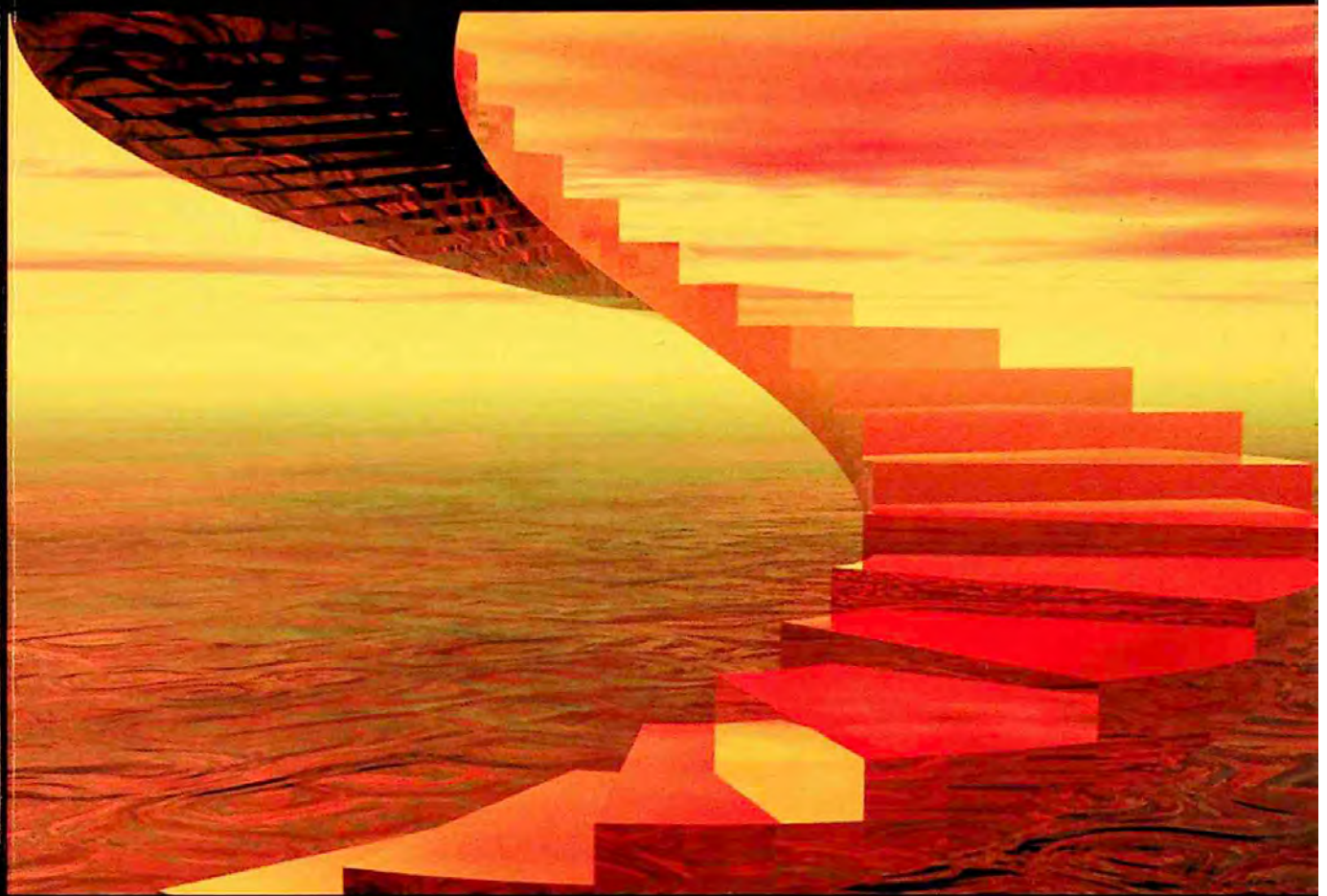


GRIGORE C. BURDEA • PHILIPPE COIFFET



Virtual Reality TECHNOLOGY

S E C O N D E D I T I O N



VIRTUAL REALITY TECHNOLOGY

Second Edition

GRIGORE C. BURDEA

Rutgers—The State University of New Jersey

PHILIPPE COIFFET

University of Versailles, France

 **WILEY-
INTERSCIENCE**

A John Wiley & Sons, Inc., Publication

ART INSTITUTE OF CA - SAN FRANCISCO
Library Resource Center Collection

Copyright © 2003 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400, fax 978-750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, e-mail: permreq@wiley.com.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services please contact our Customer Care Department within the U.S. at 877-762-2974, outside the U.S. at 317-572-3993 or fax 317-572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print, however, may not be available in electronic format.

