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## LOOK-AHEAD SEEK CORRECTION IN HIGH-PERFORMANCE CD-ROM DRIVES

Sorin G. Stan, Member, IEEE, Henk van Kempen, George Leenknecht and Ton H. M. Akkermans

*Abstract*—As the performance of the CD-ROM drives continues to increase, special attention should be paid to any element in the system that disturbs the desired specifications. When very low access times are considered, it will be mandatory to reach the target track within only one seek action, i.e. without any consequent retry or correction seek. Many CD-ROM drives count the tracks crossed during seeking and, by comparing this count with the pre-calculated seek length, the exact target location can be detected. This paper considers the error that affects the track-counting mechanism due to the rotating disc spiral. It will be shown that, for a given seek length, the number of crossed tracks differs between outside- and inside-oriented seeks. The involved equations will be derived and an algorithm will be proposed for determining the correct number of tracks to be crossed during a seek action. The proposed algorithm, which is optimized for microprocessor implementation, relies on two look-up tables and a learning scheme that allows look-ahead seek correction for both spiral rotation and system tolerances.

*Keywords*— access time, CD-ROM drive, DVD-ROM drive, optical storage, seek time, spiral correction.

### I. INTRODUCTION

ONE of the performance specifications of a Compact Disc Read-Only Memory (CD-ROM) drive is its average access time. Basically, the access time gives an indication about the capability of the drive to find the requested data and send it through the host interface as fast as possible.

The CD-ROM drive represents nowadays not only a computer storage device but it has deeply penetrated the consumer electronics market. The plastic disc, having the advantage of being standardized [1], serves as information carrier for electronic games, publishing houses, telephone companies, etc. Nevertheless, the increasing demand for improved drive performance (i.e. higher data throughput, lower access time, reduced power consumption, etc.) has always originated in the computer industry.

Minimization of the access time has not been a really hot issue until recently, although this performance specification improved continuously over the years. The increase of the data throughput, which actually led the competition between drive manufacturers, has arrived at a point where serious design efforts are needed for further improvements. On the other hand, the designers of CD-ROM drives are already paying more attention to the access performance than they previously did. Technically speaking, at bit rates of 5 MB/s or more (a 1X CD-ROM drive delivers 150 kB/s)

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it is the access time which should be minimized. Should this not be the case, the drive will spend most of its time searching for data than transferring it.

When very low access times are considered, an accurate analysis of the system behavior becomes of paramount importance. Obviously, it is desired to reach the target track while performing only one seek<sup>1</sup> action. Any additional correction seek can jeopardize the whole performance and therefore, it becomes mandatory to increase the hit rate of the target by eliminating these corrections. To give a numerical example, it is rather common for CD-ROM drives to reach the target track after two seek actions of 100 and respectively 5 ms. Eliminating the retry seek will already improve the performance with 5%.

This paper considers the elimination of the correction seeks that are due to a very special situation. Because the disc spiral is rotating, a drive which counts the number of tracks during seeking will detect a different number of crossed tracks than when counting on a fixed disc. Other disc-based optical storage systems, such as DVD-ROM<sup>2</sup>, CD-R/RW<sup>3</sup>, etc. are also affected by the rotating spiral.

### II. THE CD-ROM AS A SYSTEM

We shall briefly present herein the general architecture of a CD-ROM drive and the structure of data on the compact disc. These concepts are needed as discussion base throughout this paper. Details about the CD systems can further be found, for example, in [2] and [3].

#### A. General Architecture

The CD-ROM system can be considered as a channel for digital communications, comprising the transmission medium (i.e. the compact disc) and associated decoding electronics at the receiving side. On the other hand, typical servo circuitry is needed, resembling therefore the architecture of a disc-based data storage device. A schematic diagram of the CD-ROM system is presented in Fig. 1.

The basic engine, as delimited on Fig. 1, consists of the minimum electronics and mechanics which is necessary to read out the information stored on the disc and deliver a usable digital data stream. Several functions are needed to accomplish this task. The optics will direct an incident laser beam towards the disc and the reflected light towards the photodetectors. The laser spot is kept in focus and on

<sup>1</sup>In general, for a disc-based storage system, the servo is said to perform a seek when the radial control is directed to place the read head on a track different from the present one [4].

<sup>2</sup>Digital Versatile Disc Read-Only Memory

<sup>3</sup>Compact-Disc Recordable/Rewritable

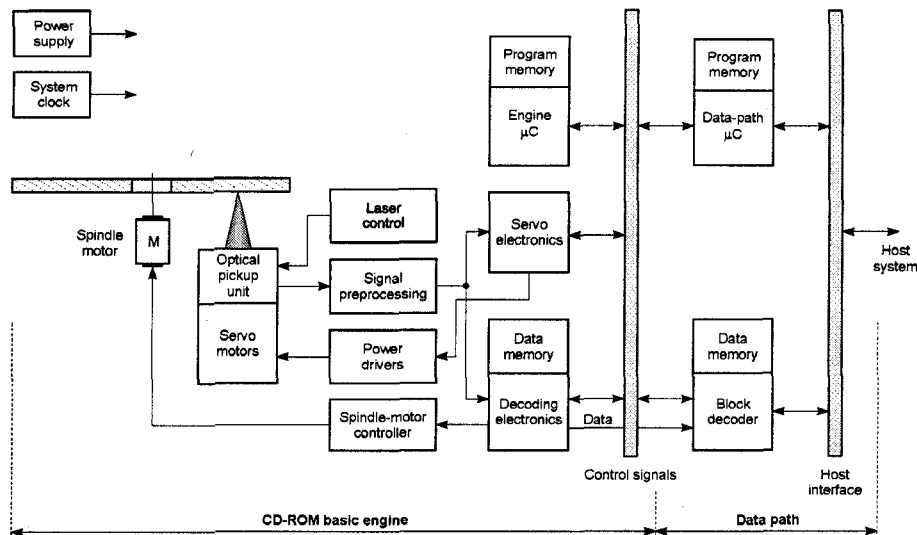


Fig. 1. Schematic diagram of the CD-ROM architecture

track by the servo electromechanics which also ensures the fast positioning during a seek procedure. Finally, a decoding circuitry extracts the digital information, performing typical functions for a transmission channel such as demodulation and error correction. The coordination between the basic-engine blocks is supervised by a microcontroller ( $\mu\text{C}$ ).

