Fine Seek Control of Extended Applicable Range for Optical Disk Drives

Jung Rae Ryoo, Kyoung Bog Jin, Tae-Yong Doh, and Myung Jin Chung

Abstract: Optical disk drive has excellent advantage of random accessibility of which performance is measured by access time. However, due to the increased rotational velocity of the disk and constraints of mechanical structure, two-stage seek algorithm which executes coarse and fine seeks sequentially has been adopted in most commercial optical disk drives. Although the laser spot is moved to a target track by a single seek operation, the limited operation range of the fine actuator restricts the application of the fine seek algorithm below a few hundreds of tracks. Especially, excessive movement of the objective lens causes a failure in generation of track-cross pulse and results in an unstable seek operation. In this paper, a new control algorithm for extending the fine seek range is proposed with an appropriate control structure. The coarse actuator is utilized to reduce the misalignment between the objective lens and the laser beam axis, and the fine actuator is controlled to follow the reference velocity trajectory. The proposed algorithm is applied to a CD-ROM drive to show its feasibility and some experimental results are presented.

Keywords: optical disk drive, fine seek, random access, direct seek, loopshaping

I. Introduction

In recent years, optical disk drive has become one of the major data storage devices in auxiliary memory devices and audio/video systems. The reasons of this popularity are its short access time compared with that of magnetic tape drive, exchangeability of disks, and almost unlimited lifetime. Many researches have been carried out in this field to improve the performance represented by data transfer rate and access time. For higher data transfer rate, disk rotation has been speeded up in optical disk drive, because it is proportional to disk rotational speed. However, the increased disk rotational velocity for higher data transfer rate has invoked many serious problems in its servo control system which should control the relative position and velocity of a laser spot with respect to a disk rotating with eccentricity. Especially, the bandwidth and magnitude of disturbance from the eccentric rotation, which deteriorate the performance of the laser spot positioning system, are inherently related to the spinning speed of disk.

The laser spot positioning system operates in two different control modes of seek control and track-following control. The data transfer rate is dependent on the track-following control which is to regulate the laser spot at the center of a track during data read-out, and various control methods have been adopted [1][2]. On the other hand, the access time related with the seek control has been reduced continually. In order to reduce the seek time, track-following control should be launched as soon as possible after seek operation. In this point of view, direct seek control is the most appropriate control scheme to reduce the access time, where the stability of track-following control is not always preserved due to the constraints of nonlinear tracking error signal, control bandwidth limitation and so on. For a remedy of this problem, laser spot velocity at a target track should be regulated as low as possible, which is an initial condition that may cause excessive overshoot in track following control [3]. For this purpose, the laser spot velocity should follow a predetermined trajectory while rejecting the effect of the extraneous disturbance. In general, coarse actuator has been used to meet the objective [4]. However, the bandwidth of coarse actuator is not wide enough to cover the entire bandwidth of the external disturbance for the result of increased disc rotational velocity. For a solution, Jin *et al.* [5] proposed a direct seek control scheme for two stage actuator, where fine actuator is controlled to reject the disturbance while coarse actuator follows the reference velocity trajectory.

For another solution, two stage seek operation composed of coarse and fine seeks is usually adopted in commercial products due to its reliability. The second seek operation called fine seek is a kind of direct seek controlled by the fine actuator with fast dynamics [6]. Although the laser spot position is controlled exactly by a single seek operation by a fine seek control, it can only be applied less than a few hundreds of tracks because the objective lens is confined in a pickup. In spite of the limitation of the fine seek, there have been no efforts to cure or to extend the applicable range. Extension of the fine seek range can bring a conspicuous reduction in data access time not only because it can move with higher acceleration but also because data access to a remote track can be accomplished by a single seek operation.

In this paper, a new fine seek control scheme with an extended bound of applicable range and an appropriate control structure are proposed. In addition, experimental results showing its feasibility are presented. In conventional fine seek schemes, only the fine actuator has been used to move the laser spot. In the proposed algorithm, however, the coarse actuator is also controlled to reduce the displacement between objective lens and beam axis.

