A Novel Fine Track-Seeking Scheme for Optical Storage Device

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Abstract — *This paper presents a novel hybrid track position (HTP) detector for the track jump controller in an optical disk drive. The servo system then draws the feedback information from the HTP position information instead of the conventional track crossing velocity. The proposed design provides more accurate feedback information, and thus more accurate velocity profile. The experimental results show that the proposed controller achieves better seek time performance. The short jump experiments also show that the proposed system can more effectively cancel the disk eccentricity effect*[1].

Index Terms — Fine track-seeking, position detection, optical storage device.

I. INTRODUCTION

An optical storage device typically includes a radial positioning servo system to precisely traverse and maintain the focus laser spot over a selected track. The operation of maintaining the spot position over the desired track is referred to as *track-following*. The operation of radially moving the pickup across one or more tracks is referred to as track-searching or *track-seeking*. The two operation modes are executed consecutively. After track-seeking operation, track-following control for data reading should be launched as soon as possible.

In practical application, a two-stage track-seeking scheme composed of *coarse* track-seeking and *fine* track-seeking is generally used in the consumer optical storage devices. Coarse track-seeking is an algorithm controlling a coarse actuator (usually a DC motor or stepping motor) to move the pickup across the majority of the accessing distance. The purpose is to locate the laser spot near the target track. The optical storage device then reads the current track information and calculates the number of remaining tracks to be traversed. The system then executes a fine track-seeking to cover the remaining tracks. In a conventional optical storage device, because of inaccuracy in counting track crossing, the fine track-seeking operation may be repeated several times before the desired track is finally reached.

Recently, many researches for reducing the seek time of optical storage devices were focused on coarse track-seeking [1~5]. However, the reduction of the seek time is limited by the mechanism of the optical storage devices. With current increased density of optical discs, like DVD or HD-DVD, the pull-in range which is a range capable of obtaining an effective tracking error signal at the time of pull-in also becomes narrow. As a result, when the system is switching from track-seeking to track-following, the frequency of overshoot caused at the servo close increases. Thus, if the overshoot is out of the control bandwidth of track-following servo loop, the track-seeking fails or it takes long until stabilization is accomplished. Accordingly, the fine track-seeking control becomes more important.

In this paper, a novel fine track-seeking scheme with a hybrid track position detector and an appropriate control structure are proposed. The paper then presents experimental results to show its feasibility. In a conventional fine track-seeking, the moving velocity is largely affected by the external disturbances and this may result in a failure of the track-following servo. The proposed scheme uses the position feedback to accomplish fine track-seeking. Thus, the effect caused by external disturbances can be minimized.

This paper is organized as follows. In section 2, a plant model of the laser spot positioning system in an optical storage device is introduced. Section 3 is a conventional fine track-seeking scheme using lens kick by velocity control. Section 4 is the novel fine track-seeking scheme proposed in this paper. In section 5, a system configuration is proposed with an appropriated design compensator. Section 6 presents the experiment results to show the feasibility and performance. Finally, some concluding remarks are given in section 7.

II. PLANT MODEL

As shown in Figure 1, the radial positioning system in the optical drive is a two-stage actuator mechanism composed of a coarse actuator and a fine actuator. The fine actuator, which directly drives the objective lens, is mounted on the top of the pickup traversed by the coarse actuator. Therefore, the position of the objective lens (X_F) and that of the pickup (X_C) determines the position of the laser spot. The two actuators have very different characteristics. The bandwidth of the fine actuator is wide, while its operating range is small. On the other hand, the operating range of the coarse actuator covers the entire disc radius at the expense of the bandwidth. Owing to the external disturbance like disc eccentricity, the laser spot position (X_L) is also dependent on the disturbance (X_D). The plant model can then be described as:

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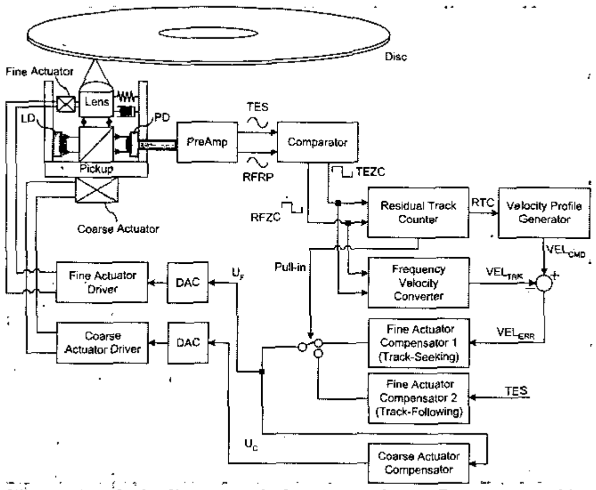

Figure 1. Block diagram of the conventional fine track-seeking scheme using velocity control

$$M_C\ddot{X}_C + B_C\dot{X}_C = U_C, \tag{1}$$

$$M_F\ddot{X}_F = U_F + B_F\left(\dot{X}_C - \dot{X}_F\right) + K_F\left(X_C - X_F\right), \tag{2}$$

$$X_L = X_F - X_D. \tag{3}$$

Where M_C and B_C are inertia and damping element of the coarse actuator, M_F, B_F, and K_F are inertia, damping and spring element of the fine actuator. However, in conventional optical storage devices, the compensators for the two actuators are designed separately for simplicity. As shown in Figure 1, the fine actuator is controlled by the fine actuator compensator only and the coarse actuator controller is cascaded on top of the fine compensator. Accordingly, the disc eccentricity, X_D, and the lens misalignment both become external disturbances to the fine actuator loop, where the lens misalignment means the displacement between the position of the fine actuator, X_F, and that of the coarse actuator, X_C. The lens misalignment comes due to the difference of bandwidth of the two actuators. Thus, a superior fine track-seeking scheme should eliminate the influence caused by the two external disturbances, namely, disc eccentricity and lens misalignment.

III. CONVENTIONAL FINE TRACK-SEEKING SCHEME

Figure 1 is the block diagram of the conventional fine track-seeking scheme using lens kick with velocity control [6~9] and this structure is widely applied to the consumer optical disk drives. The output signals from the PD (photo detector) cells in the pickup are supplied to the PreAmp for generating the TES (tracking error signal) and the RFRP (radio frequency ripple) signal. According to the type of optical discs, the generation method of TES can be either DPD (differential phase detection), push-pull, DPP (differential push-pull), or 3-beam. The RFRP, also named as focus sum signal or track sum signal, is derived from the summing output of the PD cells in the pickup, which detects the reflected main laser beam. When the spot of laser beam traversing the disc during the track-seeking operation, TES and RFRP become modulated relative to the track crossing. The modulation of the RFRP is a sinusoidal waveform with 90° phase shift from the TES, which is a sinusoidal waveform, or a saw tooth waveform depending on the generation method. The TES and the RFRP are both supplied to a comparator circuit to generate the digitized TEZC (tracking error zero cross) signal and digitized RFZC (RFRP zero cross) signal.

In Figure 1, the residual track counter uses the TEZC and the RFZC as inputs and calculates the RTC (residual track count), which is the number of remaining tracks from the current position to the destination. The RTC is then supplied to the velocity profile generator, which is generated by a look-up table. The velocity profile generator outputs velocity command, VEL_{CMD}, according to the RTC. The moving velocity between disc and laser spot, VEL_{TRK}, will be detected by a frequency-velocity conversion circuit using the TEZC and the RFZC. The velocity error, VEL_{ERR}, which is generated by the difference between the velocity command (VEL_{CMD}) and the detected moving velocity (VEL_{TRK}), will feed into the track-seeking compensator. Interested readers please refer to [10] for further detail. When the RTC becomes zero, the servo system switches to track-following, and the TRO is switched to the output of the track-following compensator, and the laser spot can pull-in to the target track.