For interfacing the basic engine with a host system, a data path is needed. This CD-ROM part involves a dedicated decoder which operates on large data structures (blocks) and a microcontroller. There is, however, a trend to group the data-path functions and those of the basic engine (including their own microcontrollers), within the same integrated circuit (IC). The demarcation line between these two parts of the drive will hence become less obvious in the future.

### B. The CD data structure

The information is recorded on the plastic disc according to the audio standard [1] established in 1981. The standard was updated several times until its approval by the International Electrotechnical Commission [5].

The information, resembling digital zeros and ones, is linearly distributed along a spiral which has an approximate thickness of  $0.6 \mu\text{m}$ . The track pitch of the spiral is  $q = 1.6 \mu\text{m}$  with a tolerance of  $\pm 0.1 \mu\text{m}$ . The physical distance between two consecutive digital symbols recorded along the disc spiral is fixed and does not vary when reading out the disc from its inner to the outer radius. These radii limit the program area to  $R_i = 25 \text{ mm}$  and  $R_o = 58 \text{ mm}$ , respectively. A tolerance of  $-0.4 \text{ mm}$  is set on the  $2R_i$  starting diameter of the program area.

The constant linear velocity<sup>4</sup> (CLV) at which data is recorded is of fundamental importance for the CD-ROM systems. This speed equals  $1.3 \text{ m/s}$  with an allowed varia-

<sup>4</sup>In a CLV-based CD-ROM system, the angular frequency  $\omega$  of the disc is continuously varied such that, at any radius  $R$  along the disc spiral, the read-out information has the same well-defined and fixed linear velocity  $v = \omega R$  with respect to the laser spot.

tion of  $\pm 0.1 \text{ m/s}$ . Its value, denoted throughout this paper by  $v_a$ , originates in the audio standard [1]. A disc containing audio information should normally spin at a constant linear velocity equal to  $v_a$ . For data discs, this CLV value is usually denoted by 1X and corresponds to a bit rate of  $150 \text{ kB/s}^5$ . Higher bit rates can be achieved by rotating the disc at  $Nv_a$ , where  $N$  defines the drive overspeed (X-factor). The current CD-ROM drives are also able to read out data while spinning the disc in constant angular velocity<sup>6</sup> (CAV) mode or when using any other speed profile [6].

The recorded data can be located along the spiral by reading its subcode timing. This information marks linearly in time each block of 2352 bytes. The finest division of the subcode timing equals  $1/75$  seconds. For a maximum playback time of the disc at 1X, say  $S_{tot} = 60$  minutes, any 2352-byte cluster can hence be uniquely located between 0 and  $S_{tot}$ . The same subcode timing can also be used for seeking a particular data cluster along the spiral. When reading out the disc at a constant linear velocity  $Nv_a$ , the total playback time of the disc is given by  $S_{tot}/N$ .

### III. GENERAL SEEK BEHAVIOR

When the host system asks for data, the access command is translated by the data path into a request for a seek of length  $\Delta S$  between an initial and a target subcode timing. The number of tracks to be crossed during the mechanical displacement of the laser spot is

$$\Delta N_{tr} = \frac{1}{q} \left( \sqrt{R_i^2 + \frac{v_a q (S_i + \Delta S)}{\pi}} - \sqrt{R_i^2 + \frac{v_a q S_i}{\pi}} \right) \quad (1)$$

with  $R_i$ ,  $R_o$ ,  $q$  and  $v_a$  already defined in Section II-B, and  $S_i$  being the initial subcode timing read before performing

<sup>5</sup>Despite other definitions based on the decimal system, it is usually assumed that  $1 \text{ kB} = 1024$  bytes.

<sup>6</sup>In a CAV-based CD-ROM system, the disc angular frequency  $\omega$  is kept constant, independent on the read-out position of the laser spot along the disc spiral. The linear velocities of the read-out data will hence be situated between  $\omega R_i$  and  $\omega R_o$ .