Library of Congress Cataloging-in-Publication Data

Burdea, Grigore.

[Réalité virtuelle. English]

Virtual reality technology / Grigore Burdea, Philippe Coiffet.—2nd ed.
p. cm.

"A Wiley-Interscience publication."

Includes bibliographical references and index.

ISBN 0-471-36089-9 (cloth)

1. Human-computer interaction. 2. Virtual reality. I. Coiffet, Philippe. II. Title.

QA76.9.H85 B8713 2003
006—dc21

Printed in the United States of America

2002038088

10 9 8 7 6 5 4 3

CONTENTS

FOREWORD	xiii
PREFACE	xv
1 INTRODUCTION	1
1.1 The Three I's of Virtual Reality / 3	
1.2 A Short History of Early Virtual Reality / 3	
1.3 Early Commercial VR Technology / 8	
1.4 VR Becomes an Industry / 10	
1.5 The Five Classic Components of a VR System / 12	
1.6 Review Questions / 13	
References / 14	
2 INPUT DEVICES: TRACKERS, NAVIGATION, AND GESTURE INTERFACES	16
2.1 Three-Dimensional Position Trackers / 17	
2.1.1 Tracker Performance Parameters / 19	
2.1.2 Mechanical Trackers / 21	
2.1.3 Magnetic Trackers / 24	
2.1.4 Ultrasonic Trackers / 32	
2.1.5 Optical Trackers / 35	
2.1.6 Hybrid Inertial Trackers / 38	
2.2 Navigation and Manipulation Interfaces / 41	
2.2.1 Tracker-Based Navigation/Manipulation Interfaces / 42	

2.2.2	Trackballs / 44	
2.2.3	Three-Dimensional Probes / 45	
2.3	Gesture Interfaces / 46	
2.3.1	The Pinch Glove / 48	
2.3.2	The 5DT Data Glove / 49	
2.3.3	The Didjiglove / 51	
2.3.4	The CyberGlove / 53	
2.4	Conclusion / 54	
2.5	Review Questions / 54	
	References / 54	
3	OUTPUT DEVICES: GRAPHICS, THREE-DIMENSIONAL SOUND, AND HAPTIC DISPLAYS	57
3.1	Graphics Displays / 58	
3.1.1	The Human Visual System / 58	
3.1.2	Personal Graphics Displays / 60	
3.1.3	Large-Volume Displays / 70	
3.2	Sound Displays / 84	
3.2.1	The Human Auditory System / 84	
3.2.2	The Convolvotron / 88	
3.2.3	Speaker-Based Three-Dimensional Sound / 90	
3.3	Haptic Feedback / 92	
3.3.1	The Human Haptic System / 93	
3.3.2	Tactile Feedback Interfaces / 97	
3.3.3	Force Feedback Interfaces / 102	
3.4	Conclusion / 110	
3.5	Review Questions / 110	
	References / 111	
4	COMPUTING ARCHITECTURES FOR VR	116
4.1	The Rendering Pipeline / 117	
4.1.1	The Graphics Rendering Pipeline / 117	
4.1.2	The Haptics Rendering Pipeline / 125	
4.2	PC Graphics Architecture / 126	
4.2.1	PC Graphics Accelerators / 129	
4.2.2	Graphics Benchmarks / 133	
4.3	Workstation-Based Architectures / 135	
4.3.1	The Sun Blade 1000 Architecture / 136	
4.3.2	The SGI Infinite Reality Architecture / 137	
4.4	Distributed VR Architectures / 139	
4.4.1	Multipipeline Synchronization / 140	

