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Three Degrees-of-Freedom Hybrid Stage With Dual Actuators and Its Precision Motion Control

Yonmook Park

*Mechatronics and Manufacturing Technology Center, Samsung Electronics Co., Ltd.
Republic of Korea*

1. Introduction

Nanotechnology can be defined as the research, development and processing of materials, devices and systems in which structure on a dimension of less than several hundreds of nanometer is essential to obtain the required functional performance. There are currently two different approaches to nanotechnology. The first approach is called engineering nanotechnology. This approach involves using classical mechanical and electrical engineering principles to build structures with tolerances at levels approaching a nanometer. The other approach is called molecular nanotechnology. This approach is concerned with self-assembled machines. Due to the startling progress of nanotechnology, we can make high density memories and flat panel display panels with the help of nano-positioning systems. Furthermore, it allows us to manipulate a molecule with scanning probe microscopes.

One of the largest challenges in the field of nanotechnology is precision motion control of macroscopic stages. Especially, precision motion control on the nanometer level that delivers precision position stability with high bandwidth is a very important issue for industrial and scientific applications that especially include the lithography and inspection of integrated circuit patterns (Lee & Kim, 1997; Kwon et al., 2001; Pahk et al., 2001) and the fabrication and operation of high-density magnetic data storage devices (Chung et al., 2000; Kim & Lee, 2004; Lee & Kim, 2004; Du et al., 2005).

In general, traditional stages are designed to operate with respect to a number of kinematic constraints, which are assemblages of mechanical parts and need to be compounded in order to perform multiple degrees-of-freedom (DOF) motion (Shan et al., 2002). These kinematic constraints provide contact friction and error accumulation (Awabdy et al., 1998), and thus, it is very difficult to implement a high-performance motion control system with high bandwidth as well as a precision multiple DOF stage that is capable of large travel with nanometer position stability.

For stages only using coarse actuators such as linear motor or hydraulic actuator, there are nonlinear friction in low-speed motion and resonance mode in high-frequency motion. Thus, it is very difficult to achieve precision motion control performance with only coarse actuators although they provide large travel. One of the methods to overcome their limitation is adopting fine actuators such as piezoelectric actuator or voice coil motor (VCM). But, the travel of fine actuators is about several hundreds of micron meters to several millimeters, which is the limitation of them. Thus, if we design a hybrid actuation

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system with coarse and fine actuators, we can utilise their advantages and mutually compensate their drawbacks. So far, there have been several studies for the design of hybrid actuation systems. For instance, ultraprecision dual-servo systems have been proposed by Lee & Kim, 1997, Kwon et al., 2001, and Pahk et al., 2001 for lithography steppers. Dual-stage actuation systems consisting of a VCM and a microactuator have been developed by Fan et al., 1995 and Li & Horowitz, 2001 to obtain high servo bandwidth and perform the disturbance rejection. A novel control design that aims to achieve a low-hump sensitivity function for a dual-stage system in hard disk drives has been studied by Du et al., 2005. Note that, according to Du et al., 2005, a servo control system with low-hump sensitivity function is able to reduce the contribution from disturbance to a system. Fundamental control designs of dual-stage hard disk drive systems have been presented by Chung et al., 2000, Kim & Lee, 2004 and Lee & Kim, 2004, and performance enhancement methods of dual-stage servo systems have been proposed by Wu et al., 2002 and Li et al., 2003.

This chapter presents a three DOF precision hybrid stage that can move and align an object on it for the measurement of its three-dimensional image using the confocal scanning microscope (CSM). The CSM can observe a sub-micron meter-sized material due to its fine resolution and has a three-dimensional surface profiling capability. The hybrid stage consists of two individually operating x - y - θ stages, called the coarse stage and the fine stage. The coarse stage is driven by the three linear motors, and the fine stage is driven by the four VCMs. The coarse and fine stages are not mechanically interconnected and can be controlled independently.

For control of the hybrid stage, the author proposes a precision motion controller in this chapter. The precision motion controller consists of a position and velocity control loop, an anti-windup compensator to eliminate the windup problem that occurs in the controller, a generator of optimal force to optimally control the fine stage, a precision position determiner to determine the exact position of the fine stage and a perturbation observer that can observe the perturbation of the fine stage and compensate it. Note that, in this chapter, the exact position of the fine stage means the centre of the fine stage that is precisely determined by considering the orientation angle of the fine stage. The performances of the precision motion controller are evaluated by experiment.

The remainder of this chapter is organized as follows. In Section 2, the system overview of the hybrid stage is described. In Section 3, the hybrid stage control method is presented. In Section 4, the experimental results of the hybrid stage motion control are given. Finally, some concluding remarks are given in Section 5.

2. Hybrid stage with dual actuators

2.1 Overview

Fig. 1 shows the schematic of the hybrid stage presented in this paper. The objective of the hybrid stage is to move and align an object on it for the measurement of its three-dimensional image using the CSM. The CSM has a capability of the optical sectioning and can generate three-dimensional surface profile. The measurement principle of the CSM is based on the fact that only light reflected from the focal point of the objective lens contributes to the image, whereas all diffusely scattered light beams are filtered out by a pinhole. This creates a focused two-dimensional image of all object points that are located during the scanning process in the focal plane, similar to the contour lines of a map. Scanning the whole samples with an automatically varying focal plane results in a highly

resolved and enlarged image of the corresponding surface section. The vertical and horizontal resolutions of the CSM are 30 and 140 nm, respectively.

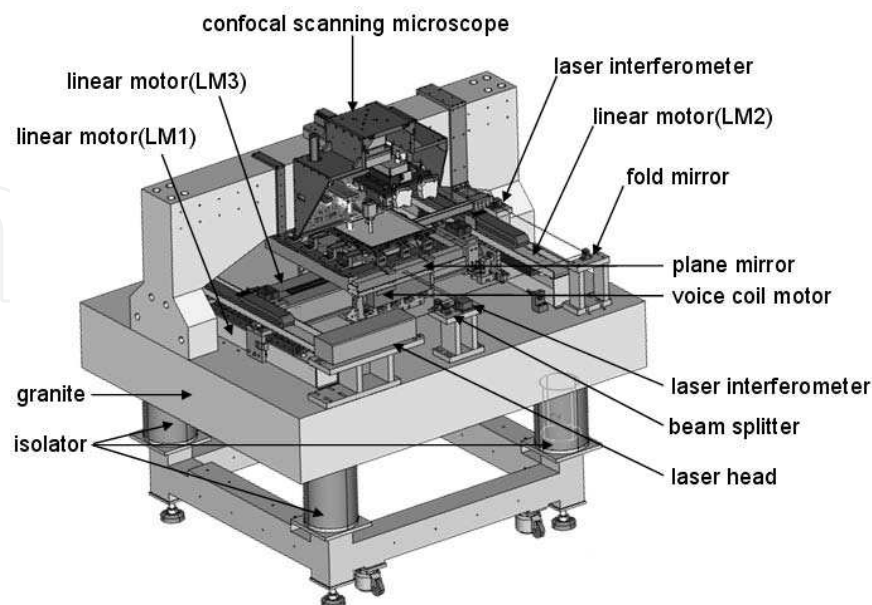


Fig. 1. Schematic of the hybrid stage

The hybrid stage consists of two individually operating x - y - θ stages, called the coarse stage and the fine stage. The coarse stage produces the initial movement of an object, and the fine stage provides the final alignment of the object. Since the laser interferometer with 0.31 nm resolution is used as position sensor in the fine stage, the precision control for the final alignment of an object can be possible. The moving parts of the hybrid stage are sustained by air bearings so that they can float on the base plate without mechanical contact. The material of the base plate is granite, and the base plate is connected with an isolator that can suppress internal and external vibrations.

