

BIOELECTRONIC VISION

Retina Models, Evaluation Metrics, and System Design

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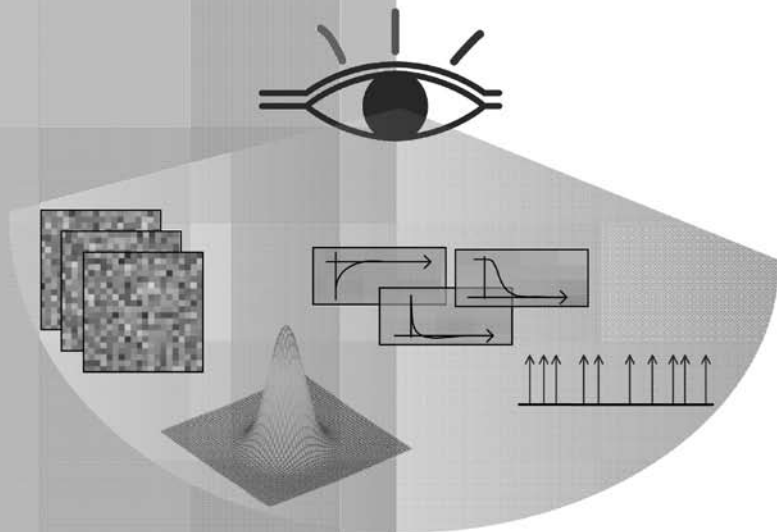
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To our families

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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.

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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