by two stages, a two-degrees-of-freedom (DOF) (X and Y) linear cross roller guide way supported stage and a 4-DOF (Z, θ_x, θ_y and θ_z) piezo-stage. Two linear shaft voice coil motor are used to actuate the roller guided X-Y stage and five piezoelectric actuators are used in the piezo-stage. The working range of the stage is 25 mm × 25 mm. The piezo-stage is used to compensate the vertical position, row, pitch and yow errors throughout the whole working range. In this note, the control systems of this stage are presented. In order not to stimulate the eigenfrequencies of the stage, a fourth order track planning method is used to derive the command curve for motion control. Moreover, a friction model based feedforward controller is added to compensate the effect of friction. Experimental results are presented to show the performance of this stage.**

***Index Terms*—precision scanning stage, piezoelectric, six-degrees-of-freedom, voice coil motor, track planning, friction compensation**

I. Introduction

In micro and nano-technology, positioning with high resolution is necessary for measuring or manipulating objects. In general, high precision stage is used to realize these tasks. Today's technology progress in electronics, the semiconductor industry, the optical industry, biotechnology and many others arise the need for operation range in mm ranges of such stages. Recently, several precision stages that can reach mm ranges were presented. For working ranges in about sever to several tens millimeters, magnetic actuator [1]-[3], voice coil motor [4], [12] or stick and slip piezoelectric actuator [5] are usually used. For longer working ranges (more than 100 mm) linear motors are commonly used [6]-[11]. In order to obtain long range and high precision, hybrid stages approach is usually applied [7]-[15]. This kind of stage is combined by two components: a coarse stage and a fine stage. The fine stage, connected to the coarse stage, improves positioning accuracy, resolution and bandwidth, whereas the coarse stage carries the fine stage over long strokes. The driver used in coarse stage may be linear motor [7]-[11], DC servo motor with ball-screw [13] or pneumatic cylinder [14], [15]. For fine stages, magnetic actuator [9], [10], piezoelectric actuator [7], [8], [11] may be used.

Manuscript received August 21, 2015; revised November 1, 2015.
This work was supported by Ministry of Science and Technology, Taiwan under grant 104-2221-E-150 -008.

Recently, a two dimensional high precision scanning stage was developed in the Department of Automation Engineering, National Formosa University, Taiwan [12]. This stage is composed by two stages, a voice coil driven 2-DOF (X and Y) cross roller guide way supported stage and a 4-DOF (Z, θ_x, θ_y and θ_z) piezo-stage. The working range of this stage is 25 x 25 mm^2 and the piezo-stage is designed for compensating the vertical positioning error and angle deviations.

In this note, the control of this stage is presented. In the control system, a 6-DOF optical measurement system that consists of four laser interferometers and one quadrant photo-diodes is used to measure the position and angle errors of the stage. In order not to stimulate the eigenfrequencies of the mechanic parts, a fourth order track planning method [16] is used to derive the command curve for motion control. Moreover, for improving the performance of tracking control, a friction model based feedforward controller [17]-[19] is added to compensate the effect of friction.

This note is arranged as follows. In Section II, the structure of the stage and the 6-DOF measurement system for measuring the feedback signals is presented. Section III describes the setup of the whole system, the structure of the feedback controller. Experimental results then presented in Section IV. Finally, some conclusions are given in Section V.

II. The Stage and the Measurement System

A. The Stage

The structure of the stage (as shown in Fig. 1) is described briefly in this subsection, for more details please refer to [12]. The stage considered is composed by two stages; a 2-DOF linear cross roller guide way supported stage (X-Y stage) and a 4-DOF piezo-stage. The piezo-stage is arranged on the top of the X-Y stage to compensate the vertical position, row, pitch and yow errors throughout the whole working range of the X-Y stage. The operation range of this stage is 25 × 25 mm^2. Each axis of X-Y stage is supported by two linear cross roller guide ways and is driven by a linear voice coil motor. The piezo-stage is a flexure hinge based design. It is composed

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doi: 10.18178/joace.4.5.360-364