2.2 Coarse stage

The schematic of the coarse stage is shown in Fig. 2. The coarse stage is driven by the three linear motors, and uses the 14 air bearings as guide and the three linear encoders as position sensor. The linear motor can be moved by the following Lorentz force

$$F_{LM}(t) = \oint i_{LM}(t) dl_{LM} \times B_{LM} \quad (1)$$

where $F_{LM}(t)$, $i_{LM}(t)$, $l_{LM}(t)$ and B_{LM} are force, current, coil length and flux density of the linear motor, respectively. A three-phase linear motor with the force of 233 N is used. The three linear motors are mechanically linked in an H-shaped rigid frame and can generate the x - y - θ motion of the coarse stage. Specifically, the stators of the two linear motors LM₁ and LM₂ are fixed to the base plate and parallel to each other. And the sliders of the two linear motors LM₁ and LM₂ are connected by the stator of the linear motor LM₃ that floats on the base plate. Thus, the movements of the three linear motors LM₁, LM₂, and LM₃ determine the x - y - θ motion of the coarse stage. The mass of each individual linear motor is 15 kg. The position sensor of the coarse stage is a linear encoder with the resolution of 5 nm. The coarse stage offers a large workspace of 500 × 500 mm².

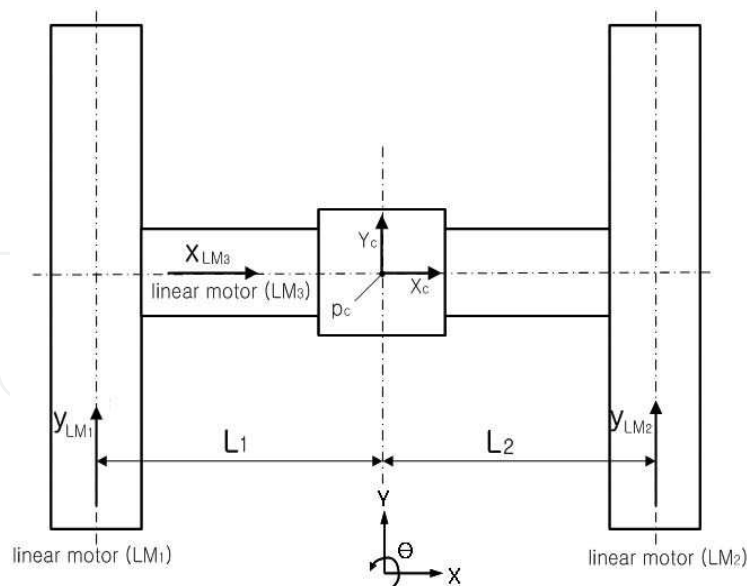


Fig. 2. Configuration of the coarse stage

Next, the kinematics of the coarse stage is derived. For the coarse stage shown in Fig. 2, let the vector $p_c(t)$ be given by

$$p_c(t) = [x_c(t) \quad y_c(t) \quad \theta_c(t)]^T \quad (2)$$

where $x_c(t)$ and $y_c(t)$ are the X_c and Y_c positions of the coarse stage, respectively, and $\theta_c(t)$ is the orientation angle of the coarse stage. Let the vector $p_{LM}(t)$ be given by

$$p_{LM}(t) = [x_{LM_3}(t) \quad y_{LM_1}(t) \quad y_{LM_2}(t)]^T \quad (3)$$

where $x_{LM_3}(t)$, $y_{LM_1}(t)$ and $y_{LM_2}(t)$ are the displacements of the three linear motors LM_3 , LM_1 and LM_2 , respectively. In (3), $x_{LM_3}(t)$, $y_{LM_1}(t)$ and $y_{LM_2}(t)$ are measured by the linear encoder. Under the assumption that the orientation angle $\theta_c(t)$ in (2) is very small, the vector $p_c(t)$ in (2) can be determined by the following equation

$$p_c(t) = H_c(t)p_{LM}(t)^T \quad (4)$$

where

$$H_c(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{L_2 - x_{LM_3}(t)}{L_1 + L_2} & \frac{L_1 + x_{LM_3}(t)}{L_1 + L_2} \\ 0 & -\frac{1}{L_1 + L_2} & \frac{1}{L_1 + L_2} \end{bmatrix} \quad (5)$$

In (5), L_1 and L_2 are the distances from the centers of the linear motors LM_1 and LM_2 to the center of the coarse stage, respectively. In the sequel, the position and orientation angle of the coarse stage are represented as in (4).

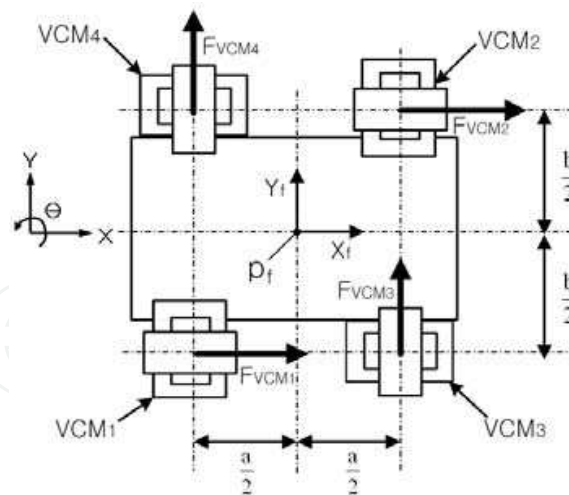


Fig. 3. Configuration of the fine stage

2.3 Fine stage

The configuration of the fine stage is shown in Fig. 3. The fine stage is driven by the four VCMs, and uses the four air bearings as guide and a laser interferometer as position sensor. The four VCMs lie on the same plane so that the tilting forces that cause the roll and pitch motions of the fine stage are negligible. The VCM can be moved by the following Lorentz force

$$F_{VCM}(t) = \oint i_{VCM}(t) dl_{VCM} \times B_{VCM} \quad (6)$$

where $F_{VCM}(t)$, $i_{VCM}(t)$, l_{VCM} and B_{VCM} are force, current, coil length and flux density of VCM, respectively. The four VCMs generate the x - y - θ motion of the fine stage by the following equation

$$AF_{VCM}(t) = u_f(t) \quad (7)$$

where

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ \frac{b}{2} & -\frac{b}{2} & \frac{a}{2} & -\frac{a}{2} \end{bmatrix} \quad (8)$$

$$F_{VCM}(t) = [F_{VCM_1}(t) \ F_{VCM_2}(t) \ F_{VCM_3}(t) \ F_{VCM_4}(t)]^T \quad (9)$$

and

$$u_f(t) = [-F_{f_x}(t) \ -F_{f_y}(t) \ T_{f_\theta}(t)]^T \quad (10)$$

In (8)–(10), a is the distance from the centre of VCM₁ to the center of VCM₃ (or from the center of VCM₂ to the center of VCM₄), b is the distance from the center of VCM₁ to the

center of VCM₄ (or from the centre of VCM₂ to the center of VCM₃), $F_{VCM_i}(t)$, $i = 1, \dots, 4$ are the forces of VCM_{*i*}, $i = 1, \dots, 4$, respectively, $F_{f_x}(t)$ and $F_{f_y}(t)$ are the X-axis and Y-axis control forces for the fine stage, respectively, and $T_{f_\theta}(t)$ is the control torque for the fine stage.

If we apply the current to coils of VCM₁ and VCM₂, the fine stage is driven in the X-axis direction. Similarly, we apply the current to coils of VCM₃ and VCM₄ for a driving in the Y-axis direction. In addition, the fine stage is driven in the θ direction if we make proper current and apply it to each coil. The VCM has the force of 220 N, and the mass of the fine stage is 36.5 kg. The position sensor of the fine stage is a laser interferometer with the resolution of 0.31 nm. The laser interferometer measures the x - y - θ motion of the fine stage by projecting laser beams onto the L-shaped plane mirror attached on top of the fine stage. The workspace of the fine stage is $5 \times 5 \text{ mm}^2$, and the range of the orientation angle of the fine stage is 0.05 deg.