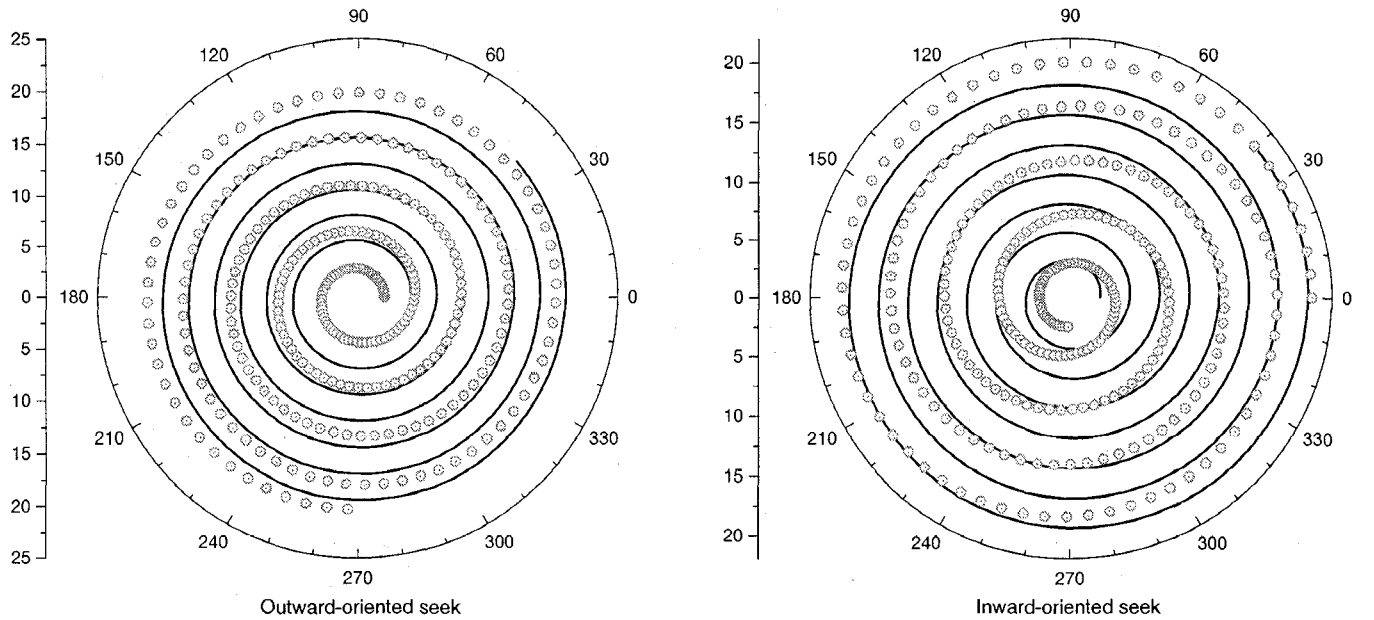


Fig. 2. Trajectories followed by the laser spot while the disc spiral (thin continuous line) is rotating with  $f_{rot} = 50$  Hz. During an outward-oriented seek, the laser spot moves along its trajectory from the inside to the outside of the disc. This direction coincides always with the increasing radius of the disc spiral but the situation reverses while seeking inwards. The plotted trajectories correspond to the following numerical values:  $v_{max} = 230$  mm/s,  $\tau_m = 8$  ms,  $T_a = 80$  ms,  $T_b = 15$  ms. The track pitch has been increased to  $q = 2.5$  mm for better visualization, which does not diminish the qualitative conclusions.

the requested seek action.

The physical displacement of the optical pickup unit<sup>7</sup> (OPU) is carried out by the drive electromechanics controlled by a dedicated feedback loop. Usually, a two-stage control system is used and it consists of an actuator mounted on a sledge (carriage). For a sledge-actuator ensemble which accelerates and brakes during  $T_a$  and respectively  $T_b$  (with  $T_{seek} = T_a + T_b$ ), the OPU velocity can be written as

$$V_{opu}(t, T_a) = \begin{cases} (1 - e^{-t/\tau_m})v_{max} & \text{if } t \leq T_a \\ [1 - e^{-T_a/\tau_m} - (1 + \alpha)(1 - e^{-(t-T_a)/\tau_m})]v_{max} & \text{if } T_a < t \leq T_{seek} \end{cases} \quad (2)$$

where  $v_{max}$  is the maximum linear speed which can be attained by the OPU and  $\tau_m$  is the time constant of the whole electromechanical ensemble. The coefficient  $\alpha$  is determined from the control equations such that  $V_{opu}(T_{seek}) = 0$  when  $T_b = const.$  due to, usually, a fixed procedure for track acquisition. These conditions lead to

$$\alpha = \frac{e^{-T_a/\tau_m} - e^{-T_b/\tau_m}}{-1 + e^{-T_b/\tau_m}} \quad (3)$$

when OPU velocity profiles as shown in Fig. 3 are considered. Other velocity profiles can also be reduced to Eq. (2).

The total seek time  $T_{seek}$ , considered as being needed to mechanically displace the OPU across a given number of

<sup>7</sup>The optical pickup unit consists of a semiconductor laser, optical elements (such as lenses, mirrors, etc.) for guiding the laser beam, photodetectors and two tiny actuators for positioning the laser spot on track and in focus.

tracks  $\Delta N_{tr}$ , can be determined by solving the equation

$$\Delta N_{tr} = \frac{1}{q} \int_0^{T_{seek}} V_{opu}(t, T_a) dt \quad (4)$$

As a matter of fact, because  $T_b$  takes usually a fixed value, the acceleration time  $T_a$  of the OPU should be determined and then  $T_{seek} = T_a + T_b$ .

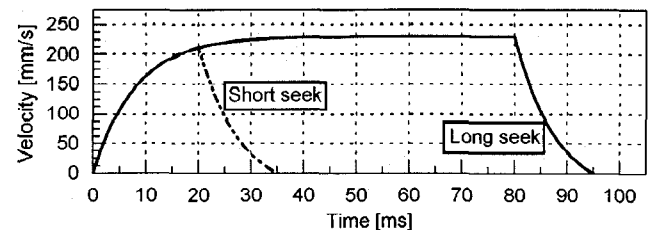


Fig. 3. Velocity profiles of the optical pickup unit during a short, respectively long seek.

#### IV. SEEKING DATA ALONG THE DISC SPIRAL

Upon receiving a request for data seek, the basic engine depicted in Fig. 1 will first use Eq. (1) to calculate the total number of tracks to be crossed. Consequently, the OPU is displaced in the radial direction between the initial disc radius  $R_{init}$  and the target radius  $R_{final}$ . These radii can be identified in Eq. (1) in the form of the two square roots.

##### A. The Effect of the Rotating Spiral

Most of the CD-ROM drives count the number of tracks between  $R_{init}$  and  $R_{final}$  in order to determine the exact position of the laser spot during its movement. However, it has been observed experimentally that a different number

of tracks is counted than one would expect from Eq. (1). This difference leads to an erroneous positioning of the laser spot while seeking.

Preceding the upcoming calculations, an example of seeking outwards/inwards is shown in Fig. 2. On both plots the disc spiral and the real trajectory of the laser spot are represented. The track pitch has been increased deliberately in order to better visualize the results. It can be seen that, while a total radial distance of 7 tracks should be covered, the spot crosses only 3 tracks while seeking outwards, respectively 12 tracks while seeking inwards. None of these number of track crossings equals the real radial distance. The reason becomes obvious when looking at the plotted trajectories: the rotating spiral travels either along with or against the movement of the laser spot.

### B. Equations of Movement

The relative motion between the rotating spiral and the radial displacement of the OPU can better be analyzed in polar coordinates. However, this relative motion is independent on the choice of the reference system. The analysis will be greatly simplified if we choose the spiral itself (i.e. the rotating disc) as reference. The trajectories followed by the laser spot can consequently be calculated and they will resemble the ones plotted in Fig. 2.