One major problem of the conventional fine track-seeking scheme is the detection delay time. The frequency-velocity conversion circuit for the laser spot velocity measurement calculates an inverse number of the cycles of TEZC and RFZC and converts the inverse number to a relative velocity between the laser spot and disc. Thus, until the next TEZC or RFZC is available, there is no information at all on the velocity measurement. During this time, the control is affected by using the latest measured velocity. As a result, a detection delay time occurs in the velocity detection operation. Specifically, because the real velocity of the optical pickup varies during the time period between two consecutive measurements, the velocity feedback value maybe way off. Furthermore, as the velocity of the laser spot decreases, the detection delay time increases. In addition, the velocity control is largely affected by the external disturbances, like disc eccentricity and lens misalignment. For example, when the real velocity decreases excessively in a low-velocity region right before the pull in to the track-following operation, the laser spot may actually move in the opposite direction owing to the eccentric velocity from the disk eccentricity. In this case, either the seek time may increase or the track-seeking operation may fail. Moreover, the detection delay time also results in a steady state deviation of the final velocity from the desired velocity profile. If the final velocity is out of the reach of the track-following servo bandwidth when pulling in to the target track, the laser spot may not be positioned on the target track.

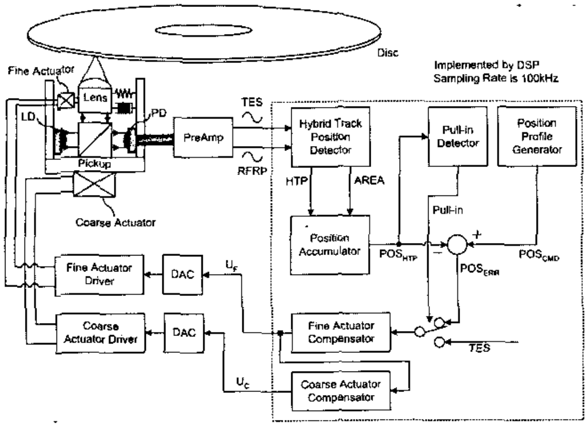

Figure 2. Block diagram of the novel fine track-seeking scheme using HTP control

To deal with the above mentioned problems, this paper proposes a novel fine track-seeking scheme using a HTP (hybrid track position) detector. The HTP detector can measure the relative position between the laser spot and the target track. Using the output of the HTP detector for the feedback signal, the fine track-seeking control loop in Figure 2 can precisely and stably control the moving velocity and the position of laser spot during the track-seeking operation. Especially when pulling in to the target track, the final moving velocity can be precisely maintained within the track-following servo bandwidth. Thus, the stability of the fine track-seeking operation and track-following servo loop can both be guaranteed. The experimental results in the following sections will demonstrate its feasibility.

IV. A NOVEL FINE TRACK-SEEKING SCHEME

The goal of a fine track-seeking servo in the optical storage devices is to achieve fast and stable access to data contained in a target track. Thus, a fine track-seeking operation is always followed by a track-following operation for data read-out. In the sense of servo control strategy, the track-following control is to minimize the TES, which is inherently nonlinear and sinusoidal (or saw-tooth). Therefore, it has a relatively narrow linear region. If the TES is allowed a large value, the global stability of track-following control system may not be ensured. The most important requirement to guarantee stability in the track-following control is to minimize the accessing velocity when pulling in to the destination track. This velocity also becomes the initial condition causing the overshoot in the transient response of the track-following control [11]. If the overshoot exceeds the linear range of the TES, which is limited by the structure inherent to the optical instrument, stability is no longer guaranteed. Therefore, the influence of the external disturbance, like disc eccentricity and the lens misalignment, must be rejected below an acceptable level. Notice that the moving velocity at the destination track depends on the disc eccentricity and is not controlled by the servo system whose bandwidth may reach 2.4kHz for a 1XS DVD.

The proposed fine track-seeking scheme can be fully implemented by executing a program in a digital signal processor (DSP) without extra circuitry. This embodiment is suitable to a system-on-a-chip (SOC) design for the optical storage drive servo chip. In Figure 2, the fine track-seeking scheme is composed of a hybrid track position detector, a position accumulator, a position profile generator and a pull-in detector. The compensator of the track-seeking operation can use the same compensator of the track-following servo loop to simplify the design of system.

