

BIOELECTRONIC VISION

Retina Models, Evaluation Metrics, and System Design

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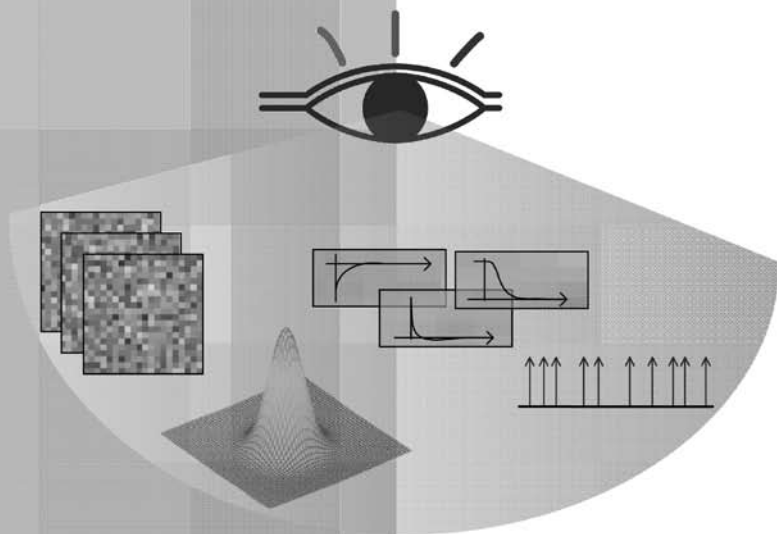
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To our families

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Preface

Vision is one of the most important senses for the human being. Blindness can be a serious impairment, preventing a person from having an ordinary life. It restricts one of the most important streams of information from the world, thus limiting any communication made through visual expression and visual arts. What is commonly understood as vision relies on a very complex system integrating the eyes, the optical nerve and the brain. Research continues in order to gain a better understanding of the structure and operation of the visual system components: the retina, the lateral geniculate nucleus, and the visual cortex. The retina is a crucial layer in the vision process, while the visual cortex is the main brain visual processing area. One of the final goals, and the most expected result of the current research effort, is the development of artificial vision systems that can restore vision to blind people. The latest advances in electronics and biology have opened new possibilities that will finally allow bio-inspired electronic devices and systems to be designed that partially replace damaged parts of the visual system. This challenging domain, which gathers knowledge from distinct disciplines, including biology, neurology, and engineering, is called *BioElectronic Vision*.

A fully functional bioelectronic vision system that provides vision restoration to completely blind people is not yet available. Since the road ahead is mainly unknown, we have to increase current knowledge and improve practices in small steps. One of the required steps is the writing of books and monographs that present, synthesize and analyze current knowledge in all the distinct domains of bioelectronic vision. This work is a contribution towards this goal. The central goals of this book are: *i*) to establish a background for an engineering audience on the physiological constitution of the human visual system; *ii*) to present the different classes

of computational retina models, *iii*) to analyze the neural activity metrics; and finally, *iv*) to discuss the electronic devices and circuits required to implement a bioelectronic vision system and metrics to determine how well it accomplishes its goal.

This book is intended to be used as a reference for those involved in the area of bioelectronic vision, in particular in modeling the retina behavior and in the design of embedded systems that underlie visual neuroprostheses. It can also be used as a textbook for first-year graduate or senior courses on advanced signal processing for artificial vision. Codification of the information in visual systems and visual prostheses are frequently topics found in bioengineering and electrical engineering curricula. We assume the reader has a basic knowledge of signal processing and programming, as might be learned with some job experience or as part of a first undergraduate course in these topics.