The linear space already covered by the laser spot at any particular time  $\xi$  is given by

$$S_{opu}(\xi, T_a) = \int_0^\xi V_{opu}(t, T_a) dt \quad (5)$$

but, under the above assumptions, this equation should further be converted into polar coordinates. At this stage, the angular distance

$$\theta(\xi) = \int_0^\xi \omega(t) dt \quad (6)$$

covered by the rotating disc should also be considered. As most of the current high-speed CD-ROM drives are prepared to use CAV mode to spin the disc, the above equation becomes

$$\theta_{cav}(\xi) = 2\pi f_{rot} \xi \quad (7)$$

with  $f_{rot} = const.$  being the disc rotational frequency.

When (7) is used to change the integration variable in Eq. (5), the space covered by the laser spot while seeking outwards and starting from the disc radius  $R_{init}$  becomes

$$S_{opu.out}(\xi, T_a) = R_{init} + \frac{1}{2\pi f_{rot}} \int_0^\xi V_{opu} \left( \frac{\theta}{2\pi f_{rot}}, T_a \right) d\theta \quad (8)$$

and similarly,

$$S_{opu.in}(\xi, T_a) = R_{init} + S_{opu}(T_{seek}, T_a) - \frac{1}{2\pi f_{rot}} \int_0^\xi V_{opu} \left( \frac{\theta}{2\pi f_{rot}}, T_a \right) d\theta \quad (9)$$

when seeking inwards. To be noticed that  $S_{opu}(T_{seek}, T_a)$  equals  $q\Delta N_{tr}$  as already given by (4). The variable  $\xi$  from the latter two equations does not denote a particular time anymore but an angle satisfying the relation

$$0 \leq \xi \leq \theta_{max} \quad (10)$$

where  $\theta_{max} = 2\pi f_{rot} T_{seek}$  represents the total angular distance covered by the disc during the seek time.

Further, the spiral trajectory when starting from the disc radius  $R_{init}$  is independent on the seek direction and can be written as

$$R_{sp}(\phi) = R_{init} + \frac{\phi}{2\pi} q \quad (11)$$

with  $q$  being the track pitch and the angle  $\phi$  varying from 0 to a maximum value  $\phi_{max}$ . This value can be determined from the condition that, at the end of the seek action, the target radius  $R_{final}$  equals that particular radius  $R_{sp}(\phi_{max})$  of the spiral. This condition is again independent on the seek direction and therefore

$$\phi_{max} = 2\pi \cdot \frac{R_{final} - R_{init}}{q} = 2\pi \cdot \frac{S_{opu}(T_{seek}, T_a)}{q} \quad (12)$$

but an alternative could be to determine  $R_{final}$  from Equations (8) and (9), respectively.

### C. The Real Number of Crossed Tracks

When the analytical analysis from the previous section is considered, it will be basically possible to correct the number of crossed tracks given by (1) with a pre-calculated value  $\Delta N_{corr}$  accounting for the rotating disc spiral. The correction can be applied just before performing a seek action. It will be therefore necessary to determine the number of points at which the laser spot trajectory intersects the disc spiral.

The desired intersection points form hence the solutions of two simultaneous equations. For the outward-oriented seek, these equations are

$$\begin{cases} R_{sp}(\phi) = S_{opu.out}(\xi, T_a) \\ \text{mod}(\phi, 2\pi) = \text{mod}(\xi, 2\pi) \end{cases} \quad (13)$$

and provide a number of points  $(\rho, \psi)$ , in polar coordinates, when solved for all combinations of  $\phi$  and  $\xi$ . Alternatively, for inward-oriented seeks the above system of equations becomes

$$\begin{cases} R_{sp}(\phi) = S_{opu.in}(\xi, T_a) \\ \text{mod}(\phi, 2\pi) = \text{mod}(\xi, 2\pi) \end{cases} \quad (14)$$

and it also leads to the number of intersection points between the disc spiral and the laser spot.

The latter systems of equations can be solved numerically and let us denote by  $\Delta N_{tr.out}$  and  $\Delta N_{tr.in}$  the number of solutions resulted from (13) and (14), respectively. It can be shown that

$$\Delta N_{tr.out} = \Delta N_{tr} - \text{floor}(\Delta N_{corr}) \quad (15)$$

when seeking outwards and

$$\Delta N_{tr\_in} = \Delta N_{tr} + \text{ceil}(\Delta N_{corr}) \quad (16)$$

when seeking inwards, respectively. The parameter

$$\Delta N_{corr} = T_{seek} \cdot f_{rot} \quad (17)$$

stands for the number of correction tracks whilst the functions  $\text{floor}(\cdot)$  and  $\text{ceil}(\cdot)$  define the closest integer which is smaller, respectively greater than the function argument. The latter relation holds only for a fixed disc rotational frequency  $f_{rot}$ . If this drive parameter does not remain constant, the correction  $\Delta N_{corr}$  needs being substituted by the number of disc revolutions taking place during the total seek time.

#### D. Algorithms for Seek Correction

Depending on the architecture of the CD-ROM drive, two algorithms for seek correction can be implemented. These algorithms involve hardware and/or software and consequently, the total cost of the implementation versus the achieved performance should also be taken into account.

Numerous high-speed CD-ROM drives use a tacho controller to regulate the speed of the spindle motor. Usually, this motor features Hall sensors which output pulsed signals of a frequency proportional to the disc angular speed. In this case, the seek correction can be performed straightforward by monitoring the disc revolutions and updating in real time, based on the relations (15), (16) and (17), the counted number of crossed tracks [7].

For systems where such Hall pulses are not available, the solution will be to generate the information about the number of disc revolutions by mounting a dedicated sensor on the disc turntable.

Another method which can be used to correct the erroneous number of crossed tracks is based on the prediction of this error. Mathematically, this error can be calculated for a given CD-ROM system and stored in a look-up table. This method will further be analyzed in detail throughout the next section.

### V. LOOK-AHEAD SEEK CORRECTION

This algorithm only involves a firmware program and can be implemented in any type of CD-ROM system which uses constant angular velocity (CAV) to spin the disc. Adaptive-speed<sup>8</sup> drives featuring a CAV-like velocity profile but no tacho controller can also benefit from this type of seek correction.