$\Delta_3(\cdot)=\left[0,\cdots,0,-c\int_{t-\tau}^{t}\eta_1(s)ds,0,0\right]^T$, and $\eta(t)=[0,\cdots,0,\eta_1(t),0]^T$. From [10], since $A_{\bar{K}}=A+B\bar{K}$ is Hurwitz where $\bar{K}=\bar{K}(1)$, we can obtain a Lyapunov equation of $A_{\bar{K}(\gamma)}^T P_K(\gamma)+P_K(\gamma)A_{\bar{K}(\gamma)}=-\gamma^{-1}E_\gamma^2$ where $P_K(\gamma)=E_\gamma P_K E_\gamma$, $E_\gamma=\mathrm{diag}[1,\gamma,\cdots,\gamma^n]$, and $A_{\bar{K}}^T P_K+P_K A_{\bar{K}}=-I$. We set a Lyapunov function $V(\xi)=\xi^T P_K(\gamma)\xi$. Then, along the trajectory of (9)

$$\begin{aligned}\dot{V}(\xi)&=\dot{\xi}^T P_{K(\gamma)}\xi+\xi^T P_{K(\gamma)}\dot{\xi}\\&=-\frac{1}{2}\gamma^{-1}(E_\gamma\xi)^T(E_\gamma\xi)+2\xi^T P_{K(\gamma)}\delta\\&\quad-\frac{1}{4}\gamma^{-1}\|E_\gamma\xi\|^2-\frac{1}{4}\gamma^{-1}\xi^T E_\gamma E_\gamma\xi\\&\quad+2\xi^T E_\gamma P_K E_\gamma\{\Delta_1(\cdot)+\Delta_2(\cdot)+\Delta_3(\cdot)+\eta(t)\}\end{aligned}\tag{10}$$

The first two terms of (10) lead to the following

$$\begin{aligned}&-\frac{1}{2}\gamma^{-1}(E_\gamma\xi)^T(E_\gamma\xi)+2\xi^T P_{K(\gamma)}\delta\\&=-\frac{1}{2}\gamma^{-1}(E_\gamma\xi)^T(E_\gamma\xi)+2(E_\gamma\xi)^T P_K E_\gamma\delta\\&=-\frac{1}{2}\gamma^{-1}(E_\gamma\xi)^T(E_\gamma\xi)\\&\quad+2(E_\gamma\xi)^T\begin{bmatrix}p_{1,1}&\cdots&p_{1,n+1}\\\vdots&\ddots&\vdots\\p_{n+1,1}&\cdots&p_{n+1,n+1}\end{bmatrix}\begin{bmatrix}\frac{c}{\beta}\frac{k_1}{\gamma^{n+1}}\\\frac{c}{\beta}\frac{k_1}{\gamma^{n-1}}\\\vdots\\\frac{c}{\beta}\frac{k_1}{\gamma^{3-n}}\\0\end{bmatrix}(E_\gamma\xi)\\&=-(E_\gamma\xi)^T\begin{bmatrix}\frac{1}{2\gamma}-*_1&-*_2&\cdots&-*_{n+1}\\-*_2&\frac{1}{2\gamma}&&\\\vdots&&\ddots&\vdots\\-*_{n+1}&&\cdots&\frac{1}{2\gamma}\end{bmatrix}(E_\gamma\xi)\\&=:-(E_\gamma\xi)^T\prod(E\ \xi)\end{aligned}\tag{11}$$

where $*_1=\frac{c}{\beta}\left(\frac{k_1}{\gamma^{n+1}}2p_{1,1}+\frac{k_2}{\gamma^{n-1}}2p_{1,2}+\cdots+\frac{k_n}{\gamma^{3-n}}2p_{1,n}\right)$,

$*_i=\frac{c}{\beta}\left(\frac{k_1}{\gamma^{n+2-i}}p_{i,1}+\frac{k_2}{\gamma^{n-i}}p_{i,2}+\cdots+\frac{k_n}{\gamma^{4-n-i}}p_{i,n}\right)$, $(i=2,\cdots,n+1)$.

