Proceedings of the 2004 IEEE
International Conference on Control Applications
Taipei, Taiwan, September 2-4, 2004

Developing a New Low-Cost XY Table Using Optical Pickup Head with Adaptive Controller

Ping-Lang Yen, Wen-I Hsiao and Tien-Sen Lu

Abstract—**A new XY table has been designed for low cost purpose and high positioning accuracy. The moving mechanism was made by a commercially available optical pickup-head unit with two added rods and one platform. The position of the platform was measured through the reflected signals on photo diodes from a fixed compact disc. In order to achieve high accuracy of trajectory following, we proposed an adaptive controller to counter the influence of coupling effects and platform mass variations. First results have shown the high potentiality of using this architecture to achieve high accurate positioning of XY table with very cheap price.**

I. INTRODUCTION

OPTICAL storage devices such as CD-ROM/ DVD-ROM drives have become very cheap devices for multi-media backup. The cost of its components, such as pickup head, even reduced to less than US 10 dollars. Even though with cheap price, the pickup head has very high performance of positioning. As indicated in the standard books, the maximal allowable position error for its focusing accuracy has to be within ±1μm for CD-ROM drive, and ±0.23μm for DVD ROM drives [1] [2]. In [3], it even mentioned that the focusing servo could have the possibility of achieving an accuracy of 2nm. Similar requirement is applied to tracking servo loop. If we mount a carrier platform on a pickup head to construct an XY table, then the XY table system will possess the positioning capability with similar accuracy as CD-ROM/DVD-ROM drives, and the cost is very low. These two advantages will make the XY table more competitive than other existent systems nowadays [4][5].

In order to achieve high accuracy positioning, the coupling behavior between focusing and radial servo has to been taken into account [6]. This opto-mechanical coupling produces crosstalk between the two servo and influences the desired trajectory following. Almost the present compensators implemented in CD-ROM/DVD-ROM drive are designed individually for each servo loop. Although careful designed compensators could meet the performance requirements for data reading purpose, it would not be adequate to achieve required positioning accuracy if the coupling effect cannot be properly eliminated for the applications on XY platform. In particular, when the movement is far from the focal point, the cross-coupling could be very severe. The positioning error due to the other servo loop may rise to unacceptable level if the servo loops remain the design based on single input and single output method. Another issue is that an XY table could carry different objects and hence the system dynamics changes from time to time. The positioning performance could degrade if the servo compensators are only optimally tuned for nominal plant parameters. In order to counter coupling effects from the other servo loop and varying system parameters, we proposed an adaptive control strategy to deal with these problems.

II. SYSTEM DESCRIPTION, MODELING AND CONTROLLER DESIGN

The main body of the XY table is a movable lens module holder, which is mounted by two parallel bars with a flat glass on its top for carrying objects. This platform is moved

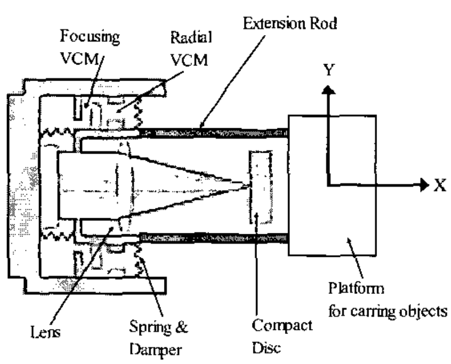

Fig. 1. Diagram of the Moving Platform of the XY table made by OPU (Optical Pickup-head Unit)

Manuscript received January 17, 2004.

P. L. Yen, W. I Hsiao and T. S. Lu are with the Institute of Automation Technology, National Taipei University of Technology, Taipei, Taiwan (corresponding author: P. L. Yen; phone: +886-2-27712171 ext:4324; fax: +886-2-87733217; e-mail: plyen@ ntut.edu.tw).

by two voice coil motors in focusing direction for X axis and radial direction for Y axis individually. When the platform with the lens module is moving, the density distribution of the laser beam, which is ejecting from laser diode, reflected by the compact disc is changing and detected by the photo diodes inside the base of the OPU. Through measuring and processing these signals on the photo diodes, the position of the platform in both X and Y axes can be determined. Therefore, we proposed a idea of using the lens module of OPU plus additional platform as our plant, two VCMs as the actuators, and laser diode, compact disc and photo diodes as

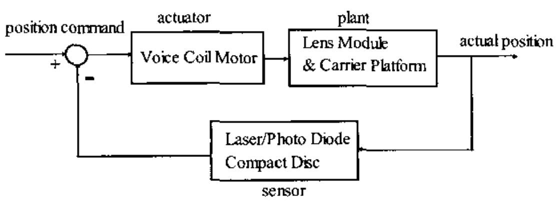

Fig. 2. Block Diagram of the OPU Platform as an XY table

the sensors to construct a new low cost XY table.