Basically, the fundamentals of the look-ahead seek correction have already been discussed in Sections III and IV. The algorithm itself determines a correction value from a

<sup>8</sup>In an adaptive-speed CD-ROM drive [6], the linear velocity of the rotating spiral (and therefore the disc angular speed) is continuously adjusted, in real time, depending on the subcode information being read out at a particular position of the laser spot. As a result, the drive overspeed  $N$  varies from the inner to the outer disc radius and describes an overspeed profile of any pre-defined shape between CAV and CLV.

look-up table and adjusts the total number of tracks to be crossed. The correction value depends both on the subcode timing read out just before seeking and on the total length of the seek. An additional program based on a learning scheme will also be executed either continuously or only during the drive initialization and will tune the look-up table depending on the disc parameters. This learning algorithm will also take into account the loop tolerances present in the seek controller (e.g. tolerances of the sledge motor, motor driver, supply voltage, etc.).

#### A. General Considerations

Usually, the seek procedure needs a variable indicating the direction of moving the optical pickup unit and the result of Eq. (1). This equation suggest a look-up table dependent on  $S_i$  and  $\Delta S$  but, from a software point of view, it will be more convenient to have a table based on  $\Delta N_{tr}$  and  $S_i$ .

A collection of numerical results is given in Table 1. As already suggested by Equation (4), the length of the seek expressed in subcode timing does not influence the number of disc revolutions counted during the OPU displacement. In addition, a table based on  $\Delta N_{tr}$  will not depend on  $S_i$  either. The results summarized in Table 1 are calculated for a CD-ROM system which operates in full CAV mode at the disc rotational frequency  $f_{rot} = 110$  Hz. The involved disc parameters are  $v_a = 1.2$  m/s for the linear velocity of the recorded information,  $q = 1.6$   $\mu$ m for the track pitch and  $R_i = 25$  mm for the start radius of the program area.

The number of disc revolutions needs being adjusted using the  $\text{floor}(\cdot)$  and  $\text{ceil}(\cdot)$  functions for the outward- and respectively inward-oriented seeks. The resulted correction will consequently be subtracted or added according to Eqs (15) and (16), respectively. Any mismatch between the calculated table and the real situation (due to, for instance, variation of the disc parameters) can further be translated into a secondary correction and will be performed using the learning algorithm.

$S_i$ [min]	Seek distance [tracks]							
	2500	5000	7500	10000	12500	15000	17500	20000
	Number of disc revolutions							
	3.8	5.8	7.7	9.6	11.5	13.4	15.3	17.3
	Seek length [minutes]							
0	6	13	20	29	38	48	60	72
10	7	15	25	34	45	57		
20	8	18	28	39	51			
30	9	20	31	43				
40	10	22	34					
50	11	23						
60	12							

Table 1. Number of disc revolutions and the seek length as function of both initial subcode timing  $S_i$  and number of tracks to be crossed. The disc rotates at 6600 rpm (110 Hz) in CAV mode and the involved disc parameters are  $v_a = 1.2$  m/s,  $q = 1.6$   $\mu$ m, and  $R_i = 25$  mm.

### B. Tolerance Analysis

The look-up table as well as the structure of the learning algorithm can only be defined if an analysis of the system tolerances is performed.

For the choice of the look-up table as already discussed in Section V-A, the number of tracks to be crossed  $\Delta N_{tr}$  remains unaffected by any of the system tolerances. However, the track pitch  $q = 1.6 \pm 0.1 \mu\text{m}$  will determine the largest value  $\Delta N_{tr_{max}}$  to be used in the look-up table. For a disc obeying the standard [1], this value becomes

$$\Delta N_{tr_{max}} = \frac{R_o - R_{i_{min}}}{q_{min}} = 22,133 \text{ tracks} \quad (18)$$

where  $R_o = 58 \text{ mm}$ ,  $R_{i_{min}} = 24.8 \text{ mm}$  and  $q_{min} = 1.5 \mu\text{m}$ . Obviously, when the track pitch  $q$  varies, the seek time  $T_{seek}$  from Eq. (4) will be affected and hence the number of correction tracks  $\Delta N_{corr}$  given by (17) will also vary. In addition, the disc rotational frequency  $f_{rot}$  brings its own contribution to the calculation of  $\Delta N_{corr}$ .

A graphical dependency of the number of correction tracks versus both track pitch and disc rotational frequency is given in Fig. 4.

It should be noticed that  $f_{rot}$  is usually not considered to have a significant tolerance for this analysis but it rather represents a choice for a particular CD-ROM drive. However, this choice should never lead to a data throughput which exceeds the maximum decoding speed in the system. This upper limit is often normalized to the standard audio speed  $v_a$  (with which data is recorded along the spiral of any compact disc) and is referred to as maximum overspeed [6] or maximum X-factor. The disc rotational frequency should therefore satisfy the relation

$$f_{rot}(R) \leq \frac{v_a \mathcal{N}_{max}}{2\pi R} \quad (19)$$

where  $\mathcal{N}_{max}$  is the maximum decoding overspeed. Because Eq. (19) should be fulfilled for any disc radius  $R$  between  $R_i$  and  $R_o$ , the choice of  $f_{rot}$  may be made once the velocity

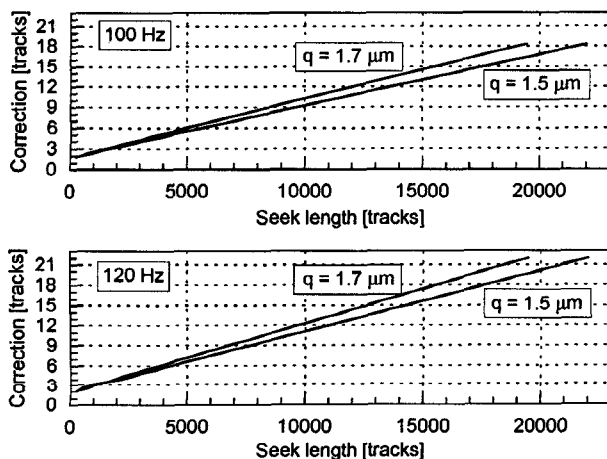


Fig. 4. Unrounded number of correction tracks at two different disc rotational frequencies and for the minimum, respectively maximum tolerated track pitch.