- 4.4.2 Colocated Rendering Pipelines / 143
- 4.4.3 Distributed Virtual Environments / 149
- 4.5 Conclusion / 153
- 4.6 Review Questions / 154
- References / 155

5 MODELING

157

- 5.1 Geometric Modeling / 158
 - 5.1.1 Virtual Object Shape / 158
 - 5.1.2 Object Visual Appearance / 164
- 5.2 Kinematics Modeling / 172
 - 5.2.1 Homogeneous Transformation Matrices / 172
 - 5.2.2 Object Position / 172
 - 5.2.3 Transformation Invariants / 175
 - 5.2.4 Object Hierarchies / 176
 - 5.2.5 Viewing the Three-Dimensional World / 178
- 5.3 Physical Modeling / 180
 - 5.3.1 Collision Detection / 180
 - 5.3.2 Surface Deformation / 183
 - 5.3.3 Force Computation / 184
 - 5.3.4 Force Smoothing and Mapping / 190
 - 5.3.5 Haptic Texturing / 192
- 5.4 Behavior Modeling / 194
- 5.5 Model Management / 197
 - 5.5.1 Level-of-Detail Management / 198
 - 5.5.2 Cell Segmentation / 202
- 5.6 Conclusion / 205
- 5.7 Review Questions / 206
- References / 206

6 VR PROGRAMMING

210

- 6.1 Toolkits and Scene Graphs / 210
- 6.2 WorldToolKit / 214
 - 6.2.1 Model Geometry and Appearance / 214
 - 6.2.2 The WTK Scene Graph / 215
 - 6.2.3 Sensors and Action Functions / 218
 - 6.2.4 WTK Networking / 220
- 6.3 Java 3D / 221
 - 6.3.1 Model Geometry and Appearance / 222
 - 6.3.2 Java 3D Scene Graph / 223
 - 6.3.3 Sensors and Behaviors / 225

6.3.4	Java 3D Networking / 227
6.3.5	WTK and Java 3D Performance Comparison / 227
6.4	General Haptics Open Software Toolkit / 231
6.4.1	GHOST Integration with the Graphics Pipeline / 231
6.4.2	The GHOST Haptics Scene Graph / 232
6.4.3	Collision Detection and Response / 234
6.4.4	Graphics and PHANTOM Calibration / 234
6.5	PeopleShop / 235
6.5.1	DI-Guy Geometry and Path / 236
6.5.2	Sensors and Behaviors / 237
6.5.3	PeopleShop Networking / 238
6.6	Conclusion / 239
6.7	Review Questions / 239
	References / 240

7 HUMAN FACTORS IN VR

243

7.1	Methodology and Terminology / 244
7.1.1	Data Collection and Analysis / 246
7.1.2	Usability Engineering Methodology / 250
7.2	User Performance Studies / 253
7.2.1	Testbed Evaluation of Universal VR Tasks / 253
7.2.2	Influence of System Responsiveness on User Performance / 256
7.2.3	Influence of Feedback Multimodality / 260
7.3	VR Health and Safety Issues / 266
7.3.1	Direct Effects of VR Simulations on Users / 267
7.3.2	Cybersickness / 269
7.3.3	Adaptation and Aftereffects / 274
7.3.4	Guidelines for Proper VR Usage / 276
7.4	VR and Society / 277
7.4.1	Impact on Professional Life / 278
7.4.2	Impact on Private Life / 278
7.4.3	Impact on Public Life / 279
7.5	Conclusion / 280
7.6	Review Questions / 280
	References / 282

8 TRADITIONAL VR APPLICATIONS

285

8.1	Medical Applications of VR / 287
8.1.1	Virtual Anatomy / 287
8.1.2	Triage and Diagnostic / 289

- 8.1.3 Surgery / 296
- 8.1.4 Rehabilitation / 304
- 8.2 Education, Arts, and Entertainment / 314
 - 8.2.1 VR in Education / 314
 - 8.2.2 VR and the Arts / 319
 - 8.2.3 Entertainment Applications of VR / 324
- 8.3 Military VR Applications / 328
 - 8.3.1 Army Use of VR / 328
 - 8.3.2 VR Applications in the Navy / 334
 - 8.3.3 Air Force Use of VR / 338
- 8.4 Conclusion / 342
- 8.5 Review Questions / 342
- References / 343

