THE CD-ROM DRIVE
A Brief System Description

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SORIN G. STAN

Philips Optical Storage
Optical Recording Development Laboratory
Eindhoven, The Netherlands

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Preface

The Compact Disc (CD), as a standardized information carrier, has become one of the most successful consumer products ever marketed. Although the original disc was intended for audio playback, its specific advantages opened very quickly the way towards various computer applications. The standardization of the Compact Disc Read-Only Memory (CD-ROM) and of all succeeding similar products, like Compact Disc interactive (CD-i), Photo and Video CD, CD Recordable (CD-R), and CD Rewritable (CD-R/W), has substantially enlarged the range of possible applications.

The plastic disc represented from the very beginning a removable medium of large storage capacity. The advent of the personal computer accompanied by the increasing demand for both data distribution and exchange have strongly marked the evolution of the CD-ROM drive. The number of sold CD-ROM units exceeded 60 millions in 1997 when compared to about 2.5 millions in 1992.

As computing power continuously improved over the years, computer peripherals have also targeted better performance specifications. In particular, the speed of CD-ROM drives increased from the so-called 1X in 1984 to double speed in 1992, and further to 32X at the beginning of 1998. The average time needed to access data on disc has dropped from about 300 ms to less than 90 ms within the same period of time.

This book tries to provide a comprehensive description of the CD-ROM drive as a complex system. Without emphasis on mathematical and physical details, the text provides the backgrounds necessary to understand the functionality of the drive. The aspects concerning current high-speed drives and the related design issues are also discussed. When extrapolated to other optical storage systems, like CD-R, CD-R/W, and even the emerging Digital Versatile Disc (DVD), the book should represent a valuable reference. A large bibliography list is attached at the end of the book and the numerous references to this list which are made throughout the text may help the reader finding the desired details. The book was written with the clear goal in mind of being equally useful to specialists in the field and readers with little or no CD-ROM experience.

The first chapter of the book introduces the reader to the world of disk-based mass storage devices and tries to position the CD-ROM within this framework. A brief history of Compact Disc Digital Audio, an overview of the CD standards and the advantages of compact disc are presented. The chapter ends with a short system description of the CD-ROM drive.

The following three chapters are dedicated to the main subsystems that cooperate to provide the binary read-out signal. These chapters describe, in order, the optics, the servomechanics, and the decoder circuitry.

The fifth chapter discusses those building blocks of the drive which are indispensable to the disc read-out and either link the main three subsystems mentioned above or represent a sort of terminator in the whole system. We approach here the laser diode, the photodetector and preprocessing circuits, the audio part, and the drive microcontroller.

The sixth chapter provides information about the signal processing unit which is specifically dedicated to both deal with CD-ROM data and interface the drive with the host PC.

Finally, the last chapter presents an overview of several system parameters and of the design choices made more than 15 years ago when the CD standards were set. This chapter ends with some issues related to the performance specifications and benchmarking of CD-ROM drives.

This book could not have arrived at its final stage without the contribution of several people. First, I would like to acknowledge the outstanding professional and moral support I had from Prof. Paul van den Bosch and Assoc. Prof. Ad Damen from the Eindhoven University of Technology, and from Dr. Maarten Steinbuch from Philips Research Laboratories in Eindhoven. They encouraged my efforts towards a more complete work related to the CD-ROM system from which this book has actually emerged as a spin-off. They also read the whole manuscript of the book, suggested improvements and contributed to its consistent structure.

Special thanks go to Hans Naus from Optical Recording Development Laboratory of Philips Optical Storage who understood the goal of my work, believed in its importance for myself and for our company, and supported it throughout the Philips organization. I am also indebted to the Philips management which allowed me to publish this book.

I am extremely grateful to Dr. Stan Baggen, Dr. Joseph Braat and Dr. Kees Schouhamer-Immink from Philips Research Laboratories in Eindhoven who scrutinized parts of the manuscript and suggested valuable improvements of its contents. It is also a pleasure to acknowledge the unexpected meeting with Prof. J. Peek from University of Nijmegen who reacted very enthusiastically to my work, including this book as a spin-off.

Many thanks go to my office colleague Ton Akkermans with whom I shared many of my thoughts and discussed plenty of technical aspects related to optical recordings. He read and commented parts of the manuscript.