The remainder of this paper is organized as follows. In sec-

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Jung Rae Ryoo, Myung Jin Chung: Div. of EE, Dept. of EECS, KAIST (ryoo@cheonji.kaist.ac.kr, michung@ee.kaist.ac.kr)

Kyoung Bog Jin: Dept. of Control System Engineering, Korea University of Technology and Education(kbjin@kut.ac.kr)

Tae-Yong Doh: Digital Media R&D Center, Samsung Electronics Co. Ltd.(eigen@samsung.com)

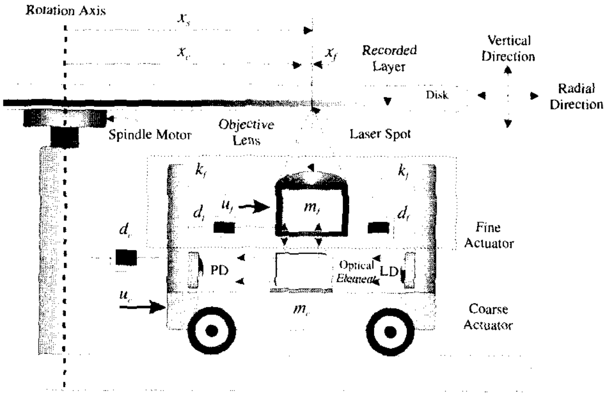


Fig. 1. A schematic diagram of a laser spot positioning system in an optical disk drive.

tion 2, a typical structure of laser spot positioning system in optical disk drive and a generalized fine seek algorithm are introduced. In addition, the problem of objective lens misalignment in the conventional fine seek algorithm is explained with an experimental result. In section 3, a new fine seek control algorithm is proposed with an appropriate control structure. In section 4, to show the feasibility, some experimental results are presented with explanations on the experimental environment. Finally, some concluding remarks are given in section 5.

II. Structure of an optical disk drive and conventional fine seek method

1. Structure of an optical disk drive

In optical disk drive, a laser spot is moved in the radial direction of an optical disk as in Fig. 1, and the two-stage actuator composed of the coarse and fine actuators is a general laser spot positioning mechanism. The fine actuator mounted on top of the pickup actuated by the coarse actuator drives the objective lens. Therefore, the position of the laser spot x_s is determined by the position of the objective lens x_f and that of the pickup x_c. Owing to the extraneous disturbance like eccentric rotation, the laser spot position is also dependent on the disturbance(x_d). A schematic diagram of a common two-stage actuator is shown in Fig. 2.

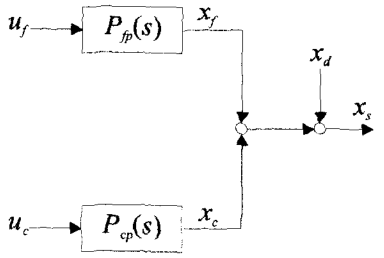


Fig. 2. A schematic diagram of a two-stage actuator.

The two actuators $P_{fp}(s)$ and $P_{cp}(s)$ have opposite characteristics. The frequency bandwidth of the fine actuator is wide, while its operating range is narrow. On the other hand, the operating range of the coarse actuator covers the entire disk radius at the expense of the bandwidth. Their mathematical models are described as

$$P_{fv}(s) \equiv sP_{fp}(s) = \frac{k_f s}{s^2+as+b} \text{ (m/s/V)} \quad (1)$$

$$P_{cv}(s) \equiv sP_{cp}(s) = \frac{k_c}{s+c} \text{ (m/s/V)}, \quad (2)$$

respectively.