While keeping the goal in mind - the implementation of an electronic visual prosthesis for bioelectronic vision - the anatomy and operation of the retina as well as the main features of the neuronal responses are presented. Retina models, representative of different model classes, are presented and a framework for training, evaluating and comparing them is established. This framework includes a set of different metrics that allows the testing and evaluation of not only the actual models, but also new retina models that will almost certainly be proposed in the future. The book follows a digital signal processing perspective, where all models and metrics are discretized, implemented, and tested in a computer environment. These computational models and programs can be implemented in an embedded system specifically designed to be an electronic visual prosthesis. The final chapter of this book is devoted to the technological challenges needed to adapt these embedded systems into artificial visual systems that can thus be used to restore visual sense to blind people.

This book was prepared to be read from cover to cover. However, while reading each chapter in order, one can skip a chapter depending on the reader's background and the chapter's purpose. Chapter 1 provides an overview of the topics related to bioelectronic vision, namely the building blocks of the visual system, the characteristics and causes of blindness, and the main components of a neuroprosthesis. Chapter 2 describes the human visual system and identifies the main classes of retina models. (This chapter can be skipped if the reader has a good background in the anatomy and operation of the human visual system.) Chapter 3 is devoted to the establishment of the required background in order to analyze neural systems in

general, and the retinal neural code in particular. Chapter 4 is dedicated to the description and analysis of the considered functional and structural classes of retina models. Chapter 5 provides a set of collected neural activity metrics, which are used throughout the book to train, test and evaluate the retina models. This chapter also presents experimental data and gives some insights into the metric's performance and its drawbacks. Chapter 6 concludes the book by presenting the main electronic components required to prototype a bioelectronic system, while discussing the principal technological features of its implementation. Chapter 5 and Chap. 6 are chiefly important for people interested in the implementation of artificial retinas and visual neuroprostheses. Each book chapter is accompanied by a group of exercises that allows the reader to evaluate his/her knowledge while guiding the reader through the implementation of the methods, algorithms and techniques presented in the book. These exercises can be a valuable instrument for instructors using the book for teaching.

The participation of the authors during the last years in research projects to develop Bioelectronic Vision systems has given them the opportunity to have a central perspective on the research in this area – namely the project "Cortical Visual Prosthesis for the Blind" (CORTIVIS), supported by the Commission of the European Communities, and the "Retinal Neural Code: Accurate Modeling Toward an Artificial Visual System" (RNC) project, supported by the Portuguese Foundation for Science and Technology (FCT). We did our best to provide both solid theoretical support and all the information needed to apply this knowledge to the design of bioelectronic vision systems. Our main goal is to contribute to the education of the next generation of researchers in this new multidisciplinary area of bioelectronic vision. We really hope you find the book useful!

João C. Martins
Leonel A. Sousa

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Acknowledgments

This book is not by any means an individual work, but instead it is a reflection of different contributions from many people.

We want to express our gratitude to the members of the Signal Processing Systems (SIPS) research group of the Instituto de Engenharia de Sistemas e Computadores - Investigação e Desenvolvimento em Lisboa INESC-ID for the friendly and challenging work environment. In particular, we want to thank Pedro Tomás for the fruitful discussions and suggestions, José Germano for implementing the retina models in the FPGA, and Moisés Piedade for the electronics necessary to implement the wireless link and the stimulator in the presented prototype.

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Contents

<i>Preface</i>	vii
<i>Acknowledgments</i>	xi
<i>List of Figures</i>	xvii
<i>List of Tables</i>	xxi
<i>List of Acronyms</i>	xxiii
1. Introduction to Bioelectronic Vision	1
1.1 Main Causes of Blindness	2
1.2 Main Components of a Bioelectronic Vision System	5
1.3 Classification of Visual Prostheses	10
1.3.1 Retinal Neuroprosthesis	12
1.3.2 Cortical Visual Neuroprosthesis	14
1.4 Conclusions and Further Reading	15
2. The Human Visual System	21
2.1 Introduction	21
2.2 The Neuron	22
2.2.1 Neuron Anatomy	22
2.2.2 Neuron Dynamics	23
2.3 The Human Visual System	28
2.3.1 The Eye	29
2.3.2 The Retina	31
2.3.3 How the Retina Operates	37
2.3.4 The Visual Pathway	44