A. Modeling of the XY Table

Theoretically, the force applied to the focusing direction is assumed to be along the X axis, and the force applied to radial direction along the Y-axis. Practically, the focusing and radial forces slightly deviate from the axes. Possible causes could be the electro-magnetic force from the VCMs cannot be guaranteed to be linear and aligned to the axes and there is no mechanical constraint to guide the motion

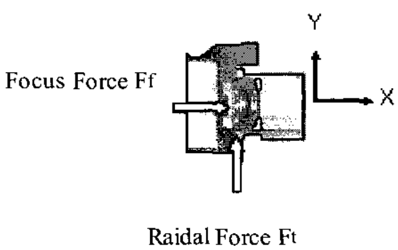

Fig. 3. Modeling of the XY table

linearly.

The motion equations for the movable platform can be derived by Newton law or Lagrange method. Furthermore, according to [6], the focusing and radial forces produced by VCM are linearly proportional to the applied voltages v_f and v_t as equation (1):

$$\begin{aligned} F_f &= K_f v_f \\ F_t &= K_t v_t \end{aligned} \tag{1}$$

where K_f and K_t is the proportionality constants. Therefore, the transfer function matrix G(s) related to the input focusing and radial voltages v_f ,v_t and the output x and y displacements can be obtained as:

$$\begin{aligned} G(s) &= \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{c_1}{s^2 + a_1 s + b_1} & \dfrac{c_2}{s^2 + a_2 s + b_2} \\ \dfrac{c_3}{s^2 + a_3 s + b_3} & \dfrac{c_4}{s^2 + a_4 s + b_4} \end{bmatrix} \begin{bmatrix} v_f \\ v_t \end{bmatrix} \end{aligned} \tag{2}$$

Interested readers in the identification of the dynamic equations can find more details in [7]. In our paper, accurate parameter identification of the platform is not required for designing an adaptive controller. Only several features of the model are needed to be known, which will be mentioned in section B.

B. Adaptive Decoupling Controller Design

Although the parameters of the moving platform can be determined through identification methods, the mechanical parameters of OPU usually differ from each other. In addition, payloads on the platform are changing from time to time, so it is unrealistic to obtain sufficiently accurate system parameters. For traditional controller design implemented in CD-ROM drives, such as lead-lag compensators, parameters variation in the plant could have large impact on its performance. The coupling effects from the other servo loop become worse because certain gain feature on the frequency band and its phase margin can not be guaranteed.

On the other hand, adaptive controller has the advantages of coping with the parameters' variation in the plant so that possess better outcomes under parameters' variation. In this paper, we will use model reference adaptive control (MRAC) [7] for the system. The desired system output is specified by assigning a reference model $G_d(s)$ and the adaptive controller attempts to drive the output of plant G(s) to

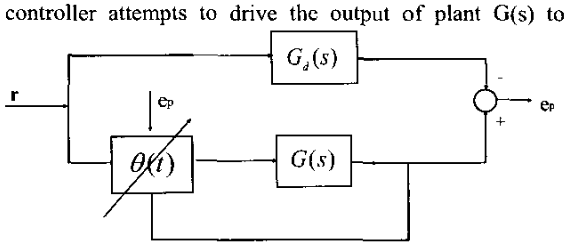

Fig. 4. Schematic Diagram of Model Reference Adaptive Control

following the output of the reference model $G_d(s)$. The schematic arrangement of the overall system is represented as below:

where r is the displacement command vector with respect to X and Y directions, and e_p is the associated position error vector. The $\theta(t)$ is the control gains adaptively tuned according to parameters adaptation.

First of all, we verified that the platform possessed the following properties:

1. All entries of plant G(s) indicated in equation (2) is stable and non-minimum phase.
2. The matrix C= $\begin{bmatrix} c_1 & c_2 \\ c_3 & c_4 \end{bmatrix}$ is non-singular, where c1,...,c4 are coefficients in equation (2). Since the diagonal coefficients c1, c4 indicate the primary dynamics and off diagonal coefficients c2, c3 are for cross-talk. Practically c1, c4 >> c2, c3, and hence the determinant of matrix C can be assumed nonzero.
3. $C + C'$ is positive definite. This will imply the high frequency gain matrix K satisfies the condition of $\Gamma K + (K\Gamma)'$ to be sign definite for some positive-definite symmetric matrix Γ.