2. Restriction of conventional fine seek

The objective of seek operation is a fast and stable access to data contained in a target track. Thus, a seek operation is followed by a track following operation for data read-out. In the sense of servo control strategy, track-following control is to minimize the tracking error signal which is inherently nonlinear and sinusoidal due to its optical sensing mechanism. Therefore, it has restricted linear regions of the tracking error signal, and global stability of the track-following control system is not ensured. For a cure of this problem, it is required to minimize the track crossing velocity of the laser spot at the destination track in order to prevent the overshoot from exceeding the linear bound [3], and the track crossing velocity is controlled to follow a predetermined reference velocity trajectory during the seek operation. As the track crossing velocity is also dependent on the eccentric rotational velocity, the influence of the external disturbance must be rejected below an acceptable level. Fine seek algorithm is adequate for the purpose, where the laser spot is moved by the fine actuator with wide frequency bandwidth. In conventional fine seek operation, the coarse actuator is not controlled at all.

Although the fine actuator can be controlled to jump to a targe track with minimized final velocity, the applicable range of the conventional fine seek is restricted due to the misalignment between the objective lens and the laser beam axis. Especially, it may cause a failure in generation of track-cross pulse due to the decrease in laser beam intensity. It usually leads to an unstable tracking of the reference velocity trajectory. Therefore, the conventional fine seek is applied below a few hundreds of tracks according to the performance of the optical mechanism. It is a serious limitation of the conventional fine seek.

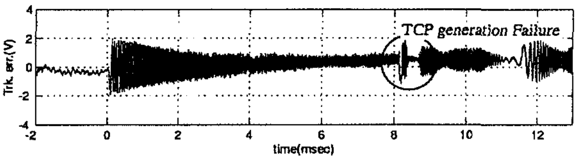
In Fig. 3, an experimental result of a conventional fine seek is shown, that was applied to an 800 tracks seek. The failure in the seek operation is represented in circles around 8 msec. It is caused by misdetection of velocity, which originates from the failure in the track-cross pulse generation. Fig. 3(a) represents the failure in generation of track-cross pulse (TCP) and an incorrect velocity is obtained as shown in Fig. 3(c). In the next section, we propose a new fine seek algorithm which extends the maximum allowable number of tracks for fine seek operation.

III. A new fine seek algorithm

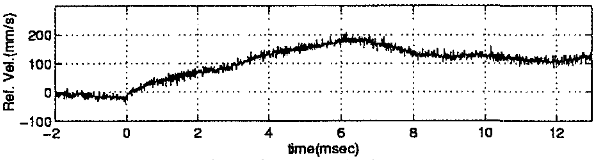
The new algorithm for fine seek control is different from the conventional one in view of the usage of the coarse actuator. In the proposed fine seek algorithm, the coarse actuator is controlled to get rid of the misalignment between the center of the objective lens and the beam axis. The proposed fine seek control structure is represented in Fig. 4. There are three controllers to be designed, *i.e.*, the feedforward controller $C_{ff}(s)$, the feedback controller $C_{fb}(s)$, and the objective lens misalignment compensator $C_c(s)$.

In the Fig. 4, the only measurable velocity is spot velocity (v_s) relative to velocity run-out(v_d) for eccentricity such as

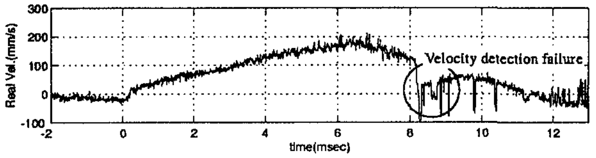
$$v_s = v_f + v_c - v_d, \quad (3)$$



(a) Tracking error signal



(b) Reference velocity



(c) Real velocity

Fig. 3. Velocity detection failure in a conventional fine seek operation.