$v_a$  of the recorded data has been determined after a calibration procedure. It follows that a look-ahead algorithm for seek correction should also take into account different disc rotational frequencies around the nominal setting.

The third parameter which can influence the accuracy of the look-ahead seek correction is the velocity  $V_{opu}(t, T_a)$  of the optical pickup unit. Numerous tolerances are usually present in the seek control loop. Moreover, this loop may also behave slightly different when the temperature of the electromechanical components changes during operation. The result will be translated into another seek time  $T_{seek}$  to be obtained from Equation (4).

Finally, it follows from (17) that the starting radius of the program area  $R_i$  has no influence at all upon the number of correction tracks. Moreover, even if the disc angular frequency varies during playback (i.e. no CAV system), the term  $R_i$  appears with the same sign in both sides of the first equations from (13) and (14) and the conclusion that  $\Delta N_{corr}$  is independent on  $R_i$  remains valid.

In general, any combination of the loop tolerances in the seek controller can be converted into a profile described by (2) and plotted in Fig. 3. For our analysis, it is the time  $T_{seek}$  which matters and the influence it has upon the number of correction tracks  $\Delta N_{corr}$  is given in Fig. 5.

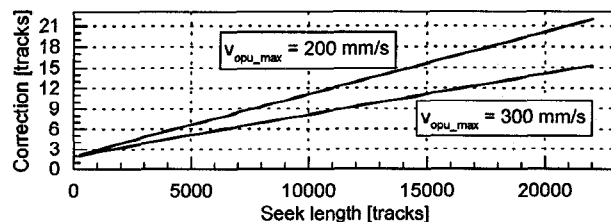


Fig. 5. Dependency of the unrounded number of correction tracks on the tolerances of the seek electromechanics. The tolerances are converted through Eq. (2) into sledge velocity profiles of different maximum velocities  $V_{opu_{max}}$ .

### C. The Look-Up Table

When compared to the brief example from Table 1, the real implementation must consider a more accurate division of the seek distance. A reasonable choice is a table based on steps of 256 tracks.

At this point, the tolerance analysis needs being taken into account. Two conclusions can be deduced from the previous section. First, the look-up table should necessarily contain enough information such that any possible seek lengths, including those occurring under extreme tolerances, could be compensated for. This implies a table which is extended up to  $\Delta N_{tr_{max}}$  given by Eq. (18).

A second conclusion can be drawn by analyzing the plots from Figures 4 and 5. These plots suggest the implementation of a table containing corrections for only one convenient combination of the parameter tolerances. This is equivalent with choosing an up-going line as being the nominal characteristic and determining its new slope once the involved parameters have changed. The learning algorithm to be discussed later will accomplish this task.

Finally, one additional remark is also needed. When applying the functions  $\text{floor}(\cdot)$  and  $\text{ceil}(\cdot)$  to  $\Delta N_{\text{corr}}$  obtained from Eq. (17), their respective results will only differ by one integer unit for any given argument. The relations (15) and (16) become

$$\Delta N_{\text{tr.out}} = \Delta N_{\text{tr}} - \text{floor}(\Delta N_{\text{corr}}) \quad (20)$$

$$\Delta N_{\text{tr.in}} = \Delta N_{\text{tr}} + \text{floor}(\Delta N_{\text{corr}}) + 1 \quad (21)$$

and it will be therefore enough to store into the look-up table only the values  $\text{floor}(\Delta N_{\text{corr}})$ .

The nominal characteristic that we choose to tabulate is the one having the smoothest slope. Any other characteristic will be situated above the nominal one and, from a microprocessor point of view, this leads to an unsigned calculation of the slope difference.

The chosen nominal characteristic for our 32X CD-ROM system relies on the parameters  $V_{\text{opu.max}} = 300 \text{ mm/s}$ ,  $f_{\text{rot}} = 100 \text{ Hz}$ , and  $q = 1.5 \mu\text{m}$ . These parameters define together a margin for the tolerance region. The implemented look-ahead seek correction is given in Table 2. It should be noticed that only the values of  $\text{floor}(\Delta N_{\text{corr}})$  need being stored whilst the seek distance can be indexed when starting from the 256-track step. The look-up table will therefore consist of one row and  $K_{\text{max}} = \text{floor}(\Delta N_{\text{tr.max}}/256) = 86$  columns.

The graphical representation of the tabulated seek correction is depicted in Fig. 6. For an inward-oriented seek, however, the tabulated values need being adjusted as indicated by Eq. (21).

Seek distance [tracks]								
256	512	768	1024	.....	21248	21504	21760	22016
Outward-oriented seek correction [tracks]								
1	1	2	2	.....	12	12	12	12

Table 2. Implemented look-up table for coarse seek correction in a 32X CAV-controlled CD-ROM system. The table contains the  $\text{floor}(\Delta N_{\text{corr}})$  values which correspond to  $V_{\text{opu.max}} = 300 \text{ mm/s}$ ,  $f_{\text{rot}} = 100 \text{ Hz}$ , and  $q = 1.5 \mu\text{m}$ .

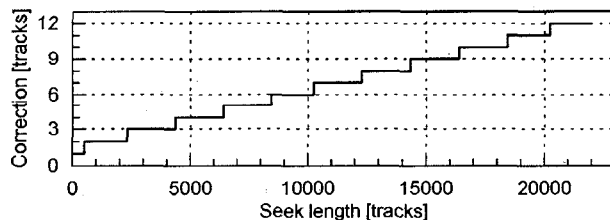


Fig. 6. Nominal values  $\text{floor}(\Delta N_{\text{corr}})$  for look-ahead seek correction during outward-oriented seeks.