I am also indebted to my colleagues Peter Coops, Conor O'Gorman, Cees Hezemans, Henk van Kempen, Aart Lighart, Job van Mil, Han Raaijmakers, and Cees Smulders from Optical Recording Development Laboratory of Philips Optical Storage in Eindhoven. They provided inspiration and improved the quality of the manuscript. I would also like to thank George Leenknegt and Peter de la Rambelje from the same laboratory and Eric van Rheden from the Business Intelligence office of Philips Optical Storage for their moral encouragement in carrying out my work. Thanks go also to Hilde Overath and Rob Groen, former managers I had, who gave me the opportunity to work on CD-ROM drive development.

I would like to express my gratitude to Prof. Yossi Chait from University of Massachusetts, Dr. Yuan Zheng from Oak Technology, Inc., and James Finlay from Kluwer Academic Publishers for their positive comments on the need for a CD-ROM monograph.

This book is the result of more than one year of efforts made independently from my current tasks within the Philips company. During our weekends spent together, my son Robert provided me with the necessary stress relaxation. I really enjoyed the evening walks together, between my daily activities at Philips and the work I carried out at home. Last but not least, I am indebted to my wife for her patience, understanding, dedication, and willingness to sacrifice many evenings in favor of my professional results.

Sorin G. Stan
Eindhoven, The Netherlands
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P.S. Several minor errors and a mistake in Equation (4.5) have been corrected in this reprinted version of the book.

Glossary

Acronyms and Abbreviations

ADC	Analog-to-Digital Conversion (or Converter)
AlGaAs	Aluminum-Gallium-Arsenide
BCLK	Bit CLocK
BER	Bit Error Rate
BERL	Burst ERror Length
BLER	BLock Error Rate
CA	Central Aperture
CAV	Constant Angular Velocity
CDBD	Compact Disc Block Decoder
CD-DA	Compact Disc Digital Audio
CD-i	Compact Disc interactive
CDM	Compact Disc Mechanism
CD-R	Compact Disc Recordable
CD-ROM	Compact Disc Read-Only Memory
CD-ROM/XA	CD-ROM eXtended Architecture
CD-RW	Compact Disc ReWritable
CD-R/RW	Compact Disc Recordable/ReWritable
CIRC	Cross-Interleaved Reed-Solomon Code
CLV	Constant Linear Velocity
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CW	Continuous Wave
D/A	Digital-to-Analog
DAC	Digital-to-Analog Conversion (or Converter)
DAT	Digital Audio Tape
DC	Direct Current
DDS	Digital Data Storage

DH	Double-Heterostructure (laser)
DMA	Direct Memory Access
DSP	Digital Signal Processing (or Processor)
DTO	Digitally-Controlled Oscillator
DVD	Digital Versatile Disc
ECC	Error Correction Code
EDC	Error Detection Code
EFM	Eight-to-Fourteen Modulation
emf	electromotive force
FE	Focus Error
FIFO	First-In-First-Out
FWHM	Full Width at Half Maximum
GaAs	Gallium-Arsenide
HF	High Frequency
HOE	Holographic Optical Element
I^2S	Inter-IC Sound
IC	Integrated Circuit
IDE	Intelligent Drive Electronics
ISI	InterSymbol Interference
laser	light amplification by stimulated emission of radiation
LDGU	Laser Diode Grating Unit
LPF	Low-Pass Filter
LSB	Least Significant Bit (or Byte)
MB	MegaByte
MO	Magneto-Optical
MSB	Most Significant Bit (or Byte)
MTF	Modulation Transfer Function
NA	Numerical Aperture
NCU	Nonlinear Control Unit
NRZ	NonReturn-to-Zero
OPU	Optical Pickup Unit
PC	Personal Computer
PCB	Printed Circuit Board
PD	Phase-change Dual
PDM	Pulse Density Modulation

PID	Proportional, Integral and Derivative
pin	p-type, intrinsic, n-type semiconductor device
PLL	Phase-Locked Loop
pn	p-type, n-type junction (or semiconductor device)
QFT	Quantitative Feedback Theory
RE	Radial Error
RLL	Run-Length Limited
RMS	Root Mean-Squared
rpm	rotations per minute
RS	Reed-Solomon (code)
SCSI	Small Computer System Interface
SI	Système International d'Unités
SNR	Signal-to-Noise Ratio
SSD	Spot-Size Detection
VCO	Voltage-Controlled Oscillator
WCLK	Word CLocK
XOR	eXclusive OR
Xtal	Crystal clock
WORM	Write-Once-Read-Many
$\Sigma\Delta$	Sigma-Delta (Modulation or Conversion)