Now, the kinematics of the fine stage is derived. Let the vector $p_f(t)$ be given by

$$p_f(t) = [x_f(t) \quad y_f(t) \quad \theta_f(t)]^T \quad (11)$$

where $x_f(t)$ and $y_f(t)$ are the X_f and Y_f positions of the fine stage, respectively, and $u_f(t)$ is the orientation angle of the fine stage. Let the vector $p_{VCM}(t)$ be given by

$$p_{VCM}(t) = [x_{VCM}(t) \quad y_{VCM}(t) \quad \theta_{VCM}(t)]^T \quad (12)$$

where $x_{VCM}(t)$ and $y_{VCM}(t)$ are the X-axis and Y-axis displacements of VCM, respectively, and $u_{VCM}(t)$ is the orientation angle of VCM, which is equal to $u_f(t)$. In (12), $x_{VCM}(t)$, $y_{VCM}(t)$ and $\theta_{VCM}(t)$ are measured by the laser interferometer. Since the orientation angle $\theta_{VCM}(t)$ in (12) is not very small compared with $\theta_c(t)$ in (2), we should consider $\theta_{VCM}(t)$ to determine $x_f(t)$ and $y_f(t)$ in (11) and obtain the following equations by lengthy calculation.

$$x_f(t) = [(x_{VCM}(t) + r)\cos\theta_{VCM}(t) - r]\cos\theta_{VCM}(t) - [(y_{VCM}(t) - r)\cos\theta_{VCM}(t) + r]\sin\theta_{VCM}(t) \quad (13)$$

$$y_f(t) = [(x_{VCM}(t) + r)\cos\theta_{VCM}(t) - r]\sin\theta_{VCM}(t) + [(y_{VCM}(t) - r)\cos\theta_{VCM}(t) + r]\cos\theta_{VCM}(t) \quad (14)$$

where r is the distance from the centre of the fine stage to the L-shaped plane mirror attached on top of the fine stage. Consequently, the position of the fine stage can be precisely determined by (13) and (14).

Note that, as shown in Fig. 4, the VCM consists of magnet, yokes and coil. The magnet and yoke of VCM are fixed on the fine stage. On the other hand, the coil of VCM is fixed on the coarse stage. In addition, the magnet sticks to the yokes and does not come into contact with the coil. Thus, the coarse and fine stages are not mechanically interconnected and can be controlled independently.

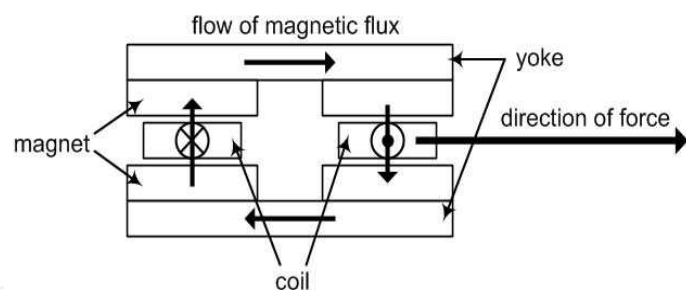


Fig. 4. Configuration of the voice coil motor

3. Precision motion control of hybrid stage with dual actuators

3.1 Overview

This section presents a precision motion control method of the x - y - θ motion of the hybrid stage. The motion control performance of the hybrid stage mainly depends on the motion control performance of the fine stage because the fine stage accomplishes the final alignment of an object. Therefore in this section the attention is focused on the precision motion control of the fine stage.

The block diagram of the hybrid stage control system is shown in Fig. 5. The coarse and fine stages are independently controlled under the common reference command. Let the reference command of the hybrid stage be given by

$$p_{ref}(t) = \begin{bmatrix} x_{ref}(t) & y_{ref}(t) & \theta_{ref}(t) \end{bmatrix}^T$$

(15)

where $x_{ref}(t)$, $y_{ref}(t)$ and $\theta_{ref}(t)$ are the X-axis position reference command, the Y-axis position reference command and the orientation angle reference command of the hybrid stage, respectively.

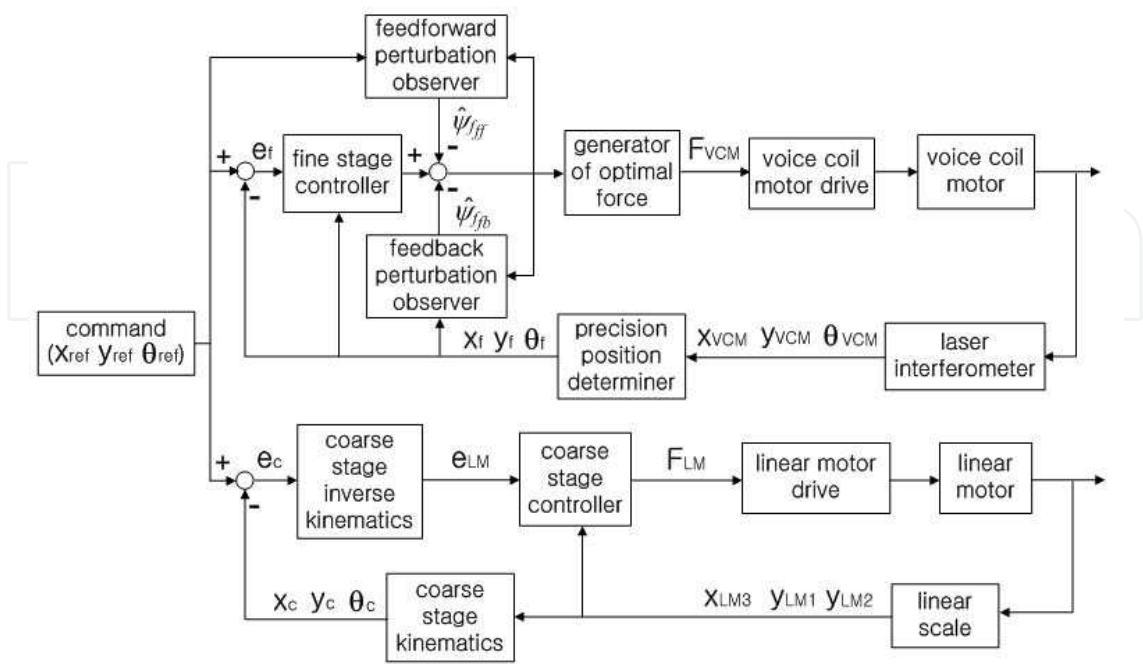


Fig. 5. Block diagram of the hybrid stage control system

3.2 Coarse stage control system

The error vector $e_c(t)$ for the coarse stage is defined as

$$e_c(t) = p_{ref}(t) - p_c(t) \quad (16)$$

where $p_{ref}(t)$ and $p_c(t)$ are defined in (15) and (2). Now the author explains each component of the coarse stage control system. First, the coarse stage controller consists of a position control loop, a velocity control loop and an antiwindup compensator. Specifically, as shown in Fig. 6, the position control loop has a proportional controller, and the velocity control loop has a proportional and integral controller. In addition, the velocity control loop is combined with an anti-windup compensator based on Bohn & Atherton, 1995 in order to eliminate the windup problem caused by the integral controller. In Fig. 6, $k_i(t)$, $i = 1, \dots, 4$ are positive scalars and s is the Laplace operator. The coarse stage controller generates the three control inputs $F_{LM_1}(t)$, $F_{LM_2}(t)$ and $F_{LM_3}(t)$ for control of the x - y - θ motion of the coarse stage where $F_{LM_1}(t)$, $F_{LM_2}(t)$ and $F_{LM_3}(t)$ are the control forces for the three linear motors LM₁, LM₂ and LM₃, respectively.