where v_f is the velocity of the objective lens, and v_c is that of the pickup. And it can be represented with v_r and v_d, *i.e.*,

$$\begin{aligned} v_s = & \frac{(C_{fb}(s)+C_{ff}(s))P_{fv}(s)(1+P_{cp}(s)C_c(s))}{1+P_{fv}(s)C_{fb}(s)(1+P_{cp}(s)C_c(s))}v_r \\ & -\frac{1}{1+P_{fv}(s)C_{fb}(s)(1+P_{cp}(s)C_c(s))}v_d, \end{aligned} \tag{4}$$

where v_r is the reference velocity. For a fixed controller $C_c(s)$, we define a virtual plant $P_v(s)$,

$$P_v(s) \equiv P_{fv}(s)(1+P_{cp}(s)C_c(s)). \tag{5}$$

And, (4) is modified with an ideal feedforward controller $C_{ff}(s)$, such that,

$$C_{ff}(s) = P_v^{-1}(s) = \frac{1}{P_{fv}(s)(1+P_{cp}(s)C_c(s))}. \tag{6}$$

Finally, the following equation is obtained:

$$v_s = v_r - \frac{1}{1+P_v(s)C_{fb}(s)}v_d. \tag{7}$$

Thus, if $C_{fb}(s)$ is designed to satisfy

$$\mid P_v(s)C_{fb}(s) \mid \gg 1, \quad \omega > \omega_d, \tag{8}$$

where ω_d is the frequency of the periodic disturbance, v_s perfectly tracks v_r. Actually, an approximated equation of (8) is given as

$$\mid P_{fv}(s)C_{fb}(s) \mid \gg 1, \quad \omega > \omega_d, \tag{9}$$

since $\mid P_{cp}(s)C_c(s) \mid$ is sufficiently small in the given frequency range. The feedback controller $C_{fb}(s)$ is a type of lead-lag compensator by means of loopshaping [7]. The reference velocity trajectory and each controller for the proposed control algorithm should satisfy the following conditions respectively.

1. Reference velocity trajectory

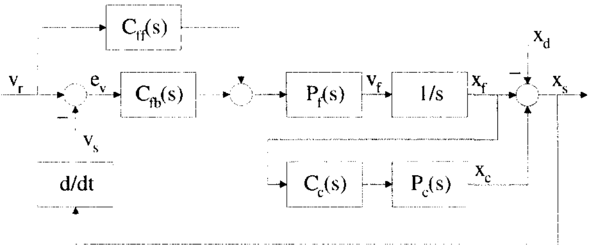


Fig. 4. A schematic diagram of the proposed fine seek control.

The velocity trajectory consists of an acceleration and deceleration region. For exact tracking, selection of a proper acceleration value is required to ensure sufficiently low velocity at the target track. If the trajectory is impossible for the fine actuator to follow, the requirement for the final velocity can not be guaranteed. In addition, there is a limit in the maximum velocity because generation of the track-cross pulse is also dependent on the velocity of the laser spot.

2. Objective lens misalignment compensator

This controller makes it possible to extend the applicable range of fine seek without failure in generating track-cross pulse. The coarse actuator is controlled in the direction of reducing the displacement of the objective lens center from the beam axis. For this purpose, low frequency gain is expected to be sufficiently large as much as possible. However, control input saturation accompanied with this large gain and narrow coarse actuator bandwidth prevents its perfect rejection of the misalignment. Moreover, control input saturation results in unstable track-following pull-in at the target track. Therefore, its control bandwidth should be restricted to lower band than that of the disturbance with sufficiently large gain and phase margine, that is,

$$\mid P_{cp}(j\omega)C_c(j\omega) \mid \ll 1, \quad \omega > \omega_d, \tag{10}$$

where ω_d is the frequency of disturbance.

3. Feedforward controller

An ideal feedforward controller is the inverse of the virtual plant model $P_v(s)$ of (5) as in (6), *i.e.*

$$C_{ff}^*(s) = P_v^{-1}(s) = \frac{1}{P_{fv}(s)}\frac{1}{(1+P_{cp}(s)C_c(s))}. \tag{11}$$

Laser spot velocity of the laser spot positioning system without modeling uncertainty or external disturbances can be controlled to track the reference velocity trajectory by this ideal feedforward controller, if it is realizable. However, the nominal model of the fine actuator($P_{fv}(s)$) is strictly proper. Thus, its inverse model includes a purely derivative term which becomes a noise amplifier when it is implemented. Therefore, a pole outside the control bandwidth should be added to $C_{ff}^*(s)$ as follows.

$$\begin{aligned} C_{ff}(s) &= C_{ff}^*(s)\frac{p}{s+p} \\ &= \frac{1}{P_{fv}(s)}\frac{p}{s+p}\frac{1}{1+P_{cp}(s)C_c(s)}, \end{aligned} \tag{12}$$

where p is the additional pole.