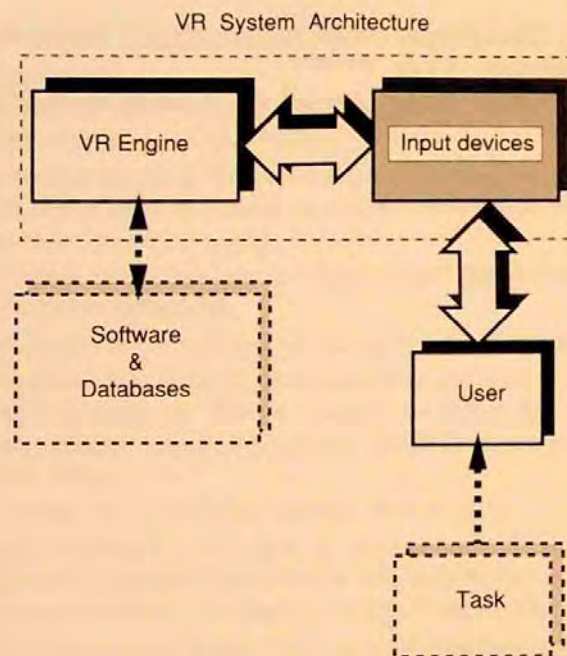
9 EMERGING APPLICATIONS OF VR **349**

- 9.1 VR Applications in Manufacturing / 349
 - 9.1.1 Virtual Prototyping / 350
 - 9.1.2 Other VR Applications in Manufacturing / 358
- 9.2 Applications of VR in Robotics / 362
 - 9.2.1 Robot Programming / 363
 - 9.2.2 Robot Teleoperation / 365
- 9.3 Information Visualization / 371
 - 9.3.1 Oil Exploration and Well Management / 374
 - 9.3.2 Volumetric Data Visualization / 376
- 9.4 Conclusion / 382
- 9.5 Review Questions / 382
- References / 383

INDEX **387**

CHAPTER 2

INPUT DEVICES: TRACKERS, NAVIGATION, AND GESTURE INTERFACES



One of the three I's defining virtual reality stands for *interactivity*. In order to allow human-computer interaction it is necessary to use special interfaces designed to input a user's commands into the computer and to provide feedback from the simulation to the user. Today's VR interfaces are varied in functionality and purpose, as they address several human sensorial channels. For example, body motion is measured with 3D position trackers or using sensing suits, hand gestures are digitized by sensing gloves, visual feedback is sent to stereo HMDs and large-volume displays, virtual sound is computed by 3D sound generators, etc. Some of these input/output (I/O) devices are commercially available, some are still prototypes in a field which has become a very active research area. The aim of researchers is to allow faster and more natural ways of interaction with the computer and thus overcome the communication bottleneck presented by the keyboard and the computer mouse.

This chapter describes the VR interfaces used in tracking, VR navigation, and gesture input. Output devices for visual, auditory, and haptic feedback to the user are

the focus of the next chapter. Our discussion of VR interface hardware includes functionality, design, and limitations, comparing, whenever possible, alternative available technologies.

2.1 THREE-DIMENSIONAL POSITION TRACKERS

Many computer application domains, such as navigation, ballistic missile tracking, ubiquitous computing, robotics, biomechanics, architecture, computer-aided design (CAD), education, and VR, require knowledge of the real-time position and orientation of moving objects within some frame of reference [Hightower and Borriello, 2001]. These applications have varying requirements in terms of such parameters as measurement range, precision, and temporal update rates. Global positioning system (GPS) transducers, for example, report position with an accuracy of 1–5 m (95% of the time) on a worldwide scale. This is great for car navigation, but VR has much more stringent accuracy requirements. On the other hand, the scale of measured distances for VR interactions is usually not larger than a room or a laboratory.

A moving object in 3D space has six degrees of freedom, three for translations and three for rotations. If a Cartesian coordinate system is attached to the moving object (as illustrated in Fig. 2.1), then its translations are along the X , Y , and Z axes. Object rotations about these axes are called yaw, pitch, and roll, respectively. These define a dataset of six numbers that need to be measured sufficiently rapidly, as the object may be moving at high speed.

