

# Engineering Haptic Devices

# **Springer Series on Touch and Haptic Systems**

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Christian Hatzfeld · Thorsten A. Kern  
Editors

# Engineering Haptic Devices

A Beginner's Guide

Second Edition

 Springer

*Editors*

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# Series Editors' Foreword

This is the 10th volume of the 'Springer Series on Touch and Haptic Systems', which is published in collaboration between **Springer** and the **EuroHaptics Society**.

*Engineering Haptic Devices* is focused on topics related to the design of effective haptic devices from an engineering point of view. The book is divided into two parts with 15 chapters. Part I is titled 'Basics', which is an introduction to general topics in haptics, such as the haptic interaction modality, the role of users in closed-loop haptic systems and several areas of applications. In Part I, you will also find a taxonomy related to haptic perception, the requirements of the user, and the performance of haptic devices. Furthermore, this part of the volume highlights several methodologies for designing haptic systems, and represents the application of general principles of engineering design to the development of new haptic interfaces. Part II of this volume is focused on studying the main components of haptic systems. The chapters in Part II focus on control, kinematics, actuators, sensors, interfaces, and software development for haptic systems. Finally, the book provides a guide to haptic evaluation. It also shows some examples for the development of haptic systems.

This volume is the second edition of a previous publication from Springer. It has been substantially expanded and several new authors have contributed to this updated edition. The content has been thoroughly revised and more in-depth material has been added to the description of most topics. Some new themes have been included such as the role of the user, the evaluation of haptic systems, and more examples of applications.

This book is of great value to the 'Springer Series on Touch and Haptic Systems' since it covers all engineering aspects for the design of haptic interfaces in a comprehensive manner. We therefore expect it to be well received by the Haptic Community and interesting for teaching these topics. Students will find most subjects studied in master-level courses on haptics, while researchers and engineers will also find it a useful and authoritative source of information for their work in haptics.

May 2014

Manuel Ferre  
Marc Ernst  
Alan Wing

# Preface

The term “haptics” unlike the terms “optics” and “acoustics” is not so well known to the majority of people, at least not in the meaning used in the scientific community. The words “haptics” and “haptic” refer to everything concerning the sense of touch. “Haptics” is everything and everything is “haptic,” because it not only describes pure mechanical interaction, but also includes thermal- and pain-(nociception) perception. The sense of touch makes it possible for humans and other living beings to perceive the “borders of their physical being,” i.e., to identify where their own body begins and where it ends. While vision and hearing will make us aware of our greater surroundings, the sense of touch covers our immediate vicinity: In the heat of a basketball match a light touch on our back immediately makes us aware of an attacking player we do not see. We notice the intensity of contact, the direction of the movement by a shear on our skin, or a breeze moving our body hairs—all without catching a glimpse of the opponent.

“Haptic systems” are divided into two classes.<sup>1</sup> There are *time-invariant systems* (the keys of my keyboard), which generate a more or less unchanging haptic effect whether being pressed today or in a year’s time. Structures like surfaces, e.g., the wooden surface of my table, are also part of this group. These haptically interesting surfaces are often named “haptic textures.” Furthermore, there are *active, reconfigurable systems*, which change their haptic properties partly or totally depending on a preselection—e.g., from a menu, or based on an interaction with real or virtual environments.

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<sup>1</sup> In engineering there are three terms that are often used but do not have definite meaning: System, Device, and Component. Systems are—depending on the task of the designer—either a device or a component. A motor is a component of a car, but for the developer of the motor it is a device, which is assembled from components (spark-plug, cocks, knocking-sensor). It can be helpful when reading a technological text to replace each term with the word “thing.” Although this suggestion is not completely serious, it surprisingly increases the comprehensibility of technical texts.

The focus of this book is on the technological design criteria for active, reconfigurable systems, providing a haptic coupling of user and object in a mainly mechanical understanding. Thermal and nociceptive perceptions are mentioned according to their significance but are not thoroughly discussed. This is also the case with regard to passive haptic systems. For active haptic systems, research and industry developed a large number of different universal haptic systems that can be used for different purposes. Because of the large variability of these devices, they sometimes fall short of requirements for certain applications or are—in short, just too expensive. We therefore believe that there is a need for a structured approach to the design of *task-specific haptic systems* on the one hand and a necessity to know about the different approaches for the components and structures of haptic systems on the other hand.

The fact that you have bought this book suggests that you are interested in haptics and its application in human–machine interaction. You might have already tried to sketch a technical system meant to provide a haptic human–machine interaction. Maybe, you are just planning a project as part of your studies or as a commercial product aimed at improving a certain manual control or introducing a new control concept. Maybe, you are a member of the increasing group of surgeons actively using haptics in medical technology and training to improve patients’ safety and trying to apply the current progresses to other interventions.

Despite of, or even because of, this great variety of projects in industry and research working with haptic systems, the common understanding of “haptics” and the terms directly referring to it, like “kinaesthetic” and “tactile,” is by no means as unambiguous and indisputable as it should be. In this book, we intend to offer a help to act more safely in the area of designing haptic devices. We consider this book as a starting point for engineers and students new to haptics and the design of haptic interfaces as well as a reference work for more experienced professionals. To make the book more usable and practical in this sense, we added recommendations for further insight into most chapters.

It begins with a presentation of the different areas that can benefit from the integration of haptics, including communication, interaction with virtual environments, and the most challenging applications in telepresence and teleoperation. Next, as a basis for the design of such systems, haptics is discussed as an interaction modality. This includes several concepts of haptic perception and haptic interaction and the most relevant results from psychophysical studies that can and have to be applied during the design process of a task-specific haptic system. Please note that this book has been written by and is addressed to engineers from several disciplines. This means that especially psychophysical content is sometimes simplified and shortened in favor of a fundamental basic insight into these topics for engineers working on a haptic device. Next, the role of the user as a (mechanical) part of the haptic system is discussed in detail, since this modeling has a large impact on system properties like stability and perceived haptic quality.