Second, the coarse stage kinematics implies the transformation of $p_{LM}(t)$ in (3) into $p_c(t)$ in (2) by (4). Finally, the coarse stage inverse kinematics represents the transformation of $e_c(t)$ in (16) into the error vector $e_{LM}(t)$, given by

$$e_{LM}(t) = H_c^{-1}e_c(t) = H_c^{-1}(p_{ref}(t) - p_c(t)) = H_c^{-1}p_{ref}(t) - p_{LM}(t) \quad (17)$$

where $H_c(t)$ is defined in (5) and its inverse matrix is given by

$$H_c^{-1}(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -L_1 - x_{LM_3}(t) \\ 0 & 1 & L_2 - x_{LM_3}(t) \end{bmatrix} \quad (18)$$

3.3 Fine stage control system

The error vector $e_f(t)$ for the fine stage is defined as

$$e_f(t) = p_{ref}(t) - p_f(t) \quad (19)$$

where $p_{ref}(t)$ and $p_f(t)$ are defined in (15) and (11). The author describes each component of the fine stage control system. First, as shown in Fig. 6, the fine stage controller has the same structure that the coarse stage controller has. The fine stage controller produces the three control inputs $F_{f_x}(t)$, $F_{f_y}(t)$ and $T_{f_\theta}(t)$ for control of the x - y - θ motion of the fine stage.

Second, the precision position determiner means the equations of (13) and (14). Third, the generator of optimal force is proposed to make the optimal forces of the four VCMs. As shown in (7), after designing the three control inputs $F_{f_x}(t)$, $F_{f_y}(t)$ and $T_{f_\theta}(t)$, we should determine the four forces $F_{VCM_i}(t)$, $i = 1, \dots, 4$ of the four VCMs. In this case, (7) has infinitely many solutions for the four forces $F_{VCM_i}(t)$, $i = 1, \dots, 4$ because it is underdetermined with three equations in four unknowns. Among many solutions to the above problem, the author presents a meaningful solution to (7) by considering a least squares problem. Before deriving a meaningful solution to (7), the following definition is given.

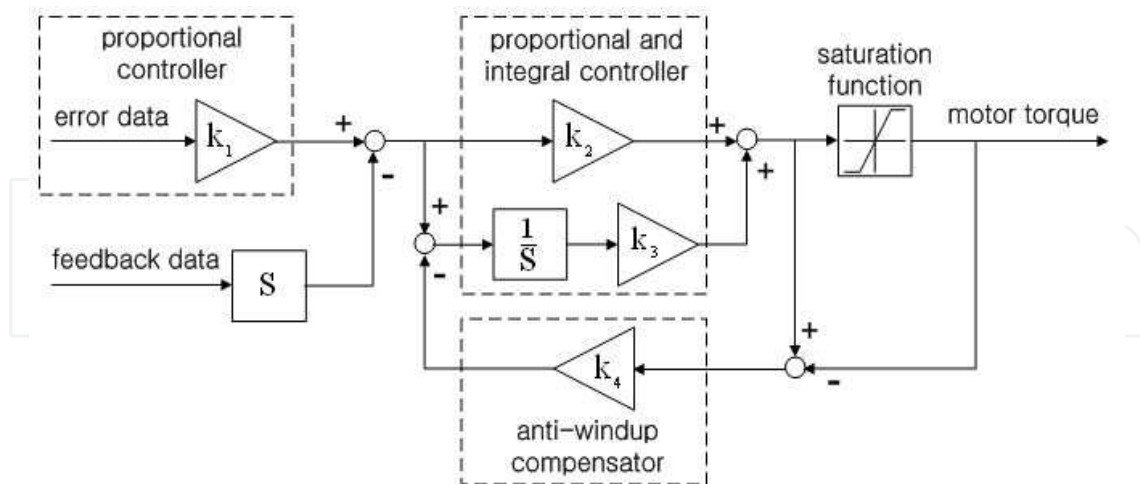


Fig. 6. Block diagram of the coarse stage and fine stage controllers

Definition 1 (Leon, 1995): Let $A \in R^{m \times n}$ have the rank of $q < n$. Then the singular value decomposition of A is given by

$$A = U \Sigma V^T = [U_1 \ U_2]^T \begin{bmatrix} \Sigma_1 & 0_{q \times (n-q)} \\ 0_{(m-q) \times q} & 0_{(m-q) \times (n-q)} \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} = U_1 \Sigma_1 V_1^T \quad (20)$$

where $U = [U_1 \ U_2] \in R^{m \times m}$ and $V = [V_1 \ V_2] \in R^{n \times n}$ are orthogonal matrices with $U_1 \in R^{m \times q}$, $U_2 \in R^{m \times (m-q)}$, $V_1 \in R^{n \times q}$ and $V_2 \in R^{n \times (n-q)}$. Moreover, $0_{m \times n}$ denotes the $m \times n$ zero matrix and $\Sigma_1 \in R^{q \times q}$ is a diagonal matrix given by

$$\Sigma_1 = \begin{bmatrix} \sigma_1 & 0 & 0 & \cdots & 0 \\ 0 & \sigma_2 & 0 & \cdots & 0 \\ 0 & 0 & \sigma_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \sigma_q \end{bmatrix} \quad (21)$$

with the entries satisfying

$$\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_q > 0 \quad (22)$$

Then the following theorem shows that the singular value decomposition provides the key to solve the least squares problem for design of the optimal forces of the four VCMs.

Theorem 1: Consider the equation (7). Let the singular value decomposition of A be $U \Sigma V^T$ and define

$$A^+ = V \Sigma^+ U^T \quad (23)$$

where A^+ denotes the pseudo-inverse of A . Then the following is a solution to (7):

$$F_{VCM}(t) = A^+ u_f(t) = \begin{bmatrix} \frac{1}{2} & 0 & \frac{b}{a^2 + b^2} \\ \frac{1}{2} & 0 & -\frac{b}{a^2 + b^2} \\ 0 & \frac{1}{2} & \frac{a}{a^2 + b^2} \\ 0 & \frac{1}{2} & -\frac{a}{a^2 + b^2} \end{bmatrix} \begin{bmatrix} -F_{f_x}(t) \\ -F_{f_y}(t) \\ T_{f_\theta}(t) \end{bmatrix} \quad (24)$$

Moreover, if $h(t)$ is any other solution to (7), then we can guarantee

$$\|F_{VCM}(t)\|_2 < \|h(t)\|_2 \quad (25)$$

where $\|\cdot\|_2$ denotes the Euclidean norm.

