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A design framework to model retinas

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Abstract

Neuro-engineering is providing biomedical engineers with technology to interface the nervous system, which is useful to create prosthetic devices to palliate sensorial or motor disabilities. Motivated by the success of cochlear implants for deaf patients, we are now facing the challenge of creating a prosthetic visual system for the blind. An artificial retina whose response to stimuli can be matched to biological ones is required. To make easier the task of modeling, tuning and testing these retinal models, we have created a software tool that allows flexible and parametric definition and testing of retina-like models. The program can be fed with a variety of video or image sources, and the results can be easily compared to biological recordings of retinal ganglionar activity in response to the same stimuli. This tool can be useful, not only for this prosthetic purpose, but for any other research involving bio-inspired image processing with a neuromorphic output.

Keywords: Retina modeling; Neuro-engineering; Visual prostheses; Neuromorphic encoding; Bio-inspired image processing

1. Introduction

Neural engineering brings together the latest discoveries unveiled by the neural sciences and the new technologies and materials of biomedical engineering to develop devices able to interface the central and peripheral nervous tissue. An overview can be found in Sanguineti et al. (2001). The purpose is to replace or partially recover damaged functionalities like perceptive or motor abilities. Neuro-engineering has lately benefited from the development of new generations of arrays of microelectrodes, allowing for better biocompatibility and finest recording and stimulation of the neural tissue. Cochlear implants are a good example of successful employment of neural engineering devices to restore audition in totally deaf individuals Shepherd (2003). Other therapeutic applications of neural engineering include the electrical stimulation of deep brain structures to alleviate pain or Parkinson's disease, the development of artificial limbs for amputees and the possibility to use EEG or intracortical recordings to control external devices (Cyberhand, 2006; Carmena et al., 2003; Bjarkam et al., 2001; Nicolelis, 2003).

The work presented in this paper has been developed within the framework of a European project, which aims to develop prototypes in the field of visual rehabilitation

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and to demonstrate the feasibility of a cortical neuroprosthesis, interfaced with the visual cortex, as a means through which a limited but useful visual sense may be restored to profoundly blind people. While the full restoration of vision seems to be impossible, the discrimination of shape and location of objects could allow blind subjects to 'navigate' in a familiar environment and to read enlarged text, resulting in a substantial improvement in the standard of living of blind and visually impaired persons.

2. A neuro-engineering tool to design artificial retinas

Several research groups are making efforts in this sense, as the tunable retinal encoder, by Eckmiller et al. (1999), or the computational models of retinal functions described by Koch et al. (1986). The project (cortical visual neuroprosthesis for the blind) (CORTIVIS), funded by the European Commission, had as a main objective the design and development of a reconfigurable software/hardware bioinspired platform able to transform the visual world in front of a blind individual into multiple electrical signals that could be used to stimulate, in real time, the neurons at his/her visual cortex (visit CORTIVIS website for further references). This project brings together the work of physicians, physicists, biologists, neurophysiologists, electronic and computer engineers of five European countries.

As depicted in Fig. 1, the approach of the CORTIVIS project consists of a set of elements, starting with a bioinspired device able to perform some of the image pre-processing functions of the retina. This bioinspired retina will transform the visual world in front of a blind individual into electrical signals that can be used to excite neurons at the occipital cortex. It is expected that the device will be able to enhance the most relevant features of the scene to be sent through a limited-bandwidth channel, and to encode this information in a way that is coherent with the output of ganglion cells in natural retinas, that is, in the form of trains of pulses (spikes). This information will be serialized and sent through a wireless link to make data and energy reach the microelectrodes inserted into the brain cortex. Since signals reaching the cortex from the retina and LGN arrive not at the surface of the cortex but a deepness of 1–2 mm (layer IV), we need intracortical penetrating electrodes with exposed tips located in layer IV and with tip sizes of the same order of magnitude as the excited neurons. For this reason we are using the Utah Electrode Array (UEA), which has 100 microelectrodes, each 1.5 mm long, arranged in a square grid contained in a package 4.2 mm × 4.2 mm. This array of penetrating electrodes has been designed to compromise as little cortical volume as possible Normann et al. (1999).

The stage of the system that performs a restricted retinal processing have to be as similar as possible to the real retina. Thus, the question of how the information about the external world is compressed in the retina, and how this compressed representation is encoded in spike trains is therefore of seminal importance. In this context, we are performing electrophysiological recordings of the responses of many ganglion cells to different spatio-temporal patterns of visual stimuli as we have reported previously Fernandez et al. (2000), Normann et al. (2001), Ortega et al. (2004). These experiments are being developed in turtle, rabbit, rat and human retinas. The objective is to get as much information as possible about the transfer functions of the retina, in order to develop a parametric model that can be applied to the input image, as depicted in Wilke et al. (2001).