Then we need to find the diagonal Hermit normal form $H_p(s)$ of G(s). Hermit normal form has the form of:

$$H_p(s) = \begin{bmatrix} \frac{1}{h^{n1}(s)} & & 0 \\ & \ddots & \\ 0 & & \frac{1}{h^{nm}(s)} \end{bmatrix} \quad (3)$$

where $h^{ni}(s)$ is the ni order of any monic polynomial of degree 1.

If a diagonal Hermit normal form of an MIMO plant G(s) can be obtained, it means that G(s) can be dynamically decoupled in practice. The condition for G(s) to have a diagonal Hermit normal form is to check whether or not the matrix C= $\begin{bmatrix} c_1 & c_2 \\ c_3 & c_4 \end{bmatrix}$ is nonsingular. Since matrix C is nonsingular, we can have the right Hermit normal form of G(s):

$$\mathrm{H(s)} = \begin{bmatrix} \frac{1}{(s+\alpha)^2} & 0 \\ 0 & \frac{1}{(s+\alpha)^2} \end{bmatrix} \quad (4)$$

where α is any positive real number.

Subsequently, form the definition of the high frequency gain matrix $K_p = \lim_{s\to\infty} H^{-1}(s)G(s)$, we have

$$K_p = \begin{bmatrix} c_1 & c_2 \\ c_3 & c_4 \end{bmatrix} \quad (5)$$

Therefore, we can assign the candidate for a reference model as H(s)Q(s), where Q(s) is unimodular matrix. For simplicity, we let $Q(s)=I_{2x2}$, and assign the reference model as:

$$\mathrm{Gd(s)} = \begin{bmatrix} \frac{1}{(s+\alpha)^2} & 0 \\ 0 & \frac{1}{(s+\alpha)^2} \end{bmatrix} \quad (6)$$

We can choose large enough α to achieve fast transient response.

The upper bound ν on the observability index can be found by calculating the smallest integer ν larger than $\frac{1}{m}\sum_{i,j} n_{ij}$, where m is the order of the matrix and n_{ij} is the relative degree of every entry. In our case, ν is equal to 4.

Based on the above, the control law is :

$$u(t) = \theta(t)\omega(t) \quad (7)$$

where the control gains K(t) are

$$\theta = [k_0 \quad k_1 \quad k_2 \quad k_3 \quad k_4 \quad k_5 \quad k_6 \quad k_7]_{2x8} \quad (8)$$

and the input signals $\omega(t)$ are

$$\omega = \begin{bmatrix} \omega_0 \\ \omega_1' \\ \omega_2' \\ \omega_3' \\ \omega_4' \\ \omega_5' \\ \omega_6' \\ \omega_7' \end{bmatrix}_{8x2} \quad (9)$$

where $\omega_0 = r_{1x2}$ is the reference input vector,

$$\begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ \omega_3(t) \end{bmatrix} = \begin{bmatrix} \frac{1}{d(s)} u'(t) \\ \frac{s}{d(s)} u'(t) \\ \frac{s^2}{d(s)} u'(t) \end{bmatrix}_{3\times 2} \quad (10)$$

$$\begin{bmatrix} \omega_4(t) \\ \omega_5(t) \\ \omega_6(t) \\ \omega_7(t) \end{bmatrix} = \begin{bmatrix} \frac{1}{d(s)} y_p'(t) \\ \frac{s}{d(s)} y_p'(t) \\ \frac{s^2}{d(s)} y_p'(t) \\ \frac{s^3}{d(s)} y_p'(t) \end{bmatrix}_{4\times 2} \quad (11)$$

The control parameter adaptation law:

$$\dot{\theta} = -e_p \omega' \quad (12)$$

i.e.

$$\dot{k}_i = -e_p \omega_i' = \begin{bmatrix} -e_{p1}\omega_{i1} \\ -e_{p2}\omega_{i2} \end{bmatrix}_{2\times 1}, \text{ i=0,1,…7} \quad (13)$$

Let a scalar function

$$V = e'e + Tr(\Phi'\Phi) \quad (14)$$

Then V(t) can be proven to be a Lyapunov's function [8]. The overall system is asymptotically stable and the plant output is then able to follow the reference model output asymptotically.