The HTP detector is a block for detecting a position change of the laser spot relative to the disc and the principle of the HTP detector will be detailed in the following section. The outputs of HTP detector, HTP and AREA, are supplied to the position accumulator, where HTP is a conversion output of the spot position relative to one track and AREA is an area changeover signal. By using AREA, the position accumulator in the HTP can detect both the occurrence of track crossing and the direction of moving. Therefore, the position accumulator can accumulate HTP and count the number of track crossing. The output of the position accumulator, POS_{HTP}, subtracted by the position command, POS_{CMD}, then forms the required control feedback error, POS_{ERR}. The output of the position accumulator, POS_{HTP}, is also output to the pull-in detector. When the laser spot reaches the vicinity of the target position, more precisely, 1/4 track to the target, the pull-in detector will change the state of the pull-in flag. The fine track-seeking is switched to the track-following operation. During the track-seeking operation, the input of the fine actuator compensator is POS_{ERR}. When pulling in to the track-following mode, the input of the fine actuator compensator is switched to TES.

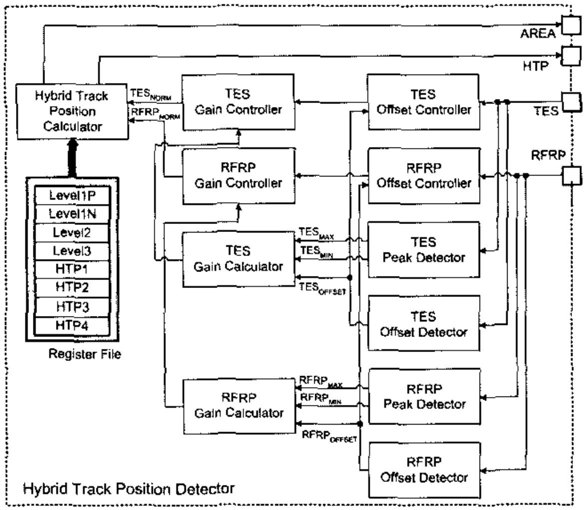

Figure 3. Block diagram of the hybrid track position detector

The position profile generator is to generate the position command, POS_{CMD}. The position command in turn comes from a well-defined velocity profile using proximate time optimal control theory. However, there is also a velocity limit imposed by the bandwidth of the HTP detector.

Figure 3 is the block diagram of the HTP detector proposed in this paper. The HTP detector is composed of a TES offset controller, a RFRP offset controller, a TES peak detector, a RFRP peak detector, a TES offset detector, a RFRP offset detector, a TES gain calculator, a RFRP gain calculator, a TES gain controller, a RFRP gain controller, a hybrid track position calculator and a register file. After focus servo is working stably, TES and RFRP become modulated due to the disc eccentricity. Then, the TES peak detector and RFRP peak detector measure the maximum value and minimum value of TES and RFRP, TES offset detector and RFRP offset detector measure the offset value of TES and RFRP. The output of the TES offset detector, TES_{OFFSET}, is supplied to the TES offset controller for removing the offset component of the TES. Similarly, the output of the RFRP offset detector, $RFRP_{OFFSET}$, is supplied to the RFRP offset controller for removing the offset component of the RFRP. Accordingly, the outputs of the TES offset controller and the RFRP offset controller are offset-free signals.

The outputs of the TES peak detector and the RFRP peak detector, TES_{MAX}, TES_{MIN}, $RFRP_{MAX}$, $RFRP_{MIN}$, are supplied to the TES gain calculator and the RFRP gain calculator together with TES_{OFFSET} and $RFRP_{OFFSET}$. Then, the TES gain calculator can calculate the gain value for normalizing the TES to fit a pre-determined range and output the gain value to the TES gain controller. Similarly, the RFRP signal can be normalized by the RFRP gain controller and the RFRP gain calculator. The normalized TES and RFRP, TES_{NORM} and $RFRP_{NORM}$, are supplied to the hybrid track position calculator. The registers file stores the parameters needed in the HTP calculator.