Proof: Let $F_{VCM}(t) \in R^4$ and define

$$j(t) = U^T u_f(t) = \begin{bmatrix} j_1(t) \\ j_2(t) \end{bmatrix} \quad (26)$$

$$k(t) = V^T F_{VCM}(t) = \begin{bmatrix} k_1(t) \\ k_2(t) \end{bmatrix} \quad (27)$$

From the definition of singular value decomposition and (26) and (27), we can obtain

$$\begin{aligned} \|u_f(t) - AF_{VCM}(t)\|_2^2 &= \|U^T\|_2^2 \|u_f(t) - AF_{VCM}(t)\|_2^2 = \|U^T u_f(t) - U^T (U \Sigma V^T F_{VCM}(t))\|_2^2 \\ &= \|U^T u_f(t) - \Sigma V^T F_{VCM}(t)\|_2^2 = \|j(t) - \Sigma V^T F_{VCM}(t)\|_2^2 = \|j(t) - \Sigma k(t)\|_2^2 \\ &= \left\| \begin{bmatrix} j_1(t) \\ j_2(t) \end{bmatrix} - \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} k_1(t) \\ k_2(t) \end{bmatrix} \right\|_2^2 = \left\| \begin{bmatrix} j_1(t) - \Sigma_1 k_1(t) \\ j_2(t) \end{bmatrix} \right\|_2^2 \\ &= \|j_1(t) - \Sigma_1 k_1(t)\|_2^2 + \|j_2(t)\|_2^2 \end{aligned} \quad (28)$$

Since $j_2(t)$ is independent of $F_{VCM}(t)$, it follows that $\|u_f(t) - AF_{VCM}(t)\|_2^2$ will be minimal if and only if $\|j_1(t) - \Sigma_1 k_1(t)\|_2 = 0$. Furthermore, $\|u_f(t) - AF_{VCM}(t)\|_2^2$ will be zero if and only if $\|j_1(t) - \Sigma_1 k_1(t)\|_2 = 0$ and $\|j_2(t)\|_2 = 0$. Thus, $F_{VCM}(t)$ becomes a solution to (7) if and only if $F_{VCM}(t) = V k(t)$ and $j_2(t) = 0$ where $k(t)$ is a vector of the form

$$k(t) = \begin{bmatrix} k_1(t) \\ k_2(t) \end{bmatrix} = \begin{bmatrix} \Sigma_1^{-1} j_1(t) \\ k_2(t) \end{bmatrix} \quad (29)$$

Especially, $F_{VCM}(t) = A^+ u_f(t)$ is a solution to (7) because

$$\begin{aligned}
 F_{VCM}(t) &= Vk(t) = V \begin{bmatrix} \Sigma_1^{-1} j_1(t) \\ 0 \end{bmatrix} = V \begin{bmatrix} \Sigma_1^{-1} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} j_1(t) \\ j_2(t) \end{bmatrix} = V \Sigma^+ j(t) = V \Sigma^+ U^T u_f(t) \\
 &= A^+ u_f(t) = \begin{bmatrix} \frac{1}{2} & 0 & \frac{b}{a^2 + b^2} \\ \frac{1}{2} & 0 & -\frac{b}{a^2 + b^2} \\ 0 & \frac{1}{2} & \frac{a}{a^2 + b^2} \\ 0 & \frac{1}{2} & -\frac{a}{a^2 + b^2} \end{bmatrix} \begin{bmatrix} -F_{f_x}(t) \\ -F_{f_y}(t) \\ T_{f_\theta}(t) \end{bmatrix}
 \end{aligned} \tag{30}$$

Next, if $h(t)$ is any other solution to (7), $h(t)$ must be of the form

$$h(t) = Vk(t) = V \begin{bmatrix} \Sigma_1^{-1} j_1(t) \\ k_2(t) \end{bmatrix} \tag{31}$$

where $k_2(t) \neq 0$. Then, for $h(t)$ of (31), we can obtain the following result:

$$\begin{aligned}
 \|h(t)\|_2^2 &= \|Vk(t)\|_2^2 = \|k(t)\|_2^2 = \|\Sigma_1^{-1} j_1(t)\|_2^2 + \|k_2(t)\|_2^2 \\
 &> \|\Sigma_1^{-1} j_1(t)\|_2^2 = \|F_{VCM}(t)\|_2^2
 \end{aligned} \tag{32}$$

This completes the proof. $\square$

Physically, $F_{VCM}(t)$ in (24) is the minimal norm solution to (7) such that the condition of (25) holds for any other solution to (7). Therefore, if we use $F_{VCM}(t)$ in (24), we can achieve the optimal performance in the sense of the control effort.

Finally, the author presents the feedforward and feedback perturbation observers by extending the study of Kwon et al., 2001. Specifically, the perturbation applied to the nominal dynamics of the fine stage can be expressed by

$$\psi_f(t) = H_{f_n} \ddot{p}_f(t) + B_{f_n} \dot{p}_f(t) - u_f(t) \tag{33}$$

where H_{f_n} and B_{f_n} are the nominal inertia matrix and the nominal viscous damping coefficient of the fine stage, respectively, $u_f(t)$ is the control input of the fine stage defined in (10). Since one-step delay in signals is inevitable for the causality between input and output in practice, the perturbation observer is presented as follows

$$\hat{\psi}_f(t) = D_f \{ H_{f_n} \ddot{p}_f(t - t_c) + B_{f_n} \dot{p}_f(t - t_c) \} - u_f(t - t_c) \tag{34}$$

where D_f is a diagonal matrix with scalar elements that plays the role of approximating $\hat{\psi}_f(t)$ to the real perturbation of $\psi_f(t)$, and t_c is the control interval. If we apply $\hat{\psi}_f(t)$ in (34) to the nominal dynamics of the fine stage in order to compensate the perturbation, the nominal dynamic equation of the fine stage can be changed to

$$H_{f_n} \ddot{p}_f(t) + B_{f_n} \dot{p}_f(t) = \eta_f(t) + \tilde{\psi}_f(t) \tag{35}$$

where $\eta_f(t) = u_f(t) + \hat{\psi}_f(t)$ is the tracking control input and $\tilde{\psi}_f(t) = \psi_f(t) - \hat{\psi}_f(t)$ is the perturbation compensation error. Since the reference command can be utilized in tracking control, the author presents the feedforward perturbation observer as follows

$$\hat{\psi}_{f_{ff}}(t) = D_{f_{ff}} \{H_{f_n} \ddot{p}_{ref}(t - t_c) + B_{f_n} \dot{p}_{ref}(t - t_c)\} - u_f(t - t_c) \quad (36)$$

where $D_{f_{ff}}$ is a diagonal matrix with scalar elements. Also, the residue of the perturbation, given by $\Delta \tilde{\psi}_f(t) = \psi_f(t) - \hat{\psi}_{f_{ff}}(t)$, is compensated by the following feedback perturbation observer

$$\begin{aligned} \hat{\psi}_{f_{fb}}(t) &= \Delta \tilde{\psi}_f(t - t_c) \\ &= D_{f_{fb}} \{H_{f_n} \ddot{p}_f(t - t_c) + B_{f_n} \dot{p}_f(t - t_c)\} - D_{f_{ff}} \{H_{f_n} \ddot{p}_{ref}(t - 2t_c) + B_{f_n} \dot{p}_{ref}(t - 2t_c)\} \\ &\quad - u_f(t - t_c) + u_f(t - 2t_c) \end{aligned} \quad (37)$$

where $D_{f_{fb}}$ is a diagonal matrix with scalar elements.

It is remarkable that the perturbation observers presented in this section are the generalization of the perturbation observers developed by Kwon et al., 2001 because their study can be regarded as a special case of the proposed method with $D_{f_{ff}} = \text{diag}[1 \ 1 \ 1]$

and $D_{f_{fb}} = \text{diag}[1 \ 1 \ 1]$ where diag means the diagonal matrix. Because of $D_{f_{ff}}$ and $D_{f_{fb}}$, we have the extra freedom of designing the perturbation observers in real application. The perturbation observers presented in this section cannot help using delayed information because the current perturbation is monitored in discrete time with one-step delay. Using delayed information may result in bandwidth degradation and it is inevitable.