III. Simulation and Experiment

A. Simulation Results

In order to demonstrate the superiority of the adaptive decoupling control to the conventionally lead-lag compensation, we presented several simulated results and compared their performances in this section. Assume the nominal plant [6] to be

$$G(s) = \begin{bmatrix} \frac{22783981}{s^2+73.51s+79943.8} & \frac{1053501}{s^2+53.28s+110895} \\ \frac{-1235840}{s^2+78.41s+106749} & \frac{25167497}{s^2+69.1s+9896} \end{bmatrix} \quad (15)$$

The associated functions of the designed adaptive decoupling controller were assigned to be:

$$d(s) = (s+1)^3 \quad (16)$$

$$\alpha = 6000 \quad (17)$$

The lead-lag compensators $D_f(s)$ and $D_t(s)$ which achieve DC gain of 50dB and phase margin of 45° for each servo loop are:

$$D_f(s) = D_t(s) = \frac{(s+549.3)(s+34.33)}{(s+9837)(s+4.182)} \quad (18)$$

The simulated results of the step response are:
(Case I): Nominal situation

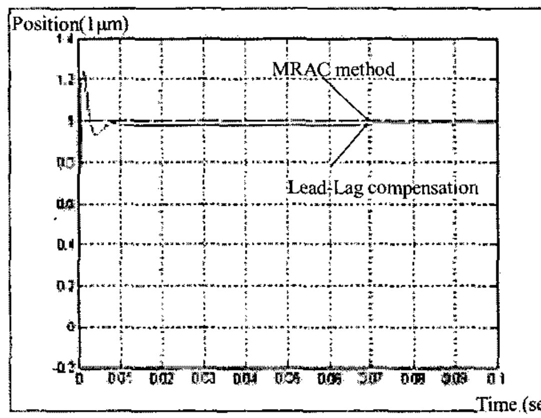

Fig. 5. The simulated results of step response under MRAC and Lead-Lag compensation in nominal case

We found that the system output under MRAC could perfectly reach the desired position. The system under lead-lag compensation, however, was 1% steady state error, which was possibly due to the coupling term from the other servo loop. Lead-lag compensation could have performed very well if the cross coupling was neglected.

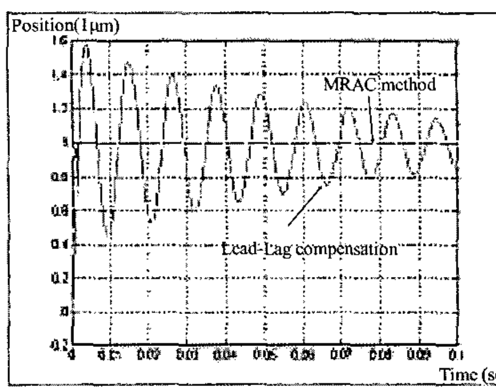

Fig. 6. The simulated results of step response under MRAC and Lead-Lag compensation when payload effect was added

(Case II): Payload effect or parameters variation

In order to understand the payload effect, we increased the coefficients of the s^2 terms in equation (15) from 1 to 5 and the simulated results are shown in fig. 6.

The system output under MRAC could still perform very good transient behavior and positioning accuracy. The lead-lag compensated system, however, was oscillatory and demonstrates the degraded transient and steady-state performance under payload effect.

B. An Experimental Setup

An XY table using a CD-ROM optical pickup-head unit (OPU) was constructed in our laboratory. The OPU was mounted with two additional rods on the two ends of lens