In order to approximate such transfer functions, we adopt as a general model of the retina a linear combination of a set of spatio-temporal filters applied to the color and intensity channels of the input image Sekuler and Blake (1994). As an example, if the researcher requires a retina-like processing enhancing yellow versus blue color contrast, plus a border intensification, and remark temporal changes, due to motion, a filtering structure as depicted in Fig. 2 should be composed.

In this figure, R, G and B stand for the red, green and blue channels of the acquired image at an instant

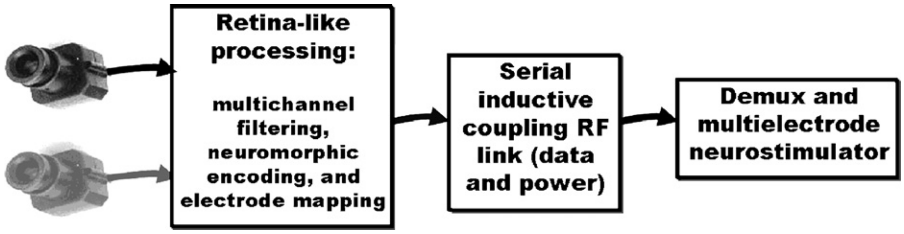

Fig. 1. Main blocks of the CORTIVIS visual prosthesis: (from left to right) one or two camera inputs, filtering and coding, and wireless transmission to one or more implanted microelectrode arrays.

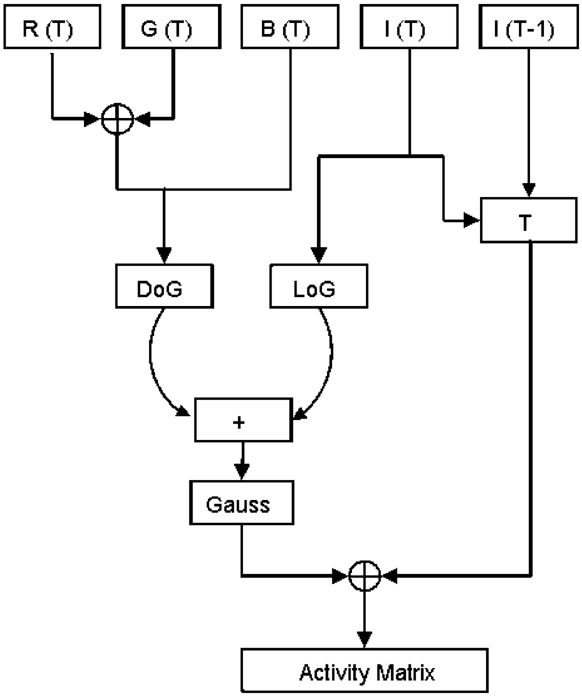

Fig. 2. Example of filter combination to enhance certain image features.

T. I(T) represents the intensity channel of the frame at time *T*. As shown in the schematic representation, the addition of red and green channels (this is, yellow) is compared against the blue channel by means of a Difference-of-Gaussians operator (DoG). A Laplacian-of-Gaussian operator (LoG) is applied to the intensity channel, and changes between consecutive frames are intensified by using a temporal filter. The information enhanced by these operations is combined into an "activity matrix", a form of "saliency map" like the introduced by Itti et al. (1998) in the context of artificial visual attention systems.

Finding out the right transfer function, and adequate values for its parameters is a hard task. To make it easier, we have developed a software platform that allows to simulate and test, in a fast and flexible way, different retinal models. This program gets image sequences from different sources and applies them a set of retino-morphic filters that can be easily defined by the researcher. The system produces as output a multi-channel response in the form of event trains, that can be compared to biological recordings for similar stimuli. This application is even able to automatically sinthesize the definition of a digital circuit implementing, in real time, the retinal processing defined by the user Martínez et al. (2005).

3. Retiner: a software environment to essay and create artificial retinas

Motivated by the need of helping the physicians and neuro-scientists of the CORTIVIS project in finding and tuning a retina model that is coherent with neurophysiological data, we developed Retiner Pelayo et al. (2003). This is the name of the program, developed under Matlab^{TM} (visit Mathworks website for details), designed to build retinal processing models in the form of spatio-temporal filters over image streams, and check the output against the recordings obtained when exposing biological retinas to selected stimuli.

3.1. Image source choices

Retiner is able to process images and video coming from a variety of source images, ranging from still image files in different standard formats (BMP, JPEG, PNG, TIFF, etc.) to AVI video files, or even live-capture from any camera supported by the Microsoft® Video for Windows® driver.

For a complete, autonomous and portable prosthetic visual system, it will be preferable the use of a logarithmic camera (in our case a sensor from (IMSchips)). Its response to high contrast scenes, where both bright and dark objects appear simultaneously, is far superior to common CCD or CMOS image sensors, that get saturated when capturing this kind of scenes (like outdoor image acquisition). Fig. 3 shows the difference between the captures from a commercial webcam versus a logarithmic camera. The results of a retina-like processing over these different inputs yield very distinct outputs. A considerable loss of information can be observed in the case of a linear sensor.

3.2. Multi-channel spatio-temporal filtering

Any incoming frame is separated by