With a similar manner presented by Kwon et al., 2001, if we assume that the fine stage is time invariant during a control interval, the full state is available, the change of external disturbances during the control intervals is bounded, and the nominal inertia matrix of the fine stage H_{f_n} satisfies the following condition for the real inertia matrix of the fine stage $H_f(k)$ for all samples k

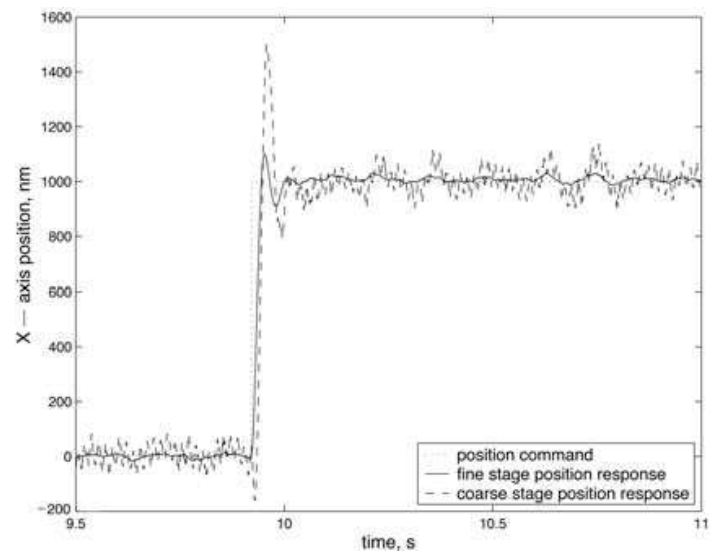
$$0 < H_{f_n} < 2H_f(k) \quad (38)$$

then the perturbation compensation error $\tilde{\psi}_f(t)$ in (35) is well bounded in a sufficiently small value.

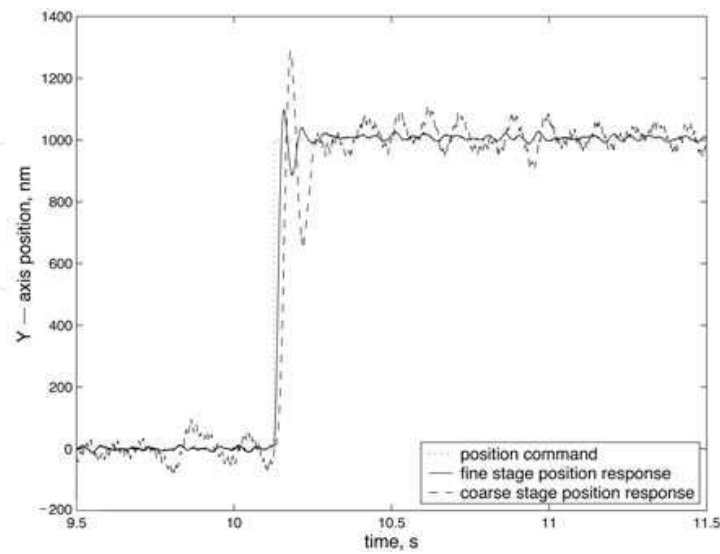
4. Experimental results

As the hybrid stage control platform, the author uses the dSPACE system that features a power PC processor and is directly connected to all dSPACE I/O boards. The dSPACE system is an efficient and reliable engineering tool to develop and test control systems, and is in widespread use in many automotive industries. The graphical user interface software is programmed in order to control the hybrid stage by using the dSPACE system. By the graphical user interface software, we can give the target position command and target orientation angle command to the hybrid stage and can set all control parameters of the precision motion controller.

Then the performances of the precision motion controller of the hybrid stage are evaluated by experiment. The update rate of the dSPACE system is set to be 1 kHz. The author initially decides the gains k_1 , k_2 and k_3 of the coarse stage and fine stage controllers by adopting the Ziegler–Nichols method (Ogata, 1996), which is very useful to select the control gains of a proportional, integral and derivative-type controller for complex dynamic systems in practice, and then further tunes these gains in order to obtain a desired control performance in terms of the step response. Also, the author designs the gain k_4 of the anti-windup compensator by an experimental method such that we make the overshoot appearing in the step response, caused by windup, as small as possible. In the sequel, the undamped natural frequencies of the X-axis and Y-axis motions are decided to lie approximately at 117.909 and 118.448 rad/s, respectively. Also, the damping ratios of the X-axis and Y-axis motions are decided to lie approximately at 0.590 and 0.595, respectively.



(a)



(b)

Fig. 7. Step responses of the hybrid stage by a step input of 1000 nm magnitude: (a) X-axis step response, (b) Y-axis step response

Fig. 7 shows the experimental result of the X-axis and Y-axis step responses of the hybrid stage by a step input of 1000 nm magnitude. From Fig. 7, we see that the maximum overshoots of the X-axis and Y-axis motions are 10.07% and 9.76%, respectively, the delay times of the X-axis and Y-axis motions are 0.014 and 0.014 s, respectively, the rise times of the X-axis and Y-axis motions are 0.026 and 0.025 s, respectively, the peak times of the X-axis and Y-axis motions are 0.033 and 0.033 s, respectively, and the 5% settling times of the X-axis and Y-axis motions are 0.071 and 0.072 s, respectively. Also, Fig. 7 demonstrates that the hybrid stage effectively responds to a step input of 1000 nm magnitude in the X-axis and Y-axis motions. Specifically, when the coarse and fine stages are operated for a step input of 1000 nm magnitude, the X-axis and Y-axis steady-state errors of the fine stage after 0.071 and 0.072 s rising periods remain within 50 nm, respectively. On the other hand, the X-axis and Y-axis steady-state errors of the coarse stage reach more than 100 and 80 nm although the time elapses 0.08 and 0.12 s after the step input, respectively. Therefore it is concluded that the hybrid stage has remarkable advantages in terms of the response time and positioning accuracy. Although there is no direct contact between the coarse and fine stages, the motion errors or vibrations of the coarse stage may lead to variations of the interaction force between the two stages. These variations present themselves as disturbances to the fine stage, and the resolution of the fine stage degrades unless the bandwidth of the fine stage is substantially higher than that of the coarse stage. This observation explains the fluctuation of the fine stage at steady state in Fig. 7.

Note that $F_{VCM}(t)$ in (24) is the minimal norm solution to (7). In order to demonstrate the result, the Euclidean norm histories of current inputs of the four VCMs is shown in Fig. 8. As shown in Fig. 8, the generator of optimal force yields the control effort of about 0.05 A. On the other hand, we need the control effort of about 2.8 A if we do not use the generator of optimal force. In this case, we can save the control effort significantly for the operation of the four VCMs by adopting the generator of optimal force.

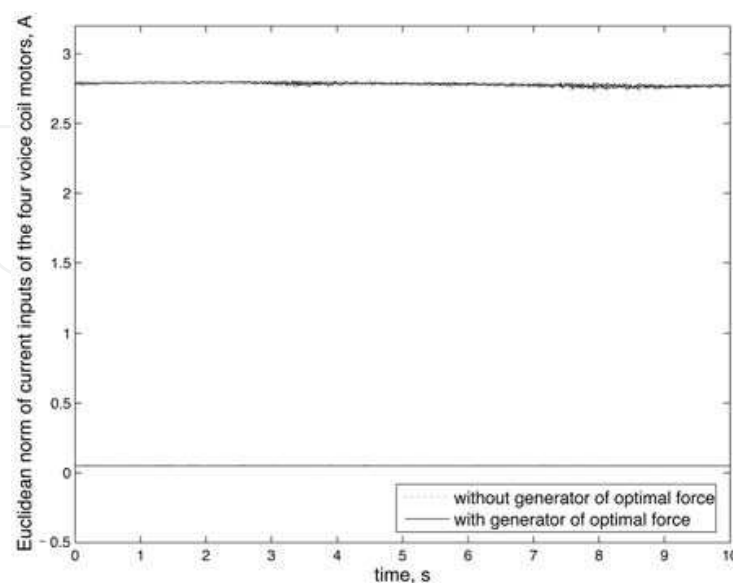


Fig. 8. Euclidean norm histories of current inputs of the four VCMs

Since the perturbation gives rise to a vibration of the hybrid stage in practice, the author determines the gains of the perturbation observers by the experimental method such that we make the position stability of the hybrid stage as small as possible. Then Fig. 9 shows the experimental result for the X-axis and Y-axis position stabilities of the hybrid stage. From Fig. 9, the X-axis and Y-axis position stabilities by the perturbation observers are about ± 10 nm, respectively. On the other hand, the X-axis and Y-axis position stabilities are about ± 30 nm, respectively, if we do not use the perturbation observers. Consequently, we see that the perturbation observers have the function of observing the perturbation and compensating it effectively about 66%.