#### D. Correction Error due to Tolerances

As the system parameters exhibit tolerances, systematic errors will be introduced while using Table 2 for seek correction. If these errors  $\delta N_{\text{corr}}$  can be predicted, the rela-

tions (20) and (21) will become

$$\Delta N_{\text{tr.out}} = \Delta N_{\text{tr}} - \text{floor}(\Delta N_{\text{corr}}) - \delta N_{\text{corr}} \quad (22)$$

$$\Delta N_{\text{tr.in}} = \Delta N_{\text{tr}} + \text{floor}(\Delta N_{\text{corr}}) + \delta N_{\text{corr}} + 1 \quad (23)$$

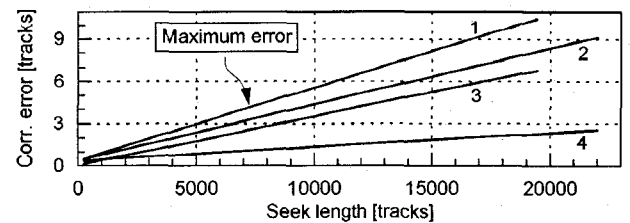
where  $\text{floor}(\Delta N_{\text{corr}})$  may take any value from Table 2.

A plot of  $\delta N_{\text{corr}}$  calculated for different tolerances is given in Fig. 7. For the time being, these errors are considered unrounded and given by

$$\delta N_{\text{corr}} = \Delta N_{\text{corr}}^{\text{tol}} - \Delta N_{\text{corr}} \quad (24)$$

where  $\Delta N_{\text{corr}}$  is the nominal correction defined by Equation (17) and  $\Delta N_{\text{corr}}^{\text{tol}}$  denotes the correction which is necessary with respect to  $\Delta N_{\text{tr}}$  when a given set of system tolerances is used.

Based on the discussions from Section V-B, it can also be concluded that the maximum deviation from  $\Delta N_{\text{corr}}$  is obtained when the laser head has the slowest maximum velocity and, at the same time, the largest track pitch and highest disc rotational frequency are taken into account.



Legend: 1 - 120 Hz, 1.7  $\mu\text{m}$ , 200 mm/s  
2 - 120 Hz, 1.5  $\mu\text{m}$ , 200 mm/s  
3 - 100 Hz, 1.7  $\mu\text{m}$ , 200 mm/s  
4 - 120 Hz, 1.5  $\mu\text{m}$ , 300 mm/s

Fig. 7. Correction error  $\delta N_{\text{corr}}$  due to different tolerances in the system. The correction is calculated with respect to the nominal characteristic given by Equation (17).

The plots depicted in Fig. 7 suggest a way to deal with these system tolerances. Basically, the maximum-error characteristic can be extrapolated up to the largest seek distance (i.e. 22,016 tracks) from Table 2, where it reaches a correction value of 12 tracks. Any set of system tolerances will then lead to a plot which is situated below the maximum error. We shall further define another separate 11 characteristics and all together form a system of error functions given by

$$\delta N_{\text{corr}}(\beta, K) = \beta \left[ 1 - \frac{K_{\text{max}} - K}{K_{\text{max}} - 1} \right] \quad (25)$$

where  $\beta = 1, 2, \dots, 12$  denotes the rank of the function,  $K = 1, 2, \dots, 86$  is the index being used to calculate the divisions (in 256-track steps) of the seek length and  $K_{\text{max}} = 86$ . The error functions are plotted in Fig. 8.

From the definition (25) it can be seen that any line of rank  $\beta \geq 2$  can be derived from the error function of rank  $\beta = 1$ . Practically, this means that one table can be used to store the latter function whilst a rank variable will determine the slope of the needed tolerance correction.



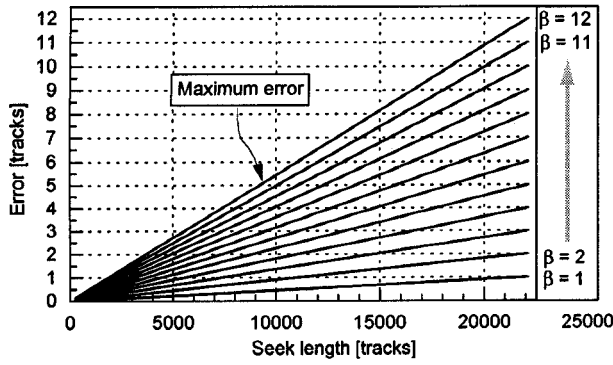


Fig. 8. Error characteristics  $\delta N_{corr}(\beta, K)$  as defined with respect to the nominal seek correction  $\Delta N_{corr}$ .

However, Equation (25) should further be rearranged to better suit the microprocessor implementation. For this reason and because the error function which needs being tabulated (i.e. for  $\beta = 1$ ) has values smaller than one, we shall tabulate the function

$$\delta N_1(K) = \text{round} [256 \cdot \delta N_{corr}(1, K)] \quad (26)$$

whose several values are indicated in Table 3. All other characteristics can subsequently be derived with

$$\delta N_{corr}(\beta, K) = \text{round} \left[ \frac{\beta}{256} \cdot \delta N_1(K) \right] \quad (27)$$

for any rank  $2 \leq \beta \leq 12$ . The function  $\text{round}(\cdot)$  approximates the given argument with its nearest integer. The latter equation can easily be implemented in microprocessor code and the result will further be used to determine  $\Delta N_{tr\_out}$  and  $\Delta N_{tr\_in}$  from (22) and (23), respectively.

Seek distance [tracks]								
256	512	768	1024	.....	21248	21504	21760	22016
Nominal error function [tracks]								
3	6	9	12	.....	246	249	252	255

Table 3. Implemented nominal correction table ( $\beta = 1$ ) for tolerance compensation. The tabulated values are already multiplied by 256 as indicated by Equation (26).

**E. The Learning Algorithm**

As already discussed in Section V-D, the look-ahead seek correction needs being tuned for the system tolerances. In the proposed implementation, a dedicated software algorithm will monitor each seek procedure and recalculate a new rank  $\beta$  depending on the accuracy of the performed seek. The flowchart of this algorithm is depicted in Fig. 9.