Symbols[1]

A_0	optical amplitude of the zeroth diffracted order
A_1	optical amplitude of the first diffracted order
A_D	detection level for the HF signal, in V
B_a	user bit rate of a CD-ROM disc rotating at 1X CLV, approximately equal to 150 kB/s
$\overline{B}_{av}$	average bit rate, in kB/s
C_{cdrom}	CD-ROM storage capacity, in MB
d_{al}	thickness of the active layer in a laser diode, in μm
d_m	minimum distance of a given code
D	damping (viscous friction) constant, in Ns/m for linear displacement or Nm/s^{-1} for rotational movement

[1]Where appropriate, either the SI unit or an SI derivative which is commonly used is given.

D_i	inner diameter of the program area, in mm
D_o	outer diameter of the program area, in mm
D_p	diffusion coefficient for holes in the n-region of a photodiode, in cm^2/s
f	frequency, in Hz
f_c	cross-over frequency of an open-loop amplitude characteristic, in Hz
f_{ch}	channel bit rate, in Mbit/s
f_{kT}	frequency of a kT EFM pattern, in kHz
f_n	natural undamped frequency of a second-order system, in Hz
f_{rot}	disc rotational frequency, in Hz
F_s	sampling frequency of digital audio, equal to 44.1 kHz
F_{unbal}	unbalance force generated by the rotating disc, in mN
g_0	gain constant defining the optical gain per unit length of a laser diode, in cm^{-1}
$\hbar$	Plank constant, equal to $6.6256 \cdot 10^{-34}$ Js
I_3	peak-peak amplitude of the HF component having the highest fundamental frequency, in A or V
I_{11}	peak-peak amplitude of the HF component having the lowest fundamental frequency, in A or V
I_{pp}	maximum variation of photodetector current, in A
I_{top}	peak value of the HF signal before high-pass filtering, in A or V
J_0	nominal current density defining the optical gain of a semiconductor laser, in A/cm^2
J_{rot}	rotational moment of inertia at the DC motor shaft, in kgm^2
J_t	threshold current density in a laser diode, in A/cm^2
K	elastic constant (stiffness) of a spring, in N/m
K_e	back-emf constant, in Vs/m for linear displacement or Vs for rotational movement
K_d	derivative gain of a PID controller
K_f	force constant (of a voice-coil motor), in N/A
K_i	integral gain of a PID controller
K_p	proportional gain of a PID controller
K_t	torque constant (of a rotary motor), in Nm/A
L_{al}	length of the active layer of a semiconductor laser, in μm

L	inductance (of a coil), in H
L_a	armature inductance (of a motor coil), in H
L_{bit}	physical length of the channel bit, in nm
L_{kT}	physical length of a pit/land, measured along the disc spiral and corresponding to a kT EFM pattern, in nm
m	order of the diffracted beam
M	radial modulation index
M_{act}	moving mass of the actuator, in kg
n_i	refraction indices of the semiconductor layers ($i = 1, 2, 3$) of a DH laser diode
n_{sub}	refractive index of the transparent substrate
N_1, N_2	oversampling factors for $F_s = 44.1$ kHz of the digital audio
N_b	number of data bits stored on an optical disk
$\mathcal{N}$	overspeed (X-factor) of the disc scanning velocity with respect to the audio reference velocity v_a
NA	numerical aperture (see also the list of abbreviations)
p	spatial period of the disc pit/land structure, in lines/μm or $\mu\mathrm{m}^{-1}$
P_i	parity symbols for C_1 decoder, $i = 1, 2, 3, 4$
q	track pitch, in μm
Q	quality factor of a second-order system
Q_i	parity symbols for C_2 decoder, $i = 1, 2, 3, 4$
r	disc radius at the current read-out point, in mm
R	electrical resistance, in Ω
R_a	armature resistance (of a motor coil), in Ω
R_{coat}	reflectance of the coating surface of a photodiode
R_{mirr}	reflectance of the mirrors of a laser diode
R_{Airy}	radius of the Airy disc, in μm
s	Laplace (complex) variable
S_{final}	final (target) subcode timing after a seek action, in s
S_{init}	initial subcode timing before a seek action, in s
S_{tot}	total subcode timing on disc (maximum playback time at 1X CLV), in s
S_x, S_y	subcode timing, in s
t	time, in s
t_r	rise time of the photodiode impulse response, in s