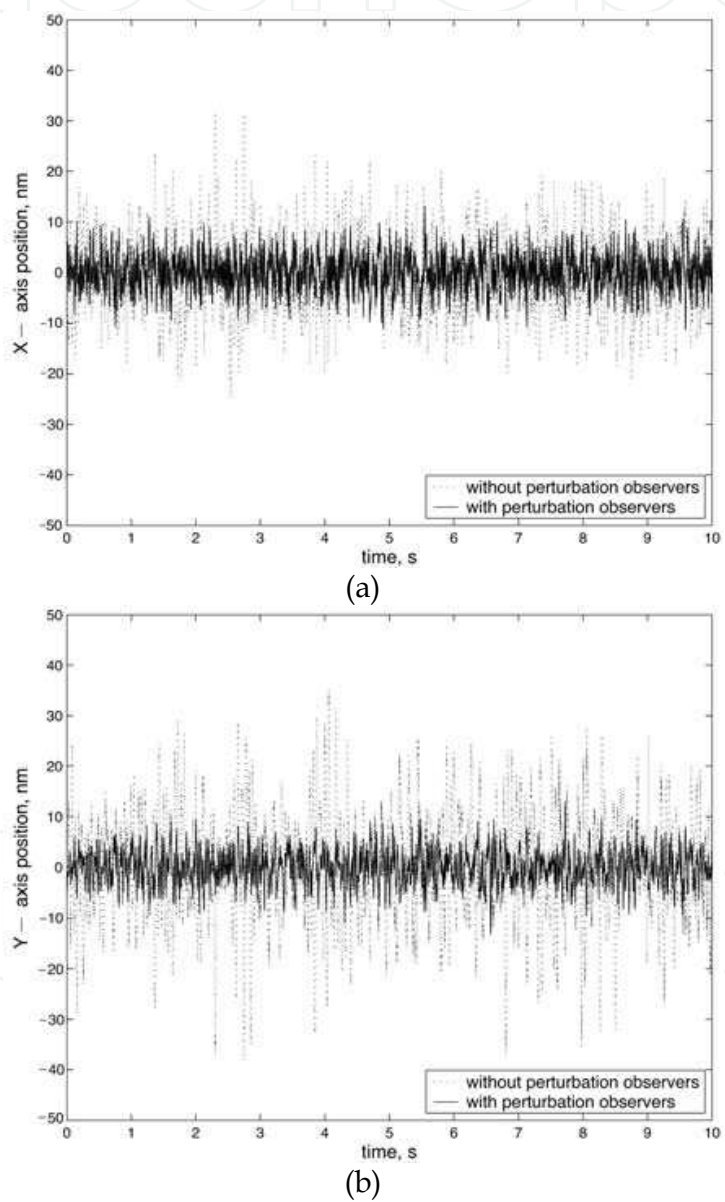


Fig. 9. Position stabilities of the hybrid stage: (a) X-axis position stability, (b) Y-axis position stability

Now the X-axis and Y-axis incremental step responses and orientation angle responses of the hybrid stage are evaluated by applying some step input to the hybrid stage. Specifically,

the X-axis and Y-axis target positions are increased by 10 nm from 0 to 50 nm, and then decreased by 10 nm from 50 to 10 nm, respectively. Note that the coarse stage is on operation when the author conducts the X-axis and Y-axis incremental step responses and orientation angle responses.

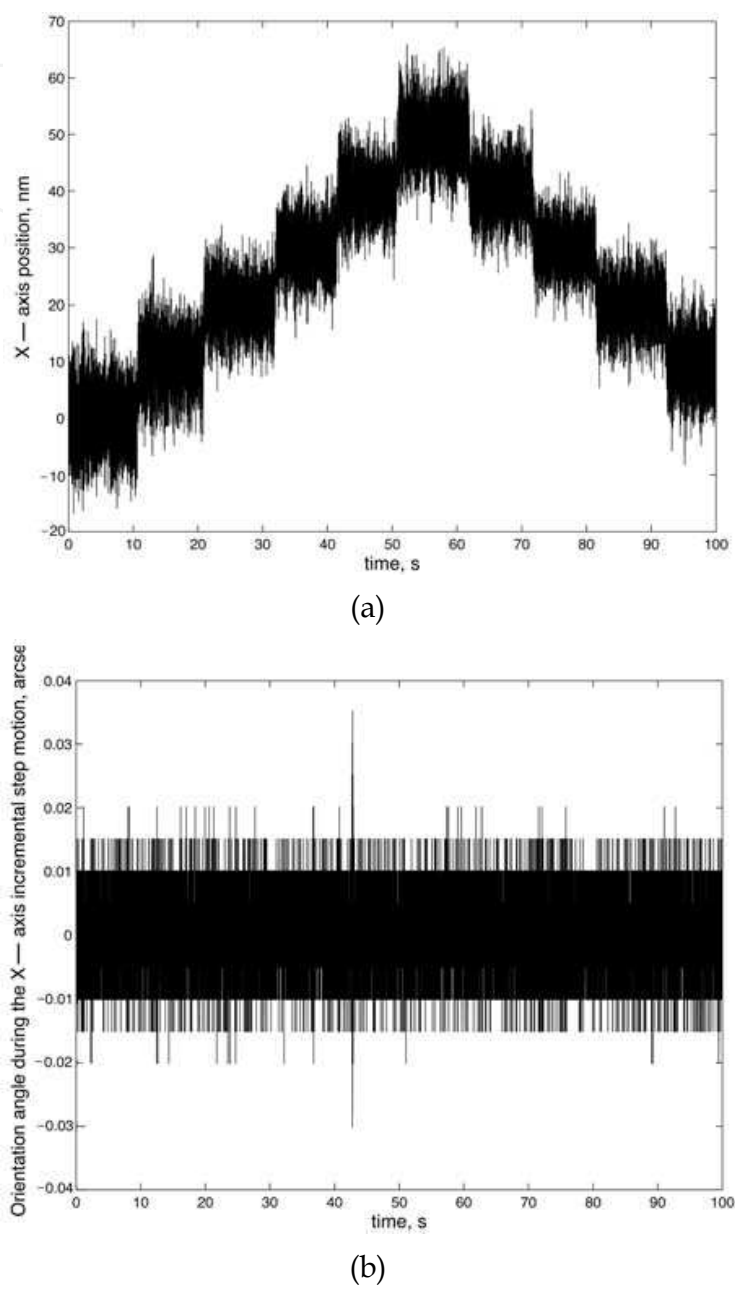


Fig. 10. X-axis incremental step response and orientation angle response of the hybrid stage: (a) X-axis incremental step response, (b) Orientation angle response during the X-axis incremental step motion

Then Fig. 10 shows the experimental results of the X-axis incremental step response and the orientation angle response during the X-axis incremental step motion, and Fig. 11 shows the experimental results of the Y-axis incremental step response and the orientation angle response during the Y-axis incremental step motion. From Figs. 10 and 11, we see that the

resolutions of the X-axis and Y-axis motions are about ± 10 nm, respectively, and the fluctuations of the orientation angle during the X-axis and Y-axis incremental step motions are about ± 0.02 and ± 0.04 arcsec, respectively. Note that 1 arcsec is equal to $1/3600$ deg. Finally, the X-axis and Y-axis bidirectional repeatabilities of the hybrid stage are tested. Note that the repeatability is the error between a number of successive attempts to move the machine to the same position (Slocum, 1992). And the bidirectional repeatability is the repeatability achieved when the target position is approached from two different directions