Part I of the book concludes with an extension of the commonly known development models of mechatronic systems to the special design of haptic systems. This chapter lays special focus on the integration of perception properties and ergonomic aspects in this process. The authors believe that the systematic consideration of perception properties and features of the sensory apparatus based on the intended interaction can reduce critical requirements on haptic systems, such as lowering the efforts and costs of development as well as leading to systems with higher perceived quality.

In Part II of the book, an overview of technological solutions, like the designs of actuators, kinematics, or complete systems including software and rendering solutions and the interfaces to simulation and virtual reality systems, is given. This is done with two aspects in mind. First, the reader should be able to find the most important and widely used solutions for recurring problems like actuation or sensing including the necessary technical basis for own designs and developments. Second, we wanted to give an overview of the large number of different principles used in haptic systems that are maybe a good solution for a new task-specific haptic system—or a noteworthy experience of which solution not to try.

The first idea for this book was born in 2003. Originally intended as an addition to the dissertation of Thorsten A. Kern, it was soon thought of as filling a gap: The regrettably small number of comprehensive recapitulating publications on haptics available for, e.g., a technically interested person, confronted with the task of designing a haptic device for the first time. In 2004, inspite of a considerable number of conference proceedings, journals, and Ph.D. theses, no document was available giving a summary of the major findings of this challenging subject.

The support of several colleagues, especially Prof. Dr.-Ing. Dr. med. Ronald Blechschmidt-Trapp and Dr.-Ing. Christoph Doerrer, helped to make the idea of this book clearer in the following years—and showed that this book would have to be much more extensive than originally expected. With the encouragement of Prof. Dr.-Ing. habil. Roland Werthschützky, the first edition was edited by Thorsten A. Kern during a post-doc time. It was funded by the Deutsche Forschungsgemeinschaft (DFG, grant KE1456/1-1) with special regard to the consolidation of the design methodology for haptic devices. Due to this funding the financial basis of this task was guaranteed. The structure of the topic made clear that the book would be considerably improved by contributions from specialists in several areas. In 2008, the German version *Entwicklung Haptischer Geräte* and in 2009 the English version *Engineering Haptic Devices* were published by Springer. Both books sold about 500 copies in total up till now.

In 2010, the idea of a second edition of the book was born. With the change of Dr. Kern from university to industrial employer, the attention also shifted from mainly kinaesthetic to tactile devices. This made severe gaps in the first edition eminent. In parallel, science made great progress in understanding the individual tactile modalities, blurring the borders between different old concepts of the same perception, offering now an opportunity to find an engineering approach to more than the pure vibrotactile perception. It took however until the year 2013 for the work on the second edition to start. In that year, Christian Hatzfeld finished his

dissertation dealing with the perception of vibrotactile forces. Also, encouraged by Prof. Dr.-Ing. habil. Roland Werthschützky, he took the lead in editing this second edition. In addition to the first edition, this work was also funded by the DFG (grant HA7164/1-1), pointing out the importance of an adapted design approach for haptic systems.

With the cooperation of Springer and the series editors, the second edition of this book was integrated in the *Springer Series on Touch and Haptic Systems*, as we felt that the design of task-specific haptic interfaces would be complemented well by other works in this series. We wish to thank all the authors who contributed to this book as well as all colleagues, students, and scientists from the haptics community who supported us with fruitful discussions, examples, and permissions to include them in this book. On behalf of many, we would like to point out Lukas Braisz, who was a great support in preparing the figures, especially in the new chapters of the second edition. Special thanks go to our mentor and advisor Prof. Dr.-Ing. habil. Roland Werthschützky, who encouraged and supported the work on both editions of this book.

Since a book is a quite static format compared to the dynamic progress of haptics in general, we set up an accompanying homepage with regular updates on the books topics at <http://www.hapticdevices.eu>. We hope that this work will alleviate the work of students and engineers new to the exciting and challenging development of haptic systems and serve as a useful resource for all developers.

Darmstadt, April 2014

Christian Hatzfeld  
Thorsten A. Kern

# Contents

## Part I Basics

<b>1 Motivation and Application of Haptic Systems</b> . . . . .	3
Christian Hatzfeld and Thorsten A. Kern	
1.1 Philosophical and Social Aspects . . . . .	4
1.1.1 Haptics as a Physical Being's Boundary . . . . .	4
1.1.2 Formation of the Sense of Touch . . . . .	5
1.1.3 Touchable Art and Haptic Aesthetics . . . . .	6
1.2 Technical Definitions of Haptics . . . . .	8
1.2.1 Definitions of Haptic Interactions . . . . .	9
1.2.2 Taxonomy of Haptic Perception . . . . .	11
1.3 Application Areas of Haptic Systems . . . . .	13
1.3.1 Telepresence, Teleaction, and Assistive Systems . . . . .	15
1.3.2 Virtual Environments . . . . .	17
1.3.3 Noninvasive Medical Applications . . . . .	20
1.3.4 Communication . . . . .	21
1.3.5 Why Use a Haptic System? . . . . .	22
1.4 Conclusions . . . . .	23
References . . . . .	23
<b>2 Haptics as an Interaction Modality</b> . . . . .	29
Christian Hatzfeld	
2.1 Haptic Perception . . . . .	29
2.1.1 Physiological Basis . . . . .	30
2.1.2 Psychophysical Description of Perception . . . . .	38
2.1.3 Characteristic Values of Haptic Perception . . . . .	53
2.1.4 Further Aspects of Haptic Perception . . . . .	65
2.2 Concepts of Interaction . . . . .	69
2.2.1 Haptic Exploration of Objects . . . . .	69
2.2.2 Active and Passive Touch . . . . .	69