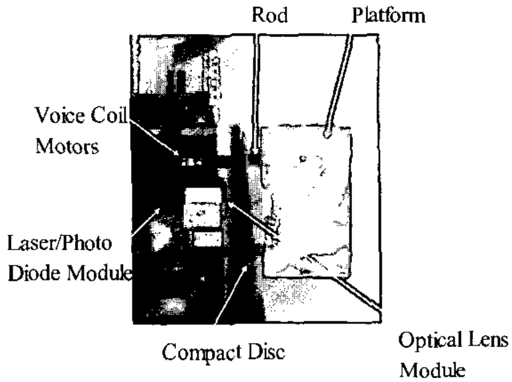

Fig.7. XY-table made by OPU of a CD-ROM drive and a Compact Disc

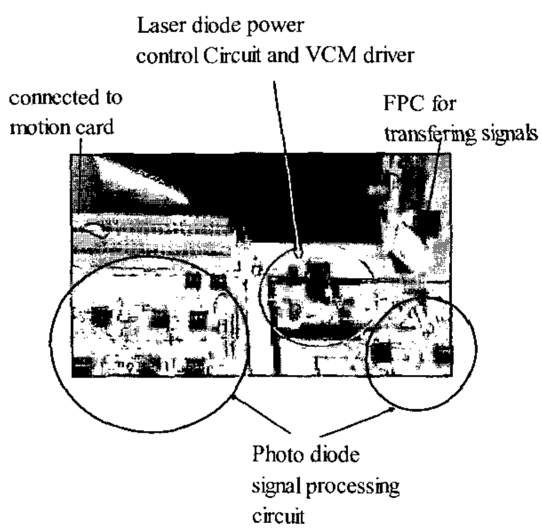

Fig.8. Positioning experiment arrangement of the XY table

module hold a platform, as shown in the figure 7. When the lens module was moved by the focusing VCM, the platform moved in X-direction; whereas the lens module was moved by the radial VCM, the platform moved in Y-direction. Due to the optio-electrical and mechanical limitations, the working range in X-axis would be confined within the linear range of the "S-curve" of focusing error [3]. The limitation is because the linear relationship between focusing error and the distance of the lens module holder way from the disc is only valid in this region. The working range in Y-axis can be go as far as the mechanical limit, since the track error and track jumping signal were easily measurable within the range. Therefore, at least an 800μm (i.e. 500 tracks) working range can be achieved. The platform was made by a thin glass used to carry objects for various kinds of purposes, such as a biological specimen or an aligned optical fiber. The position signals of the platform in X and Y directions were measured through the reflected signals from the

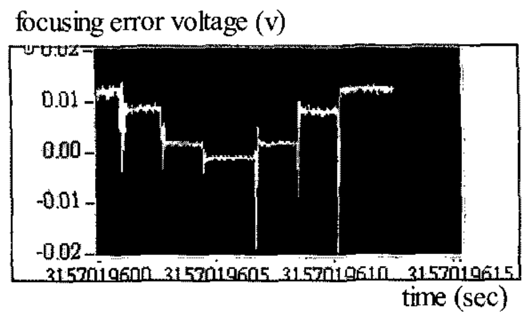

Fig.9. Positioning experimental results of moving the platform within the S-curve region of focusing

compact disc in front of the lens module. These feedback signals, i.e. focusing errors, track errors, and track crossing signals were obtained through the photo diode array of the OPU, amplified and processed by the circuitry as shown in Fig. 8. The VCM actuators were driven by a motor IC and controlled by a personal computer with an NI PCI-6024E AD/DA board. The first result of a positioning experiment is shown in Fig. 9.

At the early stage of development, we inputted a series of position commands in x-axis and observed the movement of the stage through the feedback focusing errors. From the observation of the feedback focusing errors, it indicates the platform was able to perform a designated movement. The overshoot and oscillation was obvious. It was mainly caused by the poor quality of the feedback signals, and the further improvement is undergoing.

IV. Conclusion and Future Work

In this paper, we proposed a novel idea of using optical pickup head module of optical storage devices, such as CD-ROM/DVD-ROM drives to build a XY-table. The great potential to achieve low cost and accurate positioning was also demonstrated. The positioning was carried out through proper feedback signal processing and control of the VCM actuators. We also found the superiority of adaptive control to the conventional lead-lag compensators of having better outcomes for accurate trajectory following in nominal and with payload cases by several simulations. The future work would include further improvements of the feedback signal quality, filters, and completion of implementing the adaptive controller and extensive comparisons. The positioning accuracy is also needed to be verified by a laser interferometer.

REFERENCES

[1] *CD-Audio Red Book*, Philips, Sony, 1980.

[2] *DVD Specification for Read-Only Disc / Part 1: Physical Specification"*, Version 1.0, DVD Forum, 1996.

[3] K.C. Fan, C.Y. Lin and L.H. Shyu, "Development of a Low-cost Focusing Probe for Profile Measurement", *Measurement Science and Technology*, Vol. 11, No. 1, pp. 1-7, 2000.

[4] A.F.F. Filho, A.A. Susin and M.A. da Silveira, "Investigation of the forces produced by a new electromagnetic planar actuator", *IEEE International Electric Machines and Drives Conference, IEMDC* 2001., pp. 8-13, 2001.

[5] F.N. Toth and G.C.M. Meijer, "A low-cost, accurate and fast capacitive displacement sensor with microcontroller interfacing", 9th *IEEE Instrumentation and Measurement Technology Conference, IMTC '92.*, pp. 414-417, 1992.

[6] G. Bonwhuis and A. Huger, *Principle of Optical Drive Systems*, Adam Hilger Ltd., 1985.

[7] T.J. Yeh and Y.C. Pan, "Modeling and Identification of Opto-Mechanical Coupling and Backlash Nonlinearity in Optical Disk Drives", *IEEE Trans. on Consumer Electronics*, Vol. 46, No. 1, pp. 105-115., 2000.

[8] H. Ambrose and Z. Qu, "Model Reference Robust Control for MIMO Systems", *Proceedings of the American Control Conference*, pp. 345-349, 1997.

[9] K.S. Narendra and A.M. Annaswamy, Stable Adaptive Systems, 1st ed., Prentice Hall International, Inc., 1989