TABLE I
CALCULATION OF THE HYBRID TRACK POSITION

Area	Transformation Formulas	Range
1	HTP = HTP4 – (TESNORM/Level3) × (HTP4 – HTP3)	[HTP3,HTP4]
2	HTP = HTP2 – (RFRPNORM/Level1N) × (HTP3 – HTP2)	[HTP2,HTP3]
3	HTP = HTP2 – (RFRPNORM/Level1P) × (HTP2 – HTP1)	[HTP1,HTP2]
4	HTP = (TESNORM/Level2) × (HTP1)	[0,HTP1]
5	HTP = (TESNORM/Level2) × (HTP1)	[-HTP1,0]
6	HTP = -HTP2 + (RFRPNORM/Level1P) × (HTP2 – HTP1)	[-HTP2,-HTP1]
7	HTP = -HTP2 + (RERPNORM/Level1N) × (HTP3 – HTP2)	[-HTP3,-HTP2]
8	HTP = -HTP4 – (TESNORM/Level3) × (HTP4 – HTP3)	[-HTP4,-HTP3]

Figure 4 shows an example of the HTP calculator by using DPD TES and RFRP in a case where a relative position between the track and laser spot changes at a predetermined rate. Figure 4(a) is the normalized TES ($TESN_{ORM}$), Figure 4(b) is the normalized RFRP ($RFRP_{NORM}$), Figure 4(c) is the linearization position (HTP), and Figure 4(d) is the associated area changeover. As evident from Figure 4(a) and Figure 4(b), TES is a saw tooth wave and RFRP is a sine wave signal, both TES and RFRP include some linear regions and some nonlinear regions. More precisely, when RFRP is nonlinear, the corresponding TES is linear or quasi-linear. Similarly, when TES is nonlinear, the corresponding RFRP is linear or quasi-linear. Based on this phenomenon, HTP can be generated by using RFRP or TES depending on which one is linear. Obviously, in area 1, 4, 5, 8, TES is linear or quasi-linear to HTP, HTP can be calculated by using TES only; in area 2, 3, 6, 7, RFRP is linear or quasi-linear to HTP, HTP can be calculated by using RFRP. Accordingly, HTP is calculated based on Table 1.

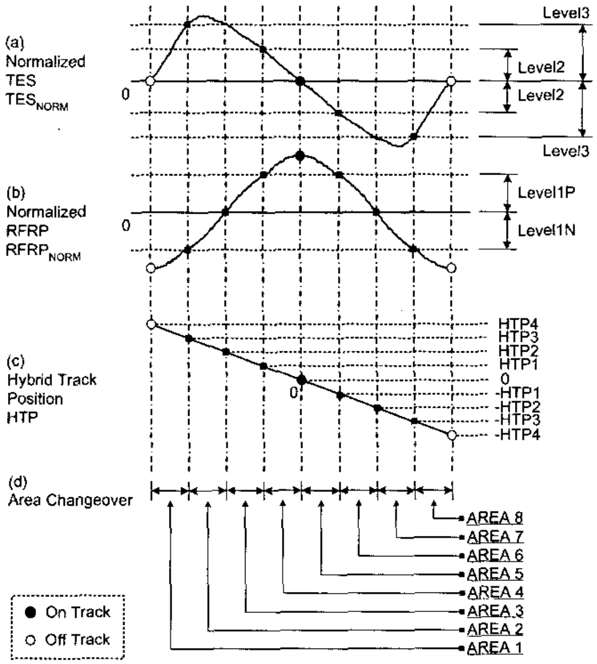

Figure 4. Principle of the hybrid track position calculator

V. SYSTEM CONFIGURATION AND COMPENSATOR DESIGN

Figure 2 depicts the block diagram of the proposed digital control system. The main processor in the experiment is a single-core 32-bit microcontroller-DSP type of Infineon TriCore, which is optimized for real-time embedded system. Sensor signals are filtered to remove high frequency noise and converted to digital value by on-chip 10-bit A/D converters. Control inputs calculated by DSP are converted by on-chip 10-bit D/A converters. Moreover, the sampling rate of the proposed fine track-seeking scheme is 100 kHz so that the max detectable velocity of HTP detector is limited to 35tracks/msec. Besides, both TES and RFRP are filtered by low pass filters for eliminating the high frequency noise, so the bandwidth of TES and RFRP are also restricted within 40 kHz. Accordingly, for stable operation of the proposed scheme, the max detectable velocity is set to 35kHz and the max velocity command should be limited within 30kHz.