- 2.2.3 Gestures . . . . . 71
- 2.2.4 Human Movement Capabilities . . . . . 72
- 2.3 Interaction Using Haptic Systems . . . . . 73
  - 2.3.1 Haptic Displays and General Input Devices . . . . . 74
  - 2.3.2 Assistive Systems . . . . . 76
  - 2.3.3 Haptic Interfaces . . . . . 76
  - 2.3.4 Manipulators . . . . . 79
  - 2.3.5 Teleoperators . . . . . 79
  - 2.3.6 Comanipulators . . . . . 80
  - 2.3.7 Haptic System Control . . . . . 81
- 2.4 Engineering Conclusions . . . . . 81
  - 2.4.1 A Frequency-Dependent Model of Haptic Properties . . . . . 81
  - 2.4.2 Stiffnesses . . . . . 84
  - 2.4.3 One Kilohertz: Significance for the Mechanical Design. . . . . 84
  - 2.4.4 Perception-Inspired Concepts for Haptic System Design . . . . . 87
- References . . . . . 89
  
- 3 The User’s Role in Haptic System Design . . . . . 101**  
 Thorsten A. Kern and Christian Hatzfeld
  - 3.1 The User as Mechanical Load . . . . . 101
    - 3.1.1 Mapping of Frequency Ranges onto the User’s Mechanical Model . . . . . 101
    - 3.1.2 Modeling the Mechanical Impedance . . . . . 104
    - 3.1.3 Grips and Grasps . . . . . 105
    - 3.1.4 Measurement Setup and Equipment . . . . . 107
    - 3.1.5 Models . . . . . 108
    - 3.1.6 Modeling Parameters . . . . . 110
    - 3.1.7 Comparison with Existing Models . . . . . 118
    - 3.1.8 Final Remarks on Impedances . . . . . 120
  - 3.2 The User as a Measure of Quality . . . . . 120
    - 3.2.1 Resolution of Haptic Systems . . . . . 120
    - 3.2.2 Errors and Reproducibility. . . . . 121
    - 3.2.3 Quality of Haptic Interaction . . . . . 121
- References . . . . . 122
  
- 4 Development of Haptic Systems . . . . . 125**  
 Christian Hatzfeld and Thorsten A. Kern
  - 4.1 Application of Mechatronic Design Principles to Haptic Systems. . . . . 125
    - 4.1.1 Stage 1: System Requirements . . . . . 127
    - 4.1.2 Stage 2: System Design. . . . . 128

- 4.1.3 Stage 3: Modeling and Design of Components . . . . . 129
- 4.1.4 Stage 4: Realization and Verification of Components and System . . . . . 130
- 4.1.5 Stage 5: Validation of the Haptic System . . . . . 131
- 4.2 General Design Goals . . . . . 131
- 4.3 Technical Descriptions of Parts and System Components . . . . . 132
  - 4.3.1 Single Input, Single Output Descriptions . . . . . 133
  - 4.3.2 Network Parameter Description . . . . . 134
  - 4.3.3 Finite Element Methods . . . . . 136
  - 4.3.4 Description of Kinematic Structures . . . . . 137
- References . . . . . 140

**Part II Designing Haptic Systems**

- 5 Identification of Requirements . . . . . 145**
  - Thorsten A. Kern and Christian Hatzfeld
  - 5.1 Definition of Application: The Right Questions to Ask . . . . . 145
    - 5.1.1 Experiments with the Customer . . . . . 146
    - 5.1.2 General Design Guidelines . . . . . 148
  - 5.2 Interaction Analysis . . . . . 149
  - 5.3 Technical Solution Clusters . . . . . 153
    - 5.3.1 Cluster ①: Kinaesthetic . . . . . 155
    - 5.3.2 Cluster ②: Surface-Tactile . . . . . 156
    - 5.3.3 Cluster ③: Vibro-Tactile . . . . . 156
    - 5.3.4 Cluster ④: Vibro-Directional . . . . . 157
    - 5.3.5 Cluster ⑤: Omnidirectional . . . . . 158
    - 5.3.6 General Requirement Sources . . . . . 158
  - 5.4 Safety Requirements . . . . . 159
    - 5.4.1 Safety Standards . . . . . 159
    - 5.4.2 Definition of Safety Requirements from Risk Analysis . . . . . 160
  - 5.5 Requirement Specifications of a Haptic System . . . . . 166
  - References . . . . . 166
- 6 General System Structures . . . . . 169**
  - Thorsten A. Kern
  - 6.1 Open-Loop Impedance Controlled . . . . . 170
  - 6.2 Closed-Loop Impedance Controlled . . . . . 171
  - 6.3 Open-Loop Admittance Controlled . . . . . 173
  - 6.4 Closed-Loop Admittance Controlled Devices . . . . . 173
  - 6.5 Qualitative Comparison of the Internal Structures of Haptic Systems . . . . . 176
    - 6.5.1 Tactile Devices . . . . . 177