2.4	Modeling the Retina	49
2.4.1	The Retina Neural Code	49
2.4.2	Classification of Retina Models	52
2.5	Conclusions and Further Reading	54
3.	Characterization of the Neural Response	57
3.1	Introduction	57
3.2	Spikes: The Essence of the Neural Code	58
3.2.1	Retina Stimulation and Responses Recording	60
3.2.2	Spike Trains and Firing Rates	71
3.2.3	Spike Triggered Average	83
3.2.4	Spike Train Autocorrelation Function	87
3.2.5	The Spike Triggered Covariance	89
3.3	Stimulus and Response Statistics, and Firing Probabilities	90
3.3.1	Spike Train Statistics	92
3.3.2	Homogeneous Poisson Model of Spike Trains	93
3.3.3	Inhomogeneous Poisson Model of Spike Trains	100
3.3.4	Spike-Count Statistics	102
3.4	Spiking Mechanisms	103
3.4.1	Generation of Poisson Spike Trains	104
3.4.2	Integrate-and-Fire Spike Generation	105
3.5	Conclusions and Further Reading	107
4.	Retina Models	113
4.1	Introduction	113
4.2	Classification of Retina Models	113
4.3	Structural Models	115
4.3.1	The Integrate and Fire Model	115
4.3.2	The Leaky Integrate-and-Fire Model	118
4.4	Functional Models	123
4.4.1	Deterministic Models	124
4.4.2	Stochastic Models	129
4.4.3	White Noise based Models	138
4.5	Conclusions and Further Reading	145
5.	Neural Activity Metrics and Models Assessment	155
5.1	Introduction	155
5.2	The Metric Definition	155

5.3	Firing Rate Metrics	156
5.3.1	Mean Squared Error	156
5.3.2	Normalized Mean Squared Error	157
5.3.3	Percent Variance Accounted For	158
5.3.4	Analysis of the Firing Rate Metrics	159
5.4	Spike Train Metrics	160
5.4.1	Spike Time Metric	161
5.4.2	Interspike Interval Metric	166
5.4.3	Spike Train Distance Metric	170
5.4.4	Spike Train Metrics Analysis	174
5.5	Spike Events Metrics	177
5.5.1	Spike Events Metric Analysis	187
5.6	Tuning and Assessment of Retina Models	188
5.6.1	Deterministic Model	189
5.6.2	Stochastic Model	191
5.6.3	White Noise Model	191
5.7	Conclusions and Further Reading	193
6.	Design and Implementation of Bioelectronic Vision Systems	199
6.1	Retinal Prostheses	199
6.1.1	Epiretinal Implants	200
6.1.2	Subretinal Implants	202
6.2	Retinal Bioelectronic Vision System Design	204
6.3	Cortical Visual Prostheses	208
6.4	Cortical Bioelectronic Vision System Design	212
6.4.1	Early Layers	213
6.4.2	Neuromorphic Pulse Coding	217
6.4.3	Spike Multiplexing	218
6.4.4	Serial Communication Link	221
6.5	Vision Prosthesis Prototype	223
6.6	Conclusions and Further Reading	226
	<i>Bibliography</i>	233
	<i>Index</i>	241