Based on the concept of the fine track-seeking scheme proposed in this paper, the compensator of the track-seeking can share the same controller as the track-following servo loop as shown in Figure 2. This is because both the track-seeking loop and the track-following loop are position feedback loops. Accordingly, the compensator design should follow the instruction of DVD book ("DVD Specification for Read-Only Disc"), the bandwidth of open loop transfer function (a series connection of compensator and plant) should be kept above 2.4kHz for 1XS DVD. Actually, the rotation speed of the spindle motor proposed in this paper is CAV (constant angular velocity) 2XS, so the bandwidth of open loop transfer function should be even higher than 2.4kHz experientially. As a result, if the sampling rate of the compensator is 100 kHz, the coefficients of a lead-lag compensator are chosen to be:

$$C(z) = 2^6 \times 0.1456 \times \frac{1 - 0.9484z^{-1} - 0.9987z^{-2} + 0.9498z^{-3}}{1 - 1.2280z^{-1} + 0.1294z^{-2} + 0.1002z^{-3}}. \quad (4)$$

The frequency response of the compensator is shown in Figure 5. The phase of the lead-lag compensator at 3kHz is about 60° that provides a large phase margin for the close loop system.

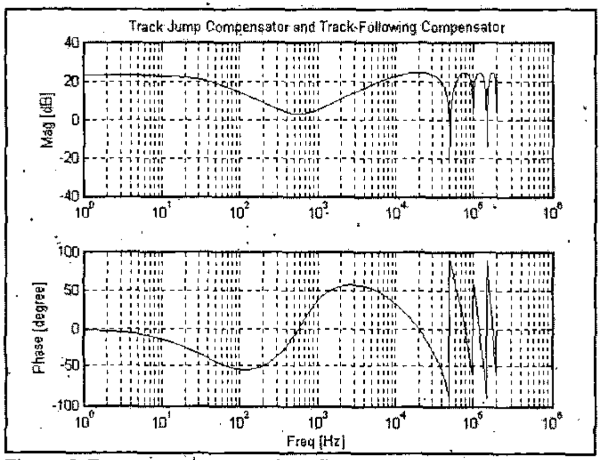

Figure 5. Frequency response of the fine actuator compensator

VI. EXPERIMENTAL RESULTS

Figure 6 shows the experimental results of five continuous 255 tracks of fine track-seeking. The test runs on an ABEX TDR-813 DVD-ROM test disc with 150μm eccentricity. Figure 6(a), (c) and (e) are the resultant signals from the proposed HTP control scheme. Figure 6(b) and (d) are the results from the conventional lens kick scheme using velocity control. The experimental data is also compared in Table 2. It is clearly seen that the performance of the proposed HTP control scheme is superior to that of the conventional servo. The proposed HTP control scheme provides shorter seek time, more efficient velocity profile, better reliability, more accurate final velocity control, and more stable pull-in condition. The 4 curves in the experiment is to compare the control ability against the external disturbances, like disc eccentricity and lens position misalignment. The conventional lens kick using velocity control is strongly affected by the external disturbance, and the final velocity cannot always converge to the control bandwidth of track-following servo loop. Notice that we always design a proximate time optimal velocity profile under rugged consideration. Therefore, a more efficient velocity profile leads to better seek time and a more reliable system.

Figure 7 and Table 3 show the experimental result of five continuous 7 tracks seek with the fine track-seeking. The test disc is also ABEX TDR-813 DVD-ROM. Figure 7(a), (c) and (e) are the resultant signals from the proposed HTP control scheme. Figure 7(b) and (d) are the results from the conventional lens kick scheme using velocity control. These experiment now show the performance of fine track-seek scheme against the disc eccentricity when the accessing distance is small. In some application, like DVD video playback, this test is very important. In DVD Video disc, the Mpeg2 stream and subtitle are located on different neighboring tracks. The optical drives need to access the mpeg2 stream and the selected subtitle back and forth by continuously repeating the fine track-seek operation. If anyone of the repeated fine track-seeking fails, the video playback will be delayed, resulting in frozen pictures. From the curves in Figure 7 and Table 3, the proposed scheme demonstrates much better velocity control ability and better reliability again.