4. Feedback controller

The feedback controller rejects the influence of disturbance within an allowed velocity error. The tolerable velocity

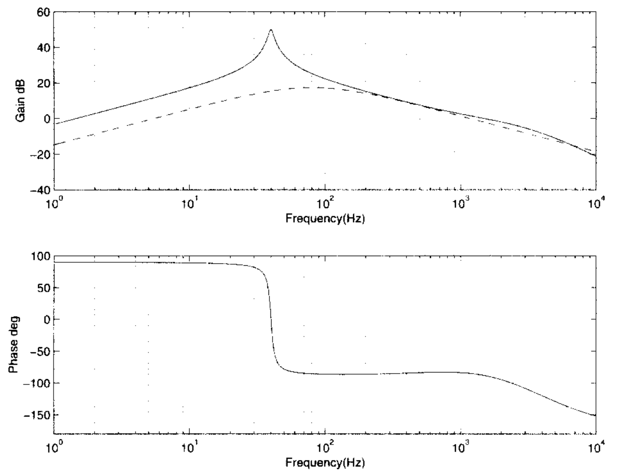


Fig. 5. $L(j\omega)$(solid) of the fine actuator feedback control loop and its weighting function $W_{v1}(j\omega)$(dashed).

error(e_v) is selected as the maximum velocity guaranteeing stable tracking pull-in [3] such as

$$| e_v | < \epsilon. \tag{13}$$

From (13) and the maximum velocity of external disturbance $V_d(s)$, the weighting function W_{v1} is chosen as

$$| W_{v1}(s) | = \frac{| V_d(s) |}{\epsilon}. \tag{14}$$

Recall that the nominal performance condition [7] for (13) is given as

$$\| W_{v1}(s) S(s) \|_\infty < 1, \tag{15}$$

where $S(s)$ is the sensitivity function and described as

$$S(s) = \frac{1}{1 + L(s)} = \frac{1}{1 + P_{fv}(s) C_{fb}(s)}. \tag{16}$$

(15) and (16) lead to

$$| 1 + L(j\omega) | > | W_{v1}(j\omega) |, \ \forall \omega \in [0, \infty). \tag{17}$$

A sufficient condition for (17) is written as

$$\begin{aligned} | L(j\omega) | &= | P_{fv}(j\omega) C_{fb}(j\omega) | \\ &> | W_{v1}(j\omega) |, \ \forall \omega \in [0, \infty). \end{aligned} \tag{18}$$

Thus, the feedback controller $C_{fb}(s)$ should be determined to satisfy (18) with sufficient phase margin.

IV. Experimental environment and results

1. Plant models and controllers

The proposed fine seek algorithm is applied to a commercial CD-ROM drive. The two actuators are modeled as

$$P_{fv}(s) = \frac{44.216s}{s^2 + 22.1s + 63289} \ \text{(m/s/V)} \tag{19}$$

$$P_{cp}(s) = \frac{12.57}{s(s + 31.42)} \ \text{(m/V)}. \tag{20}$$

The stable pull-in condition on a target track is represented as

$$| e_v | < 5 \times 10^{-3} \ \text{(m/s)}. \tag{21}$$

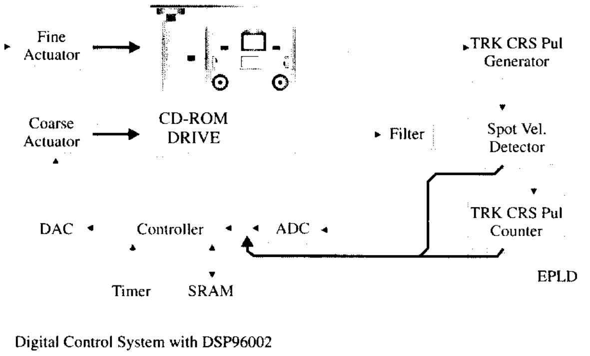


Fig. 6. A schematic diagram of the digital control system using DSP96002.