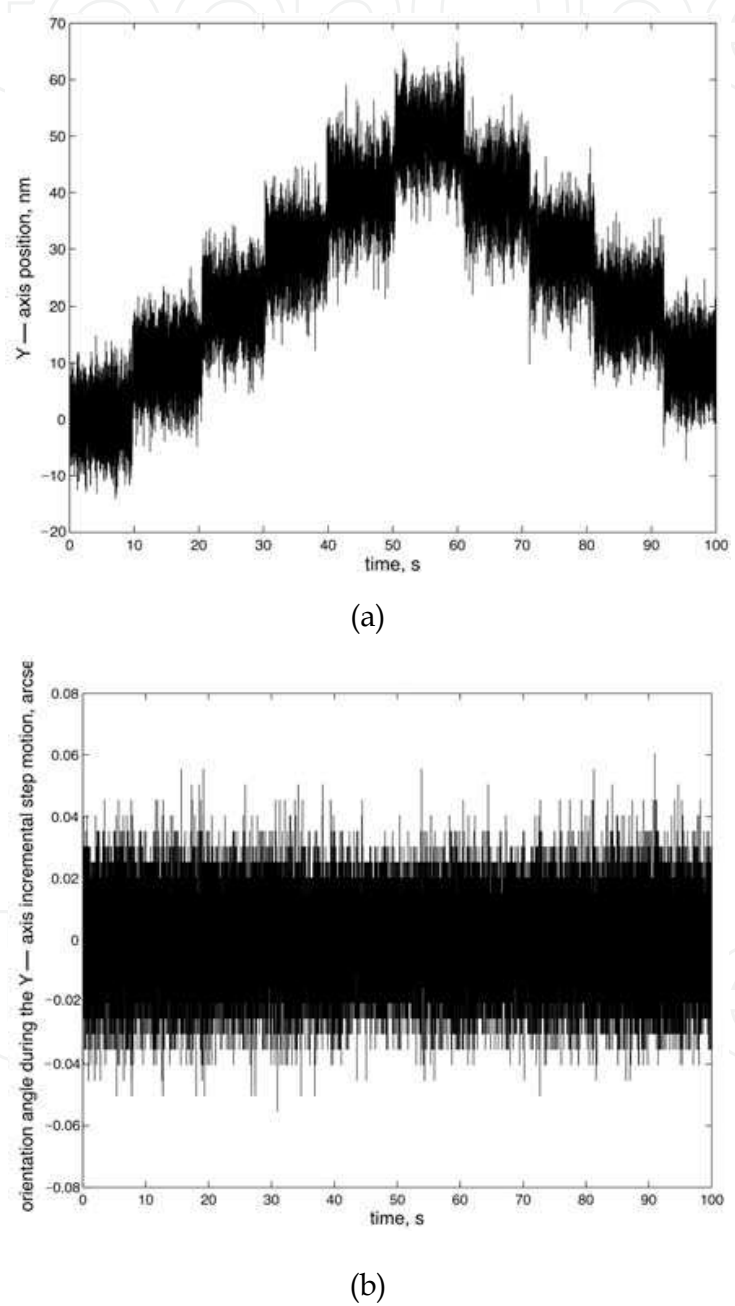
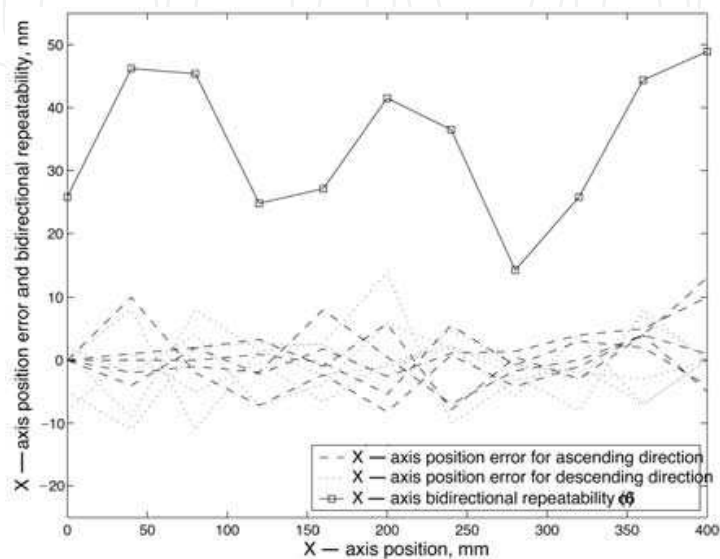
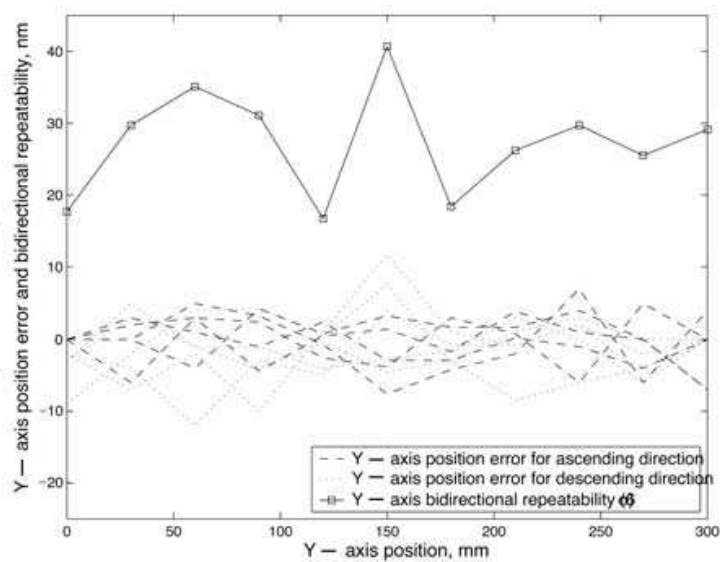


Fig. 11. Y-axis incremental step response and orientation angle response of the hybrid stage: (a) Y-axis incremental step response, (b) Orientation angle response during the Y-axis incremental step motion

(Slocum, 1992). In order to evaluate the X-axis bidirectional repeatability, the X-axis target position is increased by 40 mm from 0 to 400 mm, and then decreased by 40 mm from 400 to 0 mm. Also, in order to evaluate the Y-axis bidirectional repeatability, the Y-axis target position is increased by 30 mm from 0 to 300 mm, and then decreased by 30 mm from 300 to 0 mm. Then Fig. 12 shows the experimental results of the X-axis and Y-axis bidirectional repeatabilities. As shown in Fig. 12, the X-axis and Y-axis bidirectional repeatabilities are about 48.9 and 40.7 nm(6σ), respectively.



(a)



(b)

Fig. 12. Bidirectional repeatabilities of the hybrid stage: (a) X-axis bidirectional repeatability, (b) Y-axis bidirectional repeatability

5. Conclusion

In this chapter, the author presented a three degrees-of-freedom precision hybrid stage that can move and align an object on it for the measurement of its three-dimensional image using the confocal scanning microscope. Since the hybrid stage consists of two individually operating x - y - θ stages, it has not only a long operation travel but also a fine position stability. In order to control the hybrid stage, the author proposed a precision motion controller. The author evaluated the performances of the precision motion controller by experiment with a hardware setup. The experimental results showed that the precision motion controller provided the hybrid stage with desirable advantages in terms of the response time, positioning accuracy, control effort and perturbation compensation.

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The book reveals many different aspects of motion control and a wide multiplicity of approaches to the problem as well. Despite the number of examples, however, this volume is not meant to be exhaustive: it intends to offer some original insights for all researchers who will hopefully make their experience available for a forthcoming publication on the subject.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Unit 405, Office Block, Hotel Equatorial Shanghai
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
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