6.5.2	Kinaesthetic Devices . . . . .	177
6.6	How to Choose a Suitable System Structure . . . . .	178
<b>7</b>	<b>Control of Haptic Systems . . . . .</b>	<b>181</b>
	Thomas Opitz and Oliver Meckel	
7.1	System Description . . . . .	182
7.1.1	Linear State Space Description . . . . .	183
7.1.2	Nonlinear System Description . . . . .	184
7.2	System Stability . . . . .	186
7.2.1	Analysis of Linear System Stability . . . . .	187
7.2.2	Analysis of Nonlinear System Stability . . . . .	190
7.3	Control Law Design for Haptic Systems . . . . .	197
7.3.1	Structuring of Control Design . . . . .	197
7.3.2	Requirement Definition . . . . .	199
7.3.3	General Control Law Design . . . . .	201
7.3.4	Example: Cascade Control of a Linear Drive . . . . .	206
7.4	Control of Teleoperation Systems . . . . .	208
7.4.1	Two-Port Representation . . . . .	209
7.4.2	Transparency . . . . .	210
7.4.3	General Control Model for Teleoperators . . . . .	214
7.4.4	Stability Analysis of Teleoperators . . . . .	217
7.4.5	Effects of Time Delay . . . . .	219
7.5	Conclusion . . . . .	222
	References . . . . .	223
<b>8</b>	<b>Kinematic Design . . . . .</b>	<b>227</b>
	Sebastian Kassner	
8.1	Introduction and Classification . . . . .	227
8.1.1	Classification of Mechanisms . . . . .	229
8.2	Design Step 1: Topological Synthesis—Defining the Mechanism’s Structure . . . . .	231
8.2.1	Synthesis of Serial Mechanisms . . . . .	231
8.2.2	Synthesis of Parallel Mechanisms . . . . .	232
8.2.3	Special Case: Parallel Mechanisms with Pure Translational Motion . . . . .	233
8.2.4	Example: The DELTA Mechanism . . . . .	235
8.3	Design Step 2: Kinematic Equations . . . . .	237
8.3.1	Kinematics: Basic Equations for Design and Operation . . . . .	239
8.3.2	Example: The DELTA Mechanism . . . . .	241
8.4	Design Step 3: Dimensioning . . . . .	244
8.4.1	Isotropy and Singular Positions . . . . .	245
8.4.2	Example: The DELTA Mechanism . . . . .	250
	References . . . . .	251

<b>9</b>	<b>Actuator Design</b> . . . . .	<b>253</b>
	Henry Haus, Thorsten A. Kern, Marc Matysek and Stephanie Sindlinger	
9.1	General Facts About Actuator Design . . . . .	254
9.1.1	Overview of Actuator Principles. . . . .	254
9.1.2	Actuator Selection Aid Based on Its Dynamics . . . . .	257
9.1.3	Gears . . . . .	258
9.2	Electrodynamic Actuators . . . . .	261
9.2.1	The Electrodynamic Effect and Its Influencing Variables . . . . .	262
9.2.2	Actual Actuator Design . . . . .	276
9.2.3	Actuator Electronics . . . . .	281
9.2.4	Examples for Electrodynamic Actuators in Haptic Devices . . . . .	286
9.2.5	Conclusion About the Design of Electrodynamic Actuators . . . . .	288
9.3	Piezoelectric Actuators . . . . .	288
9.3.1	The Piezoelectric Effect . . . . .	289
9.3.2	Designs and Properties of Piezoelectric Actuators . . . . .	294
9.3.3	Design of Piezoelectric Actuators for Haptic Systems . . . . .	298
9.3.4	Procedure for the Design of Piezoelectric Actuators . . . . .	299
9.3.5	Piezoelectric Actuators in Haptic Systems . . . . .	304
9.4	Electromagnetic Actuators . . . . .	314
9.4.1	Magnetic Energy . . . . .	314
9.4.2	Design of Magnetic Circuits . . . . .	317
9.4.3	Examples for Electromagnetic Actuators . . . . .	321
9.4.4	Magnetic Actuators in Haptic Devices . . . . .	324
9.4.5	Conclusion on the Design of Magnetic Actuators . . . . .	326
9.5	Electrostatic Actuators . . . . .	327
9.5.1	Definition of the Electric Field . . . . .	327
9.5.2	Designs of Capacitive Actuators with Air-Gap . . . . .	329
9.5.3	Dielectric Elastomer Actuators . . . . .	335
9.5.4	Designs of Dielectric Elastomer Actuators . . . . .	338
9.5.5	Electrorheological Fluids . . . . .	342
9.6	Special Designs of Haptic Actuators . . . . .	350
9.6.1	Haptic-Kinaesthetic Devices . . . . .	350
9.6.2	Haptic-Tactile Devices . . . . .	356
	References . . . . .	364

**10 Sensor Design** . . . . . 373  
 Jacqueline Rausch, Thorsten A. Kern and Christian Hatzfeld

10.1 Force Sensors. . . . . 373  
 10.1.1 Constraints. . . . . 374  
 10.1.2 Sensing Principles . . . . . 381  
 10.1.3 Selection of a Suitable Sensor . . . . . 413

10.2 Positioning Sensors. . . . . 419  
 10.2.1 Basic Principles of Position Measurement . . . . . 419  
 10.2.2 Requirements in the Context of Haptics . . . . . 421  
 10.2.3 Optical Sensors . . . . . 422  
 10.2.4 Magnetic Sensors . . . . . 425  
 10.2.5 Other Displacement Sensors. . . . . 427  
 10.2.6 Electronics for Absolute Positions Sensors . . . . . 428  
 10.2.7 Acceleration and Velocity Measurement . . . . . 429  
 10.2.8 Conclusion on Position Measurement . . . . . 432

10.3 Touch Sensors . . . . . 433  
 10.3.1 Resistive Touch Sensors . . . . . 433  
 10.3.2 Capacitive Touch Sensors . . . . . 434  
 10.3.3 Other Principles . . . . . 435

10.4 Imaging Sensors . . . . . 436

10.5 Conclusion. . . . . 436

References . . . . . 437

**11 Interface Design** . . . . . 443  
 Thorsten A. Kern

11.1 Border Frequency of the Transmission Chain. . . . . 444  
 11.1.1 Bandwidth in a Telemanipulation System . . . . . 444  
 11.1.2 Bandwidth in a Simulator System. . . . . 445  
 11.1.3 Data Rates and Latencies . . . . . 446

11.2 Concepts for Bandwidth Reduction. . . . . 447  
 11.2.1 Analysis of the Required Dynamics . . . . . 447  
 11.2.2 Local Haptic Model in the Controller . . . . . 447  
 11.2.3 Event-Based Haptics . . . . . 448  
 11.2.4 Movement Extrapolation . . . . . 450  
 11.2.5 Compensation of Extreme Dead Times . . . . . 450  
 11.2.6 Compression . . . . . 450