Definition The special-purpose hardware used in VR to measure the real-time change in a 3D object position and orientation is called a tracker.

Virtual reality applications typically measure the motion of the user's head, limbs or hands, for the purpose of view control, locomotion, and object manipulation [Foxlin,

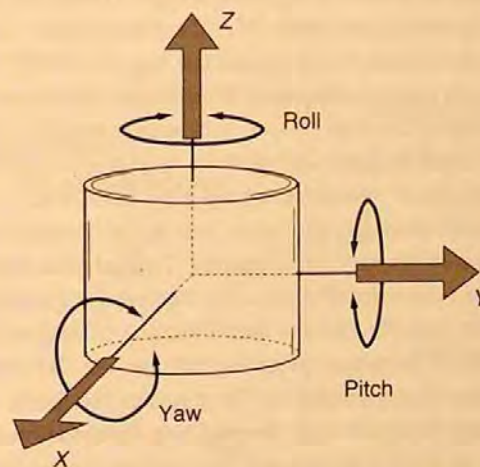


Fig. 2.1 System of coordinates of a moving 3D object. From Burdea and Coiffet [1993].
© Editions Hermes. Reprinted by permission.

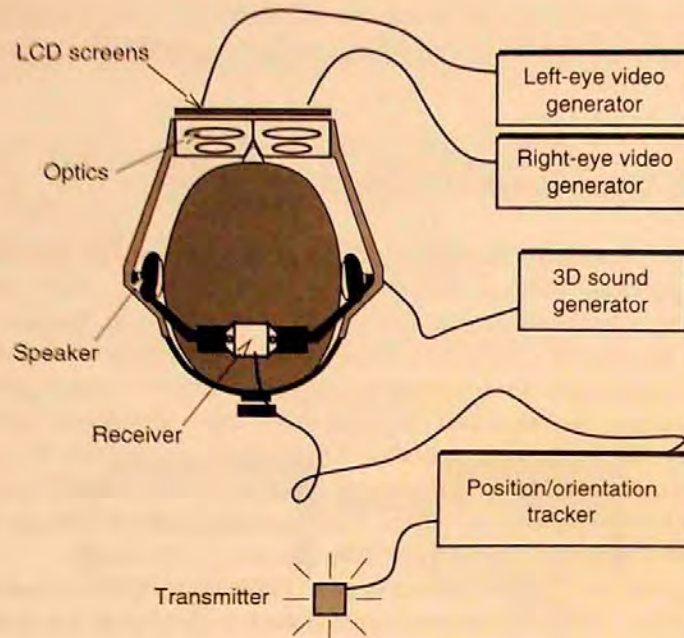


Fig. 2.2 A 3D magnetic sensor in a HMD. Adapted from Pimentel and Teixeira [1993]. Reprinted by permission.

2002]. A newer tracker application in VR is for the control of an avatar, or virtual body, mapped to the user. In the case of the head-mounted display illustrated in Figure 2.2, the tracker receiver is placed on the user's head, so that when the posture of the head changes, so does the position of the receiver. The user's head motion is sampled by an electronic unit and sent to a host computer (in this case a graphics workstation). The computer uses the tracker data to calculate a new viewing direction of the virtual scene and to render an updated image. This scene is then converted to National Television System Committee (NTSC) video signals displayed by the two LCD screens. While this example illustrates the use of a HMD tracker, the display could have been a much larger Immersive Workbench (discussed in Chapter 3), but the requirement to measure the user's viewing direction remains. Without the 3D head tracker the computer could not have changed the spatial view to match the user's head posture, and the "immersion" sensation would have been lost.

Another VR sensorial modality that uses tracker information is 3D sound, which in Figure 2.2 is presented through headphones. Tracker data allow the computer to collocate sound sources with virtual objects the user sees in the simulation. This helps increase the simulation realism and the user's feeling of immersion in the synthetic world. The measurement accuracy requirements for the 3D sound application are much less stringent than those needed by the graphics feedback. As noted by Foxlin [2002], the visual acuity is higher than the auditory localization acuity, and auditory depth perception is even weaker in humans. Several competing tracking technologies are available, such as mechanical, magnetic, optical, ultrasonic, and hybrid. It is therefore necessary to look at tracker performance parameters in order to match their

measurement capabilities to different sensorial channel requirements and available budgets.