Three controllers to meet this requirement (21) is given by

$$\begin{aligned} C_{ff}(s) &= \frac{35.58(s^2 + 30.17s + 28780)}{s(s + 24000)} \\ C_{fb}(s) &= \frac{807860(s + 7000)}{(s + 20000)(s + 18850)} \\ C_c(s) &= \frac{12.68 \times 10^3 (s + 100)}{s + 1200}. \end{aligned}$$

In Fig. 5, the frequency response of loop gain $L(j\omega)$ is depicted with weighting function $W_{v1}(j\omega)$ where $W_{v1}(s)$ is given by

$$W_{v1}(s) = \frac{7379s}{s^2 + 1005s + 252662}.$$

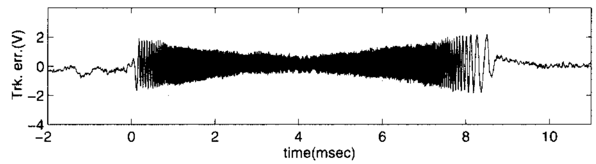
The reference velocity trajectory consists of acceleration and deceleration region with the same magnitude of 30 m/s^2. Therefore, it has a triangularly shaped velocity profile.

2. Experimental setup and results

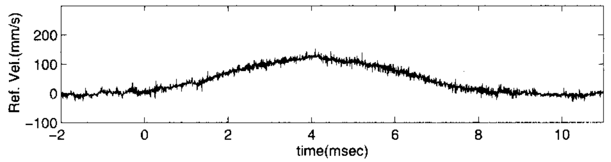
Remarkable advances in the field of microprocessor technology have enabled easy implementation of various control algorithms. Especially, digital signal processors are widely used for implementation of controllers because of their fast computational speed whereby some barriers to realtime implementation have been removed.

Fig. 6 depicts the schematic diagram of the developed digital control system using DSP [1]. The main processor is a 32 bit floating point type DSP of Motorolla DSP96002 which has a highly parallel executable instruction set. In addition, with the help of shortened delay in interrupt handling, a high sampling rate of 100 kHz can be realized. Sensor signals are filtered to remove noise and converted to digital values by a 12 bit A/D converter. Control inputs calculated by DSP are converted to analog signals by 12 bit D/A converters. For seek or tracking operation, various control inputs for each actuator should be generated, while DSP executes the program sequentially. Therefore, time sharing is required in the DSP execution and a multirate sampling method [8] is adopted, which is an efficient algorithm for assigning different sampling rates to each controller according to their control bandwidths.

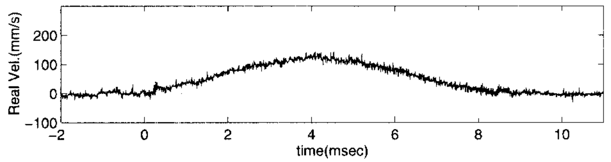
The experimental results of the proposed fine seek scheme for 400 and 800 tracks are depicted in Fig. 7 and 8, respectively. In each figure, tracking error signal(a), reference velocity trajectory(b), and real velocity(c) are depicted. As shown in the figures, the spot velocity is controlled to track the reference velocity during the fine seek operation. The frequency of