11.3 Technical Standard Interfaces. . . . . 451  
 11.3.1 Serial Port . . . . . 451  
 11.3.2 Parallel Port. . . . . 452  
 11.3.3 USB . . . . . 453  
 11.3.4 FireWire: IEEE 1394 . . . . . 454  
 11.3.5 Ethernet. . . . . 454  
 11.3.6 Measurement Equipment and Multifunctional  
 Interface Cards. . . . . 455



- 11.3.7 HIL Systems . . . . . 455
- 11.4 Final Remarks on Interface Technology . . . . . 455
- References . . . . . 456
- 12 Software Design for Virtual Reality Applications. . . . . 457**
  - Alexander Rettig
  - 12.1 Overview About the Subject “Virtual Reality” . . . . . 458
    - 12.1.1 Immersion . . . . . 458
    - 12.1.2 Natural Interaction . . . . . 458
    - 12.1.3 Natural Object Behavior . . . . . 459
  - 12.2 Design and Architecture of VR Systems . . . . . 461
    - 12.2.1 Hardware Components . . . . . 461
    - 12.2.2 Device Integration and Device Abstraction . . . . . 462
    - 12.2.3 Software Components . . . . . 464
    - 12.2.4 Simulation . . . . . 466
    - 12.2.5 Subsystems for Rendering . . . . . 469
    - 12.2.6 Decoupling of the Haptic Renderer from Other  
Sense Modalities . . . . . 471
    - 12.2.7 Haptic Interaction Metaphors . . . . . 473
  - 12.3 Algorithms. . . . . 474
    - 12.3.1 Virtual Wall. . . . . 476
    - 12.3.2 “Penalty” Methods . . . . . 479
    - 12.3.3 Constraint-Based Methods . . . . . 481
    - 12.3.4 6 DoF Interaction: Voxmap-PointShell Algorithm . . . . . 484
    - 12.3.5 Collision Detection . . . . . 490
  - 12.4 Software Packages for Haptic Applications . . . . . 497
  - 12.5 Perception-Based Concepts for VR software . . . . . 499
    - 12.5.1 Event-Based Haptics . . . . . 499
    - 12.5.2 Pseudo-haptic Feedback . . . . . 499
  - 12.6 Conclusion. . . . . 500
  - References . . . . . 500
- 13 Evaluation of Haptic Systems . . . . . 503**
  - Carsten Neupert and Christian Hatzfeld
  - 13.1 System-Centered Evaluation Methods . . . . . 504
    - 13.1.1 Workspace. . . . . 505
    - 13.1.2 Output Force-Depending Values. . . . . 505
    - 13.1.3 Output Motion-Depending Values. . . . . 508
    - 13.1.4 Mechanical Properties . . . . . 508
    - 13.1.5 Impedance Measurements . . . . . 509
    - 13.1.6 Special Properties. . . . . 511
    - 13.1.7 Measurement of Psychophysical Parameters. . . . . 511
  - 13.2 Task-Centered Evaluation Methods. . . . . 512
    - 13.2.1 Task Performance Tests . . . . . 512

- 13.2.2 Identification of Haptic Properties and Signals. . . . . 514
- 13.2.3 Information Input Capacity (Fitts' Law) . . . . . 516
- 13.3 User-Centered Evaluation Methods. . . . . 518
  - 13.3.1 Workload . . . . . 518
  - 13.3.2 Subjective Evaluation . . . . . 520
  - 13.3.3 Learning Effects. . . . . 521
  - 13.3.4 Effects on Performance in Other Domains. . . . . 521
- 13.4 Conclusion. . . . . 522
- References . . . . . 522
  
- 14 Examples of Haptic System Development . . . . . 525**
  - Limin Zeng, Gerhard Weber, Ingo Zoller, Peter Lotz,  
Thorsten A. Kern, Jörg Reisinger, Thorsten Meiss, Thomas Opitz,  
Tim Rossner and Nataliya Stefanova
  - 14.1 Tactile You-Are-Here Maps. . . . . 526
    - 14.1.1 Introduction . . . . . 526
    - 14.1.2 The TacYAH Map Prototype . . . . . 527
    - 14.1.3 Evaluation . . . . . 532
    - 14.1.4 Conclusion and Outlook . . . . . 532
  - 14.2 Automotive Interface with Tactile Feedback . . . . . 532
    - 14.2.1 Context . . . . . 533
    - 14.2.2 The Floating TouchPad of Mercedes Benz . . . . . 534
    - 14.2.3 Actuator Design . . . . . 536
    - 14.2.4 Evaluation . . . . . 541
    - 14.2.5 Discussion and Outlook. . . . . 544
  - 14.3 HapCath: Haptic Catheter . . . . . 546
    - 14.3.1 Introduction . . . . . 546
    - 14.3.2 Deriving Requirements . . . . . 547
    - 14.3.3 Design and Development. . . . . 548
    - 14.3.4 Verification and Validation . . . . . 551
    - 14.3.5 Conclusion and Outlook . . . . . 552
  - References . . . . . 552
  