2.1.1 Tracker Performance Parameters

All 3D trackers, regardless of the technology they use, share a number of very important performance parameters, such as accuracy, jitter, drift, and latency. These are illustrated in Figure 2.3.

Definition Tracker accuracy represents the difference between the object's actual 3D position and that reported by tracker measurements.

The more accurate a tracker, the smaller this difference is and the better the simulation follows the user's real actions. Accuracy is given separately for tracking translation (fraction of a millimeter) and rotation (fraction of a degree). Accuracy is typically not constant and is degraded with distance from the origin of the reference

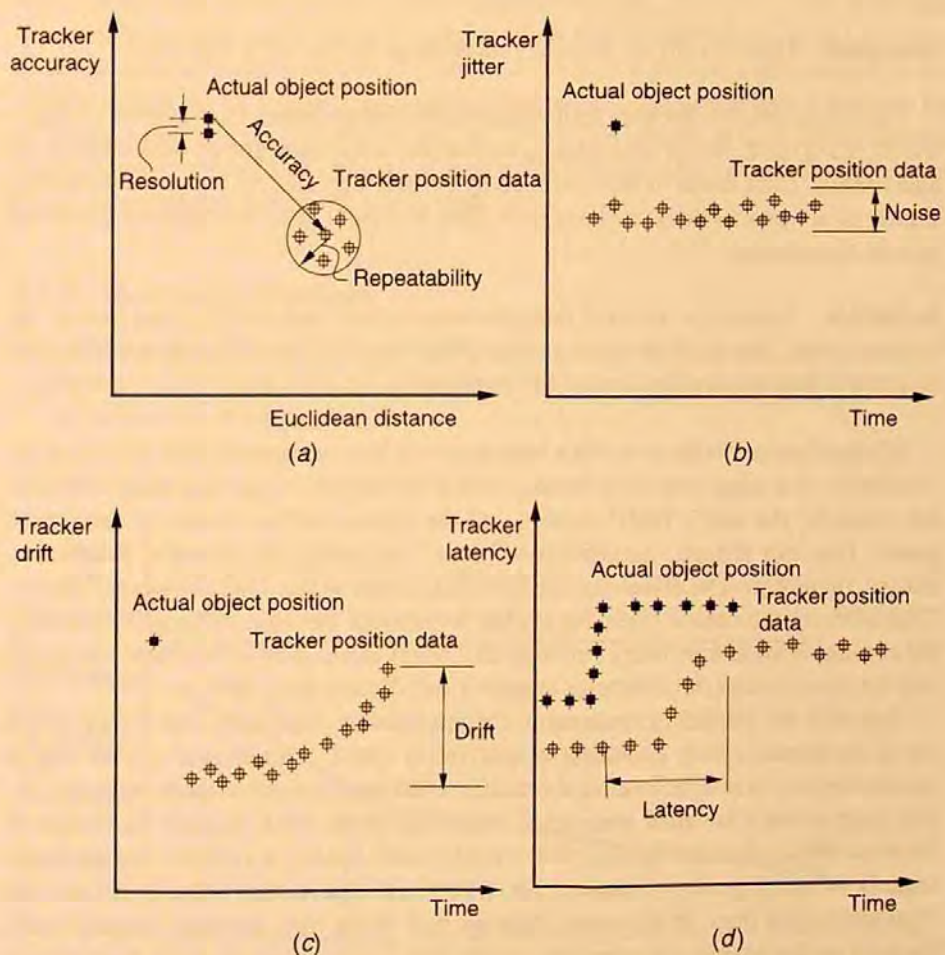
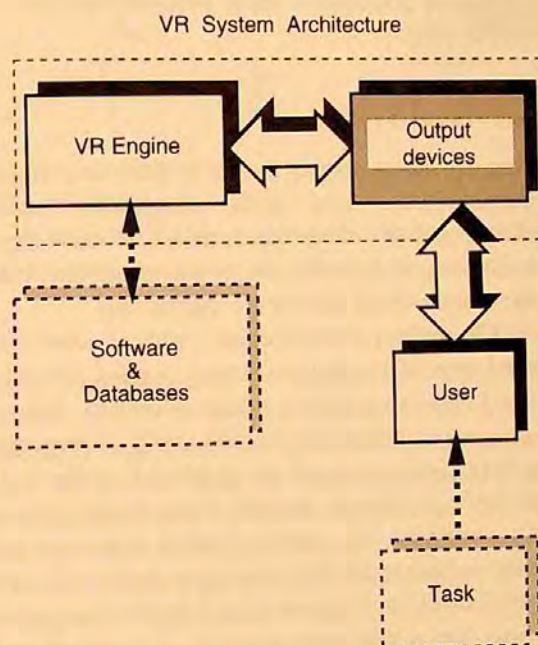