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List of Figures

1.1	Causes of blindness in the world.	3
1.2	World map of vision neuroprosthesis groups.	6
1.3	Diagram of the human visual system.	7
1.4	Main components of a visual neuroprosthesis.	8
1.5	Main components of a retinal neuroprosthesis	13
2.1	Neuron anatomy.	24
2.2	Propagation of an action potential along a neuron's axon.	25
2.3	Neuron gap junction.	28
2.4	Diagram section of the human eye.	29
2.5	Light micrograph of a vertical section through the retina.	32
2.6	Simplified schematic organization of the retina.	33
2.7	Photoreceptors' spectral sensitivity.	34
2.8	Spatial distribution of photoreceptors.	34
2.9	Photographs of the cross section of the fovea and of the foveal periphery.	35
2.10	Human retina photograph.	36
2.11	The receptive field of a cone.	38
2.12	Photoreceptor to bipolar cell connections.	39
2.13	Connections of a horizontal cell.	41
2.14	Connections between bipolar cells and ganglion cells.	42
2.15	AII amacrine cell connections.	44
2.16	Visual pathways	46
2.17	Lateral geniculate nucleus cell layers	47
3.1	Representation of a spike train.	58
3.2	Spike waveform of a ganglion cell from a rabbit's retina.	59
3.3	Neuronal response function of a retinal ganglion cell.	59

3.4	Cellular recording of neuronal signals.	61
3.5	Rabbit type-ON RGC responses for a ON-OFF full-field stimulus.	63
3.6	Salamander type-ON RGC responses for sampled white-noise full-field stimulus.	64
3.7	Spatially uniform visual stimuli.	65
3.8	Spatially non-uniform visual stimuli.	65
3.9	Spatially nonuniform Gabor functions.	66
3.10	Stimuli with spatial and temporal modulation.	67
3.11	Gaussian white noise stimulus sequence with spatial, temporal and chromatic variation.	68
3.12	Spatially non-uniform visual stimuli	69
3.13	Microelectrode array.	69
3.14	Experimental apparatus for retina data acquisition and analysis.	70
3.15	Retina preparation for data acquisition.	71
3.16	The δ_{Δ} function.	73
3.17	Neural spike trains from a Salamander ON-type retinal ganglion cell and the stimulus	74
3.18	Firing rate ON-type RGC.	75
3.19	The rectangular (boxcar) filter window.	79
3.20	The Gaussian filter window.	80
3.21	The α function filter.	81
3.22	Firing rate obtained by filtering the neural response with different types of filter windows.	82
3.23	Procedure for the STA computation.	84
3.24	Spike triggered average time reversed	85
3.25	Spike number probability density for a train described by a homogeneous Poisson process.	95
3.26	Interspike time interval exponential probability density for a spike train described by a homogeneous Poisson process.	95
3.27	Integrate-and-fire spike generation from firing rate.	106
4.1	The leaky integrate-and-fire (LI&F) model.	116
4.2	Integrate and fire model's responses for constant input stimulus current	117
4.3	Leaky integrate-and-fire model's response for constant input stimulus current	120
4.4	Firing rate versus the stimulus current for integrate-and-fire models.	122
4.5	Integrate-and-fire model of the retina.	123

4.6	Block diagram of the deterministic model.	124
4.7	Discrete spatial DoG.	128
4.8	Block diagram of the pseudo-stochastic model.	130
4.9	Distorted sinus basis functions.	133
4.10	Spike triggered average represented by bases functions.	134
4.11	Generation of a noise sequence with a specific autocorrelation.	137
4.12	The white noise model structure	138
4.13	White noise model characterization of a salamander and of a rabbit RGC.	144
4.14	Function integral between nT_s and $(n + 1)T_s$	149
4.15	Forward rectangular approximation for the integral.	149
4.16	Trapezoidal approximation for the integral.	149
4.17	Backward approximation for the integral.	149
5.1	Comparison of two firing rates.	157
5.2	Comparing smoothed and not smoothed PSTHs.	161
5.3	Comparison of two spike trains.	161
5.4	Path to transform a spike train into the other in the spike time metric.	163
5.5	Path to transform a spike train into another in the interspike interval metric.	167
5.6	Changing of the spike shape for comparison with the spike distance metric.	172
5.7	Evolution of the spike time and interspike metrics for a set of spike trains for a salamander ON-type RGC.	175
5.8	Distance metric between a salamander ON-type RGC responses.	177
5.9	Parsing a set of spike trains into firing events.	178
5.10	Characterization of spike trains into firing events.	181
5.11	Deterministic model responses, when tuned with the NMSE and with the spike events metrics, to the flash stimulus.	190
5.12	Deterministic model responses, when tuned with the NMSE and with the spike events metrics, to the white noise stimulus.	190
5.13	Stochastic model responses when tuned with the NMSE and with the spike events metrics to the flash stimulus.	191
5.14	Responses of the stochastic model to the white noise stimulus, when tuned with the NMSE and spike event metrics.	192
5.15	White noise model responses to the flash and to the white noise stimuli.	192
5.16	Models errors for the ON-OFF stimulus.	193