- 15 Conclusion . . . . . 555**
  
- Appendix A: Impedance Values of Grasps. . . . . 557**
  
- Appendix B: URLs . . . . . 559**
  
- Glossary . . . . . 565**
  
- Index . . . . . 567**

# Symbols

$a$	Sensory background noise (Weber's Law) (-)
$a$	Acceleration ( $\frac{\text{m}}{\text{s}^2}$ )
$\mathbf{a}$	Vector, summarizing actuator displacement and angles $a_i$ (-)
$A$	Area, cross section ( $\text{m}^2$ )
$A(j\omega)$	Amplitude response (Chap. 7) (dB)
$\mathbf{A}$	Matrix of a linear system of equations (-)
$\alpha$	Positive number (-)
$\alpha$	Angle, Euler rotation (around the $x$ -axis) (degree, radian)
$\alpha_{VK}$	Coefficient of thermal expansion ( $\text{K}^{-1}$ )
$b$	Wave impedance
$B, B_0$	Magnetic flux density (T)
$\mathbf{B}_r$	Remanence flux density (T)
$\mathbf{B}$	Matrix of a linear system of equations (-)
$\beta$	Angle, Euler rotation (around the $y$ -axis) (degree, radian)
$c_{\text{index}}$	Arbitrary constant, further defined by index (-)
$c$	Spring constant (-)
$c_\theta$	Threshold parameter of the psychometric function (-)
$c_\sigma$	Sensitivity parameter of the psychometric function (-)
$c_\lambda$	Decision criterion (Signal Detection Theory) (-)
$C_{ijlm}$	Elastic constants ( $\frac{\text{m}^2}{\text{N}}$ )
$C, C_Q$	Capacity ( $F = \frac{\Delta s}{V}$ )
$C_b$	Coupling capacity (at mechanical full-stop) (F)
$C$	Transmission elements, controller (Chap. 7) (-)
$\mathbf{C}$	Matrix of a linear system of equations (-)
$\frac{\Delta C}{C_0}$	Capacity change (-)
$\mathbb{C}$	Complex numbers (-)

$d$	Damping/friction $\left(\frac{\text{N}}{\text{m}\cdot\text{s}}\right)$
$d$	Distance, deflection, diameter (m)
$d_{ij,k}, d_{im}$	Piezoelectric charge constant $\left(\frac{\text{V}}{\text{m}}\right)$
$\frac{d_i}{d}$	Detectability (Signal Detection Theory) (-)
$D$	Density
$D$	Dielectric flux density ( $\text{A s m}^{-2}$ )
<b>D</b>	Dielectric displacement/electrical displacement density $\left(\frac{\text{C}}{\text{m}^2}\right)$
<b>D</b>	(transmission-) Matrix of a linear system of equations (-)
$\Delta D$	Position-discrete resolution (-)
$\delta$	Phase difference (Sect. 10.1) (-)
$e$	Piezoelectric voltage coefficient $\left(\frac{\text{A}\cdot\text{s}}{\text{m}^2}\right)$
$\mathbf{e}_i$	Directional unit vector (-)
$E$	E-modulus, modulus of elasticity $\left(\frac{\text{N}}{\text{m}^2}\right)$
$E$	Electrical field strength $\left(\frac{\text{V}}{\text{m}}\right)$
$\underline{\varepsilon}_T$	Absolute transparency error (Sect. 7.4.2) (-)
$\underline{\varepsilon}_T^i$	Relative transparency error (Sect. 7.4.2) (-)
$E_{ref}$	Reference field strength, with $C_s$ of an ERF being given $\frac{\text{V}}{\text{m}}$
<b>E</b>	Electrical field $\left(\frac{\text{V}}{\text{m}}\right)$
$\varepsilon$	Permittivity ( $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$ ) $\left(\frac{\text{A}\cdot\text{s}}{\text{V}\cdot\text{m}}\right)$
$\varepsilon$	Relative dielectric constant of piezoelectric material (at constant mechanical tension) $\left(\frac{\text{A}\cdot\text{s}}{\text{V}\cdot\text{m}}\right)$
$\varepsilon$	Remaining error (Chap. 7) (-)
$\varepsilon_0$	Electrical field constant $\left(\varepsilon_0 = 8,854 \cdot 10^{-12} \frac{\text{C}}{\text{V}\cdot\text{m}}\right)$
$\varepsilon_r$	Relative permittivity ( $\varepsilon_r = \frac{E_0}{E}$ ) (-)
$f$	Frequency (Hz)
$f_0, f_R$	Resonance-frequency (Hz)
$f_b, f_g$	Border-frequency (Hz)
$f_{tot}$	Sum of all joint degrees-of-freedom of a mechanism (-)
$f_{i,\dots,g}$	Degree-of-freedom of the $i$ th joint in a mechanism (-)
$f_{id}$	Sum of all identical links in a mechanism (-)
$f_{ink}$	Dynamics of the detection of all increments for positioning measurement (Hz)
$f(\cdot)$	Static non-linearity (-)
$F$	Bearing-/movement-DOF of a mechanism (-)
$F$	Force (-)
$\Delta F$	Force-resolution (N)

$\Phi$	Magnetic flux (Wb = V · s)
$\phi(j\omega)$	Phase plot (degree)
$\phi$	Roll angle, rotation (around $z$ -axis) (degree, radian)
$\varphi$	Angle (degree)
$\varphi_R$	Phase margin (degree)
$\Phi$	Stimulus (–)
$\Psi$	Subjective percept (–)
$g$	Number of joints in a mechanism (Chap. 8) (–)
$g$	Piezoelectric constant $\left(\frac{\text{V}\cdot\text{m}}{\text{N}}\right)$
$g(x, u, t)$	Transfer function (time domain)
$G(s), \underline{G}$	Transfer function in LAPLACE domain (–)
$\gamma$	Angle, Euler rotation (around the $z$ -axis) (degrees, radians)
$\dot{\gamma}$	Shear-rate ( $\text{s}^{-1}$ )
$h$	Height (m)
$h$	Viscous damping/friction (network theory, see Table 4.1) (–)
$h(t)$	Transfer function (–)
$\underline{h}$	Mobility $\underline{h} = \frac{1}{\underline{z}}\left(\frac{\text{m}}{\text{N}\cdot\text{s}}\right)$
$h$	Element of the complex hybrid matrix $\mathbf{H}$ (–)
$\mathbf{H}$	Complex hybrid matrix (Chap. 7) (–)
$H_c$	Coercitive field strength $\left(\frac{\text{A}}{\text{m}}\right)$
$\mathbb{H}$	Hamilton numbers (–)
$i, \underline{i}$	(AC) Current (A)
$I$	(DC) Current (–)
$\mathbf{I}, \mathbf{I}'$	Interaction path <i>intention</i> (Sect. 2.3) (–)
$I_D$	Index of difficulty (Sect. 13.2) (–)
$I_p$	Index of performance (Sect. 13.2) (–)
$I$	Moment of inertia ( $\text{m}^4$ )
$j, i$	Imaginary unit, $i = \sqrt{-1} \in \mathbb{C}$ (–)
$J$	Current density $\left(\frac{\text{A}}{\text{m}^2}\right)$
$\mathbf{J} = \frac{\partial \mathbf{x}}{\partial \mathbf{q}}$	JACOBIAN matrix defined by the relation of actuator and TCP speeds (–)
$k$	Spring constant, mechanical stiffness, elasticity ( $\text{N m}^{-1}$ )
$k$	Geometrical design dependent constant of ERFs ( $\text{m} \cdot \text{s}$ )
$k$	Fill-factor of a coil ( $\geq 1$ ) (–)
$k$	Coupling-factor or k-factor (Sect. 10.1) (–)
$k$	Number of chains in a mechanism (–)
$k_M$	Motor constant (–)
$K_{krit}$	Critical amplification
$K_R$	Amplification of a proportional controller
$\kappa$	Conditioning number of a mechanism (–)