T_{access}	access time, in s
T_{lat}	latency time, in s
$\overline{T}_{lat}$	average latency time, in s
T_{mot}	turntable motor time, in s
T_{ov}	overhead time, in s
T_r	retry time, in s
T_{seek}	seek time, in s
v_a	linear velocity of recorded data, in m/s
W	width of the photodiode depletion layer, in μm
x	linear displacement, in m
α	loss in optical energy (absorption coefficient) per unit length within a laser diode or photodiode, in m^{-1}
ΔE	difference between energy levels in a photonic device, in eV
ΔN_{tr}	number of tracks crossed during a seek action
$\overline{\Delta N}_{tr}$	average number of tracks crossed during a seek action
ΔR_{gr}	distance between the disc center of gravity and the rotation axis, in mm
$\overline{\Delta S}$	average seek length, in s
ΔS_{foc}	low-frequency sensitivity of the focus loop
ΔS_{rad}	low-frequency sensitivity of the radial loop
Δz	focal depth, in μm
Δx	spatial frequency for the MTF, in lines/μm or μm^{-1}
η	quantum efficiency of a photonic emitting device
η_{rec}	recording efficiency
η_{ext}	external quantum efficiency of a photodetector
η_{in}	internal quantum efficiency of a photodetector
θ_0	angle between the direction of the zeroth order and the direction normal to the incidence plane, in rad
θ_2	reflection angle inside the resonator of a laser diode, in rad
θ_m	angle between the direction of the m^{th} order and the direction normal to the incidence plane, in rad
λ	wavelength of the laser light, in nm
ξ	damping ratio of a second-order system
τ	time constant, in s
τ_{el}	electrical time constant, in s
τ_p	lifetime of excess holes in the n-region of a photodiode, in s

φ_m	phase margin of a control loop, in rad
Γ	confinement factor within a semiconductor laser
Φ_{spot}	diameter of the laser spot, in μm
ψ_{10}	phase shift between zeroth and first diffracted orders, in rad
ω	angular frequency, in rad/s
ω_d	disc angular frequency, in rad/s

Notational conventions

$(2, 10)$	RLL binary sequence with at least 2 and at most 10 zeros between any two consecutive ones (EFM code)
$3T$	smallest EFM pattern (see also kT below)
$B(S_x)$	user bit rate measured at the subcode timing S_x
C_1	first error detection and correction code (CIRC)
C_2	second error detection and correction code (CIRC)
$d(s)$	internal/external disturbances affecting a control loop
$e(s)$	error compensated by a closed control loop
$e_t(s)$	tracking error in a closed control loop
$F(t)$	force, as a function of time
$g(x)$	generator polynomial of a CRC code
$G_1(s)$	transfer function of the error detector in a control loop
$G_2(s)$	transfer function of the power driver in a control loop
GF(q)	Galois field with q elements
$H(s)$	open-loop transfer function, in general
$H_{act}(s)$	actuator transfer function
$H_{mot}(s)$	transfer function of the turntable motor
$i(t)$	electrical current, as a function of time
j	$\sqrt{-1}$
$I_{det}(t)$	intensity of the light received by the CA photodetector, as a function of time
$K(s)$	transfer function of the compensation network
kT	EFM pattern of $k-1$ zeros between two ones
MTF(Δx)	modulation transfer function, as dependent on the spatial frequency
$n(s)$	measurement noise affecting a control loop

(n, k)	RS code of length n and dimension k
$\mathcal{N}(S_x)$	overspeed factor measured at the subcode timing S_x
$\mathrm{RE}(x)$	radial error signal, as function of the radial displacement x
$S(s)$	sensitivity of a closed control loop
$\mathrm{SAT}_k(x, x_0)$	signal delivered by one of the lateral photo-detectors $(k = 1, 2)$
$(t=2, e=4)$	CIRC error detection and correction system with at most 2 direct corrections at C_1 level and at most 4 erasure corrections at C_2 level
$u_a(t)$	applied voltage, as a function of time
$u_b(t)$	back emf, as a function of time
$U_a(s)$	applied voltage, in Laplace domain
$U_b(s)$	back emf, in Laplace domain
$x(t)$	linear displacement, as function of time
$X_a(s)$	actuator position with respect to its carriage (sledge)
$X_d(s)$	position of a read-out point on the disc surface
$X_s(s)$	spot position as controlled by a focus/radial servo loop