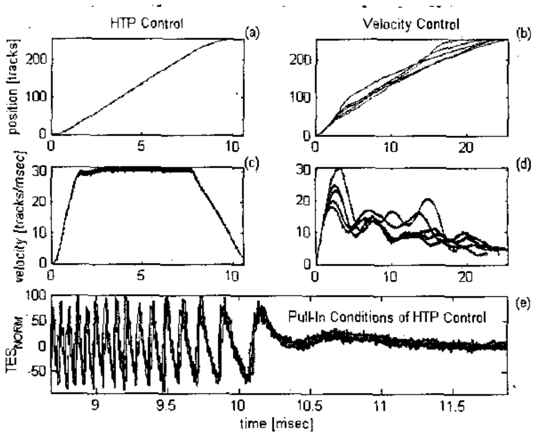

Figure 6. Experimental results of 255 tracks of fine track-seeking

TABLE 2
EXPERIMENTAL DATA OF 255 TRACKS OF FINE TRACK-SEEKING

Item	HTP Control	Velocity Control
Max. seek time	10.5637 [msec]	25.2920 [msec]
Min. seek time	10.5581 [msec]	19.1400 [msec]
Avg. seek time	10.5604 [msec]	23.0056 [msec]
Max peak velocity	31.5059 [tracks/msec]	30.7588 [tracks/msec]
Min peak velocity	31.3100 [tracks/msec]	20.2027 [tracks/msec]
Max final velocity	2.0493 [tracks/msec]	5.8127 [tracks/msec]
Min final velocity	1.9279 [tracks/msec]	3.0227 [tracks/msec]

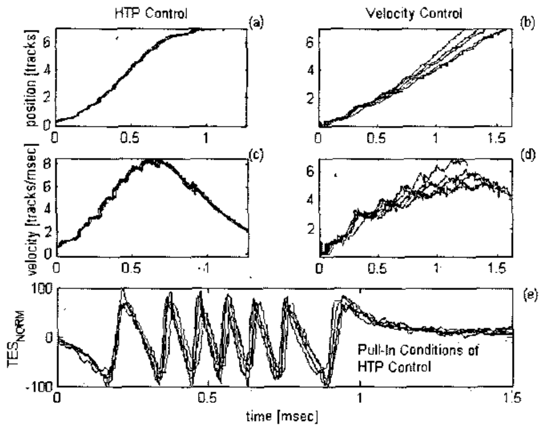

Figure 7. Experimental results of 7 tracks of fine track-seeking

TABLE 3.
EXPERIMENTAL DATA OF 7 TRACKS OF FINE TRACK-SEEKING

Item	HTP Control	Velocity Control
Max. seek time	1.2751 [msec]	1.6200 [msec]
Min. seek time	1.2670 [msec]	1.2600 [msec]
Avg. seek time	1.2701 [msec]	1.4802 [msec]
Max peak velocity	8.5188 [tracks/msec]	6.9098 [tracks/msec]
Min peak velocity	8.2937 [tracks/msec]	5.2341 [tracks/msec]
Max final velocity	2.2246 [tracks/msec]	6.4361 [tracks/msec]
Min final velocity	2.1024 [tracks/msec]	3.9276 [tracks/msec]

VII. CONCLUSION

This paper proposed a novel fine track-seeking scheme using a new hybrid track position detector. The proposed HTP detector and the position accumulator enable a linear position measurement over a wide range of accessing travel. The fine track-seeking scheme is then designed based upon the HTP position information. Because both the track-following servo and the fine track-seeking servo are position feedback systems, the two servo loops share the same compensator. The result is a simplified tuning process in the system integration phase. The experimental results show that the proposed scheme achieves very accurate position control, better seek time performance, more reliable operations and better velocity control performance. The final velocity control is especially efficient. This final velocity control performance also assures successful pull-in to track-following operation. In addition, the fine track-seeking experiment demonstrates the ability of the proposed scheme against the external disturbances, like disc eccentricity and lens position misalignment.

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