$l$	Length (m)
$L$	Inductivity $\left(\text{H} = \frac{\text{V}\cdot\text{s}}{\text{A}}\right)$
$\lambda$	Pole of a transfer function (-)
$\lambda$	Wavelength (m)
$\lambda$	Eigenvalue of a matrix (-)
$m$	Mass (kg)
$M$	Torque (Nm)
$\mu$	Movability of a charge-carrier $\left(\frac{\text{m}^2}{\text{V}\cdot\text{s}}\right)$
$\mu$	Frictional coefficient (-)
$\mu$	Mean value (-)
$\mu$	Magnetic permeability $\left(\mu = \mu_0 \cdot \mu_r\right)\left(\frac{\text{V}\cdot\text{s}}{\text{A}\cdot\text{m}}\right)$
$\mu_0$	Magnetic field constant $\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{V}\cdot\text{s}}{\text{A}\cdot\text{m}}$
$\mu_r$	Relative permeability (-)
$n, N$	Number $\in \mathbb{N}$ (-)
$n = \frac{1}{k}$	Compliance (m N <sup>-1</sup> )
$n_0, n_i$	Refraction index (-)
$\mathbb{N}$	Natural numbers
$\nu$	Global conditioning index (-)
$\omega = 2\pi f$	Angular frequency (rad s <sup>-1</sup> )
$\underline{\omega}, \underline{\Omega}$	Angular velocity $\left(\frac{\text{rad}}{\text{s}}\right)$
$p$	Pressure $\left(\frac{\text{N}}{\text{m}^2}\right)$
$p$	Probability (-)
$p_L$	Lapse rate of the psychometric function (-)
$p_G$	Guess rate of the psychometric function (-)
$p_\psi$	Psychometric function (-)
$P$	Dielectric polarization $\left(\frac{\text{C}}{\text{m}^2}\right)$
$P$	Power (-)
$P_g$	Degree of parallelism (-)
$\mathbf{P}, \mathbf{P}'$	Interaction path <i>Perception</i> (Sect. 2.3) (-)
$\pi$	Piezoresistive coefficient $\left(\frac{\text{m}^2}{\text{N}}\right)$
$\pi_l$	Piezoresistive coefficient in longitudinal direction $\left(\frac{\text{m}^2}{\text{N}}\right)$
$\pi_q$	Piezoresistive coefficient in transversal direction $\left(\frac{\text{m}^2}{\text{N}}\right)$
$\psi$	Yaw angle, rotation around $x$ -axis (degree, radian)
$\Psi$	Subjective percept (-)
$q, Q$	Electrical charge (C = A · s)
$q_i, i \in \mathbb{N}$	Driven joint $i$
$q$	Fluidic volume flow (-)

$\mathbf{q}$	Vector of actor coordinates (-)
$r$	Distance, radius (m)
$r_i, i \in \mathbb{N}$	Active resistors ( $\Omega = \frac{V}{A}$ )
$R$	Electrical resistance ( $\Omega$ )
$R_m$	Magnetic resistance/reluctance ( $\frac{A}{V \cdot s}$ )
$\mathbb{R}$	Real numbers (-)
$\Re$	Real part (-)
$\frac{dR}{R_0}$	Relative resistance change (-)
$\Delta R_{inch}$	Position resolution given in dots-per-inch (dpi)
$\Delta R_{mm}$	Position resolution given in millimeter (mm)
$\rho$	Density ( $\frac{kg}{m^3}$ )
$\rho$	Small number $\geq 0$ (-)
$\rho$	Specific resistance/conductivity ( $\Omega \cdot m$ )
$s(t), \underline{s}$	Arbitrary signal in time and frequency domain (-)
$s$	Elasticity coefficient at a constant field strength ( $\frac{m^2}{N}$ )
$s$	LAPLACE operator, $s = \sigma + j\omega$ (-)
$S$	Mechanical stress ( $m \cdot m^{-1}$ )
$S$	Number of constraints in a mechanism (-)
$\sigma$	Conductivity, $\sigma = \frac{1}{\rho} \left( \frac{S}{m} = \frac{A}{V \cdot m} \right)$
$\sigma$	Singular value of a matrix (-)
$t$	Time/point in time (s)
$tr$	Transmission ratio of a gear (-)
$T$	Mechanical tension ( $\frac{N}{m^2}$ )
$T$	Time constant, time delay (s)
$\tau$	Shear force (Chap. 9) (N)
$\tau$	Time constant of the step response of an electrical transmission system ( $\tau = \frac{L}{R}, \tau = \frac{1}{RC}$ ) (s)
$\tau$	Torque (Chap. 8) (N m)
$\theta$	Pitch angle, rotation about the y-axis (degree, radians)
$\Theta$	Magnetomotive force (A)
$\vartheta$	Temperature (K)
$u(t)$	(AC) Voltage (V)
$U$	(DC) Voltage (V)
$\mathbf{u}$	Multidimensional input value of a linear system (-)
$v$	Velocity ( $m \cdot s^{-1}$ )
$V$	Magnetic tension, magnetic voltage (A)
$V$	Volume ( $m^3$ )
$V_x$	LYAPUNOV function (Chap. 7) (-)
$V(\mathbf{x})$	Scalar nonlinear positive definite storage function of system states $\mathbf{x}$
$\dot{V}$	Volume flow ( $\frac{m^3}{s}$ )