5.17	Models errors for the white noise stimulus.	194
6.1	IRP test device.	205
6.2	Layout of a retinal implant.	206
6.3	Electrode layout.	209
6.4	A diagram of the Dobelle apparatus.	209
6.5	Microelectrode array.	211
6.6	Bioelectronic vision system based on the CORTIVIS neuroprosthesis.	212
6.7	Modules of the bio-inspired processing module of the artificial retina.	212
6.8	Extended RGB model for replacing natural human retina processing.	213
6.9	Architecture for computing the spatial filter.	214
6.10	Signal flow graphs for the temporal (high pass filter and contrast gain control) and rectifier components for the <i>Early Layers</i> model.	215
6.11	Architecture of the temporal part of the <i>Early Layers</i> model. .	216
6.12	Simplified architecture of the <i>Neuromorphic Pulse Coding</i> module; one register per microelectrode.	217
6.13	Structure of an Address Event Representation (AER) tree and possible implementations for the arbiters.	219
6.14	Architecture of the FIFO based AER module.	220
6.15	Block diagram of the RF link and the <i>Microelectrode Stimulator</i> module.	221
6.16	The RF link.	223
6.17	Elonica prototype vision system.	224
6.18	Matlab code to read and write an AVI file.	230

List of Tables

1.1	Main pros and cons of visual prostheses approaches.	19
5.1	Values of the firing rate metrics applied to salamander ON-type RGC responses.	160
5.2	Limit values for the spike train metrics using the neuronal responses of a ON-type salamander RGC.	175
6.1	FPGA circuit area (from [Piedade <i>et al.</i> (2005)]).	225
6.2	Main features of implants for visual neuroprostheses.	226

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List of Acronyms

AER	Address Event Representation
AGC	automatic gain control
AMD	age-related macular degeneration
ASK	Amplitude Shift Keying
BPSK	Binary Phase Shift Keying
CCD	charged couple device
CDF	cumulative density function
CGC	contrast gain control
CRT	cathode ray tube
DAC	digital-to-analog converter
DoG	difference of Gaussians
EM	Expectation-Maximization
FIFO	First In First Out
FPGA	Field Programable Gate Array
fps	frames-per-second
FSK	Frequency Shift Keying
GCL	ganglion cell layer
I&F	integrate-and-fire
INL	inner nuclear layer
IPL	inner plexiform layer
IRP	Intraocular Retinal Prosthesis
ISI	interspike time interval
LCD	liquid crystal display
LI&F	leaky integrate-and-fire
LGN	lateral geniculate nucleus
LoG	Laplacian of Gaussian
MEA	microelectrode array

MEMS microelectromechanical systems
modDoG modified-difference of Gaussians
MSE mean squared error
NIR near-infrared
NMSE normalized mean squared error
ONL outer nuclear layer
OPL outer plexiform layer
pdf probability density function
pixel picture element
pmf probability mass function
PCA principal component analysis
PSG Poisson spike generator
PSTH peri-stimulus time histogram
RAM random access memory
RF receptive field
RGB red-green-blue
RGC retinal ganglion cell
ROC region of convergence
ROM read only memory
RP retinitis pigmentosa
SFG signal flow graph
STA spike triggered average
STC spike triggered covariance
TFT thin-film transistor
%VAF percent-Variance-Accounted-For
V1 cortex visual area 1
VLSI very large scale integration