To investigate the positive definiteness of the matrix $\prod$, we see that

$$\begin{aligned}&\text{i)}\ \left(\frac{1}{2\gamma}-*_1\right)>0\\&\quad\to\frac{\beta}{2\gamma}>c\left(\frac{k_1}{\gamma^{n+1}}2p_{1,1}+\cdots+\frac{k_n}{\gamma^{3-n}}2p_{1,n}\right)\\&\text{ii)}\ \frac{1}{2\gamma}\left(\frac{1}{2\gamma}-*_1\right)-*_2^2>0\\&\quad\to\frac{\beta^2}{4\gamma^2}>\frac{c\beta}{2\gamma}\left(\frac{k_1}{\gamma^{n+1}}2p_{1,1}+\cdots+\frac{k_n}{\gamma^{3-n}}2p_{1,n}\right)\\&\qquad+c^2\left(\frac{k_1}{\gamma^{n}}p_{2,1}+\cdots+\frac{k_n}{\gamma^{2-n}}p_{2,n}\right)^2\\&\text{iii)}\ \frac{1}{(2\gamma)^2}\left(\frac{1}{2\gamma}-*_1\right)-\frac{1}{2\gamma}*_3^2-\frac{1}{2\gamma}*_2^2>0\\&\quad\to\frac{\beta^2}{8\gamma^3}>\frac{c\beta}{4\gamma^2}\left(\frac{k_1}{\gamma^{n+1}}2p_{1,1}+\cdots+\frac{k_n}{\gamma^{3-n}}2p_{1,n}\right)\\&\qquad+\frac{c^2}{2\gamma}\left(\frac{k_1}{\gamma^{n}}p_{2,1}+\cdots+\frac{k_n}{\gamma^{2-n}}p_{2,n}\right)^2\\&\qquad+\frac{c^2}{2\gamma}\left(\frac{k_1}{\gamma^{n-1}}p_{3,1}+\cdots+\frac{k_n}{\gamma^{1-n}}p_{3,n}\right)^2\\&\text{iv)}\ \frac{1}{(2\gamma)^3}\left(\frac{1}{2\gamma}-*_1\right)-\frac{1}{(2\gamma)^2}*_3^2>0\\&\quad\to\frac{\beta^2}{16\gamma^4}>\frac{c\beta}{8\gamma^3}\left(\frac{k_1}{\gamma^{n+1}}2p_{1,1}+\cdots+\frac{k_n}{\gamma^{3-n}}2p_{1,n}\right)\\&\qquad+\frac{c^2}{4\gamma^2}\left(\frac{k_1}{\gamma^{n-1}}p_{3,1}+\cdots+\frac{k_n}{\gamma^{1-n}}p_{3,n}\right)^2\\&\text{v)}\ \frac{1}{(2\gamma)^j}\left(\frac{1}{2\gamma}-*_1\right)>0,\qquad(j=4,\cdots,n)\\&\quad\to\frac{\beta}{(2\gamma)^{j+1}}>\frac{c}{(2\gamma)^j}\left(\frac{k_1}{\gamma^{j+1}}2p_{1,1}+\cdots+\frac{k_n}{\gamma^{3-j}}2p_{1,n}\right)\end{aligned}\tag{12}$$

Thus, from (12), we see that if $\beta\gg\gamma$, $\beta>c$ and $k_i<0$, we have $\prod=\prod^T>0$.

Similarly to [10], we apply the Razumikhin theorem [11] with $\|E_\gamma\xi_t\|\le q\|E_\gamma\xi\|$, $q>1$. Here, we let $\xi_t=\xi(t+\theta)$, $-\tau\le\theta\le 0$ [11]. With this, we first have

$$\begin{aligned}\|E_\gamma\Delta_1(\cdot)\|&\le\tau\gamma^{n-2}\frac{c}{\beta}\|B\tilde{K}(\gamma)\|\|\xi(t+\theta)\|\\&\le\tau q\gamma^{-2}\frac{c}{\beta}\|B\tilde{K}(\gamma)\|\|E_\gamma\xi\|\\\|E_\gamma\Delta_2(\cdot)\|&\le\tau\gamma^{n-2}|\xi_{n+1}(t+\theta)|\le\tau q\gamma^{-2}\|E_\gamma\xi\|\end{aligned}\tag{13}$$

From (10) and (13), we have

$$\begin{aligned}\dot{V}(\xi)&\le-(E_\gamma\xi)^T\prod(E_\gamma\xi)\\&\quad-\frac{1}{4}\left(\gamma^{-1}-8\tau q\sigma\gamma^{-2}-8\tau q\sigma\gamma^{-2}\frac{c}{\beta}\|B\tilde{K}(\gamma)\|\right)\|E_\gamma\xi\|^2\\&\quad-\frac{1}{4}\gamma^{-1}\xi^T E_\gamma E_\gamma\xi+2\xi^T E_\gamma P_K E_\gamma\{\Delta_3(\cdot)+\eta(t)\}\end{aligned}\tag{14}$$