$\Delta V$	Volume-element ( $\text{m}^3$ )
$w$	General value for in- and output values (-)
$\mathbf{w}$	Unity vector (-)
$W$	Work, energy ( $\text{J} = \frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$ )
$x$	Distance, displacement, translation, amplitude, elongation, position (m)
$\mathbf{x} = (x, y, z)$	Cartesian coordinates (-)
$\mathbf{x}$	Inner states of a linear system (-)
$\mathbf{x}$	Vector of TCP coordinates (position and orientation) (-)
$\Delta x$	Position resolution (m)
$X$	Transformation constant (-)
$\xi$	Displacement (m)
$y$	Control value (-)
$y$	Output (-)
$\mathbf{y}$	Multidimensional output value of a linear system (-)
$Y$	Gyratoric transformation constant (-)
$\underline{Y}$	Mechanical admittance ( $\frac{\text{m}}{\text{N}\cdot\text{s}}$ )
$z$	Disturbance variable (-)
$\underline{Z}$	Mechanical impedance ( $\frac{\text{N}\cdot\text{s}}{\text{m}}$ )
$\underline{Z}$	Electrical impedance ( $\text{V A}^{-1}$ )

## Indices and Distinctions

The usage of the most relevant indices and distinctions used throughout the book is shown using the replacement character  $\blacksquare$

$\blacksquare_0$	Base or reference value
$\blacksquare_E$	Referring to the real or VR environment
$\blacksquare_H$	Referring to the master side of a teleoperator (probably derived from “handle”)
$\blacksquare_M$	Referring to the master device of a haptic system
$\blacksquare_{max}$	Maximum value
$\blacksquare_{min}$	Minimum value
$\blacksquare_{rot}$	Referring to a rotational value
$\blacksquare_S$	Referring to the slave device of a haptic system
$\blacksquare_T$	Referring to the master side of a teleoperator
$\blacksquare^T$	Transformed vector or matrix
$\blacksquare_{trans}$	Referring to a translational value
$\blacksquare_{user}$	Referring to the user of a haptic system
$\delta\blacksquare$	Small change, differential
$\Delta\blacksquare$	Discretized element
$\blacksquare_\theta$	Referring to a psychophysical threshold



$\mathbf{X}$	Vector or matrix
$\blacksquare(t)$	Time-dependent value
$\underline{\blacksquare}$	Complex value with amplitude/phase or real/imaginary part
$\dot{\blacksquare}$	Derivative with respect to time

# Abbreviations

AAL	Ambient Assisted Living, term for technical systems used to support needy people in daily life
ALARP	As Low as Reasonably Practicable, general decision principle used in risk analysis
API	Application Programming Interface
COTS	Commercial off-the-shelf Products or Devices
DoF	Degrees of freedom, the number of independent motions that can be carried out by a body or mechanism
EMG	Electromyography, non-invasive method to record muscular activity based on the electric potential generated by muscle cells
ERF	Electro-Rheological Fluid, fluid changing its rheological properties when exposed to an electric field
FDA	United States Food and Drug Administration
FEM	Finite Element Method or Finite Element Model
FTA	Fault Tree Analysis, method to identify risks during the development of a system
GUM	Guide to the Expression of Uncertainty in Measurement, ISO/IEC Guide 98-3
HCI	Human-Computer-Interaction
IEC	International Electrotechnical Commission, international organization issuing standards and conformity assessment for electrical, electronics and related technologies, <a href="http://www.iec.ch">www.iec.ch</a>
IEEE	Institute of Electrical and Electronics Engineers, professional organization that arranges conferences, publishes journals (like the IEEE Transactions on Haptics) and technology standards. <a href="http://www.ieee.org">www.ieee.org</a>
ISO	International Organization for Standardization, organization for the development of technical standards with head office in Geneva, CH. <a href="http://www.iso.org">www.iso.org</a>
IT	Information Transfer, measure of the ability of a haptic display to convey information from system to user

JND	Just Noticeable Difference, psychometric parameter describing the smallest detectable difference $\Delta\Phi$ from a base stimulus $\Phi_0$ that can be detected by a person
LCT	Lane Change Test, test to simulate in vehicle secondary task demands, standardized in ISO 26022
MRF	Magneto-Rheological Fluid, fluid changing its rheological properties when exposed to an magnetic field
MRI	Magnetic Resonance Imaging, non-invasive imaging technique based on the magnetic spin properties of—mostly—hydrogen atoms
PDE	Partial Differential Equations
PWM	Pulse-Width-Modulation
QS	Quasi-Static, i.e., with a small low border frequency limited by the duration of the measurement
SDT	Signal Detection Theory, approach to describe decision and perception processes mainly based on statistical modeling
SIL	Safety Integrity Level, assessment of the reliability of safety functions according to IEC 61508
SISO	Single Input, Single Output (model)
TCP	Tool Center Point, reference point for kinematic and dynamic measures
TPM	Translational Parallel Machines, mechanisms, whose TCP can only move in three Cartesian coordinates $(x, y, z)$
TPTA	Telepresence and Teleaction
VR	Virtual Reality

# Contributors



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