When entering the algorithm, a pre-defined choice, say  $\beta_{init}$ , should be made for the tolerance correction. One can choose for  $\beta_{init} = 0$  or for a value determined during testing on the production line. If the CD-ROM engine receives a seek command which needs being carried out by sledge displacement, the algorithm will calculate the seek length

$\Delta N_{tr}$  or get this value if it has already been calculated by another software routine. The index

$$K = \text{round} \left( \frac{\Delta N_{tr}}{256} \right) \quad (28)$$

will further be used to determine both the coarse correction floor( $\Delta N_{corr}$ ) from Table 2 and the rank  $\beta$  of the error characteristic. The latter value is given by the relation

$$\beta = \text{round} \left[ \frac{256 \cdot \Delta N'_{tr}}{\delta N_1(K)} \right] \quad (29)$$

with  $\delta N_1(K)$  determined from Table 3 and  $\Delta N'_{tr}$  being the length of the correction (retry) seek. The division involved in (29) can simply be carried out as successive additions of the nominal tolerance correction  $\delta N_1(K)$  until the round-off condition is met.

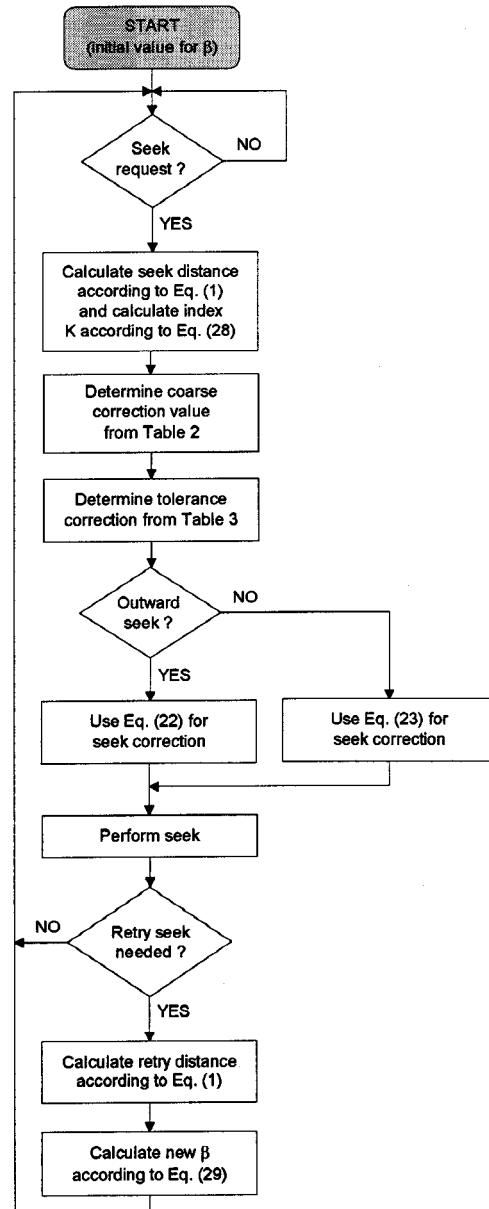


Fig. 9. Flowchart of the learning algorithm

Once the two necessary corrections have been determined, the real number of tracks to be crossed will be calculated and the seek will be performed. If the target track is not reached, the newly calculated seek distance  $\Delta N'_{tr}$  (which is also needed for the retry seek) will be used to determine a new rank  $\beta$  and retune the tolerance correction  $\delta N_{corr}(\beta, K)$ . If necessary, a history of the last found  $\beta$ -values can also be recorded in order to avoid any erroneous out-of-range calculation.

## VI. CONCLUSIONS

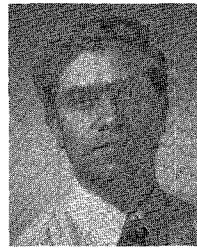
This paper addressed the track-counting errors which occur in a CD-ROM system during any seek procedure and are due to the rotating disc spiral. It has been shown analytically that these errors are systematic and correlated with several disc and drive parameters. The dependency of these errors on the system tolerances has also been analyzed. In many CD-ROM drives, the desired information is located during a seek by counting the crossed number of tracks. The equations governing the relative motion between the laser spot and the disc spiral are derived in this paper and the real number of crossed tracks is calculated by solving numerically the motion equations.

The paper presents a brief overview of the methods which can be used to avoid the erroneous detection of the target track during seeking. For systems based on constant angular velocity (CAV) to spin the disc, it becomes possible to implement a software-only algorithm for spiral correction. The paper proposes a look-ahead method which can (a) predict the spiral-based track-crossing error and (b) adjust the seek length accordingly, before the seek is performed. The method relies on two pre-defined tables based on analytical calculations and on a learning scheme which can keep track of the system tolerances.

The presented algorithm for seek correction has the advantage that is independent on the drive hardware. It is software-based and it can also be implemented in other optical storage systems, like DVD-ROM, magneto-optical (MO) drives, etc. where data is stored along the disc spiral. The only condition which needs being fulfilled is to control the spindle motor in full CAV mode.

## REFERENCES

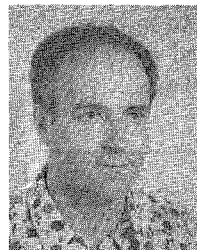
- [1] Philips Electronics N.V. and Sony Corp., *Compact-Disc Digital Audio. System Description*, 1981.
- [2] Bouwhuis, G., Braat, J., Huijser, A., Pasman, J., Rosmalen, G. van, and Schouhamer Immink, K., *Principles of Optical Disc Systems*, Adam Hilger Ltd., Bristol and Boston, 1985.
- [3] Nakajima, H. and Ogawa, H., *Compact Disc Technology*, Ohmsha, Ltd., 1992.
- [4] Mee, C.D. and Daniel, E.D., *Magnetic Recording. Volume II: Computer Data Storage*, McGraw-Hill, Inc., 1988.
- [5] International Electrotechnical Commission, *Compact Disc Digital Audio System*, IEC 908. First Edition, 1987.
- [6] Stan, S.G. and Bakx, J.L., "Adaptive-Speed Algorithms for CD-ROM Systems", *IEEE Transactions on Consumer Electronics*, Vol. 42, No. 1, pp. 43-51, Febr. 1996.
- [7] Bakx, J.L., *Personal communication*, Philips Optical Storage, Optical Recording Development Laboratory, The Netherlands, 1997.



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