Fig. 2.3 Tracker performance parameters: (a) accuracy; (b) jitter; (c) drift; (d) latency.

CHAPTER 3

OUTPUT DEVICES: GRAPHICS, THREE-DIMENSIONAL SOUND, AND HAPTIC DISPLAYS



The previous chapter described 3D trackers, trackballs, and sensing gloves, which are devices used to mediate the user's input into the VR simulation. Now we look at special hardware designed to provide feedback from the simulation in response to this input. The sensorial channels fed back by these interfaces are sight (through graphics displays), sound (through 3D sound displays), and touch (through haptic displays).

For reasons of simplicity, this chapter treats each sensorial feedback modality separately. A further simplification here is the decoupling of sensorial feedback from the user's input. Modern VR systems are, however, multimodal, and feedback interfaces usually incorporate hardware to allow user input (such as trackers, pushbuttons, etc.). Combining several types of sensorial feedback in a simulation increases the user's immersion into VR. Furthermore, combining several sensorial modalities improves the simulation realism and therefore the usefulness of VR applications.

A groundbreaking Virtual Reality textbook is now even better

Virtual reality is a very powerful and compelling computer application by which humans interact with computer-generated environments in a way that mimics real life and engages various senses. Although its most widely known application is in the entertainment industry, the real promise of virtual reality lies in such fields as medicine, engineering, oil exploration, and the military, to name just a few. Through virtual reality, scientists can triple the rate of oil discovery, pilots can dogfight numerically superior "bandits," and surgeons can improve their skills on virtual (rather than real) patients.

This *Second Edition* of the first comprehensive technical book on virtual reality provides updated and expanded coverage of the technology such as:

- Input and output interfaces including touch and force feedback
- Computing architecture (with emphasis on the rendering pipeline and task distribution)
- Object modeling (including physical and behavioral aspects)
- Programming for virtual reality (WorldToolKit, Java 3D, GHOST, and PeopleShop)
- An in-depth look at human factors issues, user performance, and sensorial conflict aspects of VR
- Traditional and emerging VR applications

The new edition of *Virtual Reality Technology* is specifically designed for use as a textbook. Thus, it includes definitions, review questions, and a CD-ROM with video clips that reinforce the topics covered. The CD-ROM also contains a *Laboratory Manual* with homework and programming assignments in VRML and Java 3D, as follows:

- Introduction to VRML and Java 3D
- Sensor and Event Processing
- VRML and JavaScript
- Scene Hierarchy, Geometry, and Texture
- VRML PROTO and Glove Devices
- Viewpoint Control, Sound, and Haptic Effects

The *Second Edition* will serve as a state-of-the-art resource for both undergraduate and graduate students in engineering, computer science, and other disciplines.

GRIGORE C. BURDEA is a professor at Rutgers, the State University of New Jersey, and author of the book *Force and Touch Feedback for Virtual Reality*, also published by Wiley. **PHILIPPE COIFFET** is a Director of Research at CNRS (French National Scientific Research Center) and Member of the National Academy of Technologies of France. He has authored twenty books on robotics and virtual reality, which have been translated into several languages.

Cover Design and Illustration: Michael Rutkowski

 **IEEE**
IEEE PRESS



ISBN 0-471-36089-9