(a) Tracking error signal

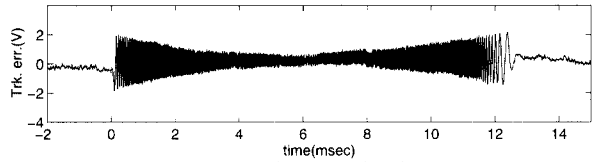


(b) Reference velocity

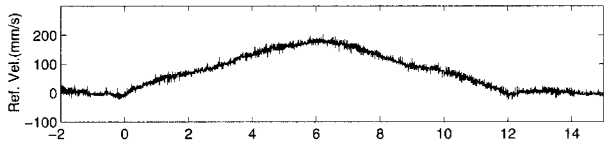


(c) Real velocity

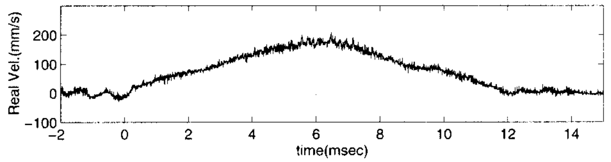
Fig. 7. Experimental results of 400 tracks inward seek.



(a) Tracking error signal



(b) Reference velocity



(c) Real velocity

Fig. 8. Experimental results of 800 tracks inward seek.

the tracking error signal is dependent on the laser spot velocity and its amplitude is small at the high velocity region due to a low-pass filter which rejects high frequency noise.

The performance of the proposed algorithm is superior to that of conventional one depicted in the Fig. 3. In conventional seek algorithm, 800 tracks seek usually consists of two seek operations, *i.e.*, coarse seek and fine one. Of course, there must be a data read operation between the coarse and fine seeks to find out the number of left tracks to the target track, which takes additional time. On the other hand, the proposed algorithm accomplishes the same objective with only one seek operation.

V. Conclusions

In this paper, a new fine seek algorithm was presented. It extends the upper bound of the conventional fine seek range. Experimental results proving its feasibility were presented and compared with that of a conventional one. The most important difference is to introduce a controller for the coarse actuator. This controller diminishes the misalignment of the objective lens generated for the result of movement of the objective lens by fine actuator. For more improved performance, an additional compensator may be introduced to get rid of the effect of friction and a more systematic method can also be applied to design of the coarse actuator compensator.

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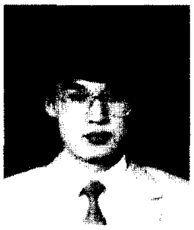
Jung Rae Ryoo
received the B.S. and M.S. degrees in electrical engineering from Korea Advanced Institute of Science and Technology in 1996 and 1998, respectively. He is currently studying toward the Ph.D. degree in electrical engineering at Korea Advanced Institute of Science and Technology. His research interests include robust motion control, optical disk servo control, and trajectory generation.



Kyoung Bog Jin
received the B.S. and M.S. degrees in electrical engineering from Hanyang University in 1985 and 1987, respectively and the Ph.D. degree in automation and design engineering at Korea Advanced Institute of Science and Technology in 1999. He is currently with Department of Control System Engineering at Korea University of Technology and Education, where he is currently a Assistant Professor. From 1987 to 1994, he worked for Samsung Electronics Co., Ltd. in the field of servo technology and from 1999 to 2000 he worked for ODD R&D Group of Samsung Electronics Co., Ltd as a senior research engineer. His research interests include optical disk servo control, robust control, and iterative learning control.

Tae-Yong Doh
received the B.S. degree in electrical engineering from Kyungpook National University in 1992, the M.S. and Ph.D. degrees from Korea Advanced Institute of Science and Technology in 1994 and 1999, respectively. He is currently with Digital Media R&D Center of Samsung Electronics Co., Ltd. as a research engineer. His research interests include iterative learning control, robust control, optical disk servo control, and repetitive control.

Myung Jin Chung
received the B.S. degree in electrical engineering from Seoul National University in 1973, the M.S. degree in electrical and computer engineering in 1977 and the Ph.D. degree in computer, information, and control engineering in 1983 both from the University of Michigan. Since 1983, he has been with the Department of Electrical Engineering and Computer Science at Korea Advanced Institute of Science and Technology, where he is currently a Professor. In 1976, he worked for the Agency for Defense Development, Seoul, as a member of technical staff and from 1981 to 1983 he worked for the Center for Robotics and Integrated Manufacturing, the University of Michigan. His research interests include robust control, intelligent control, robot path planning and control, telerobot control, and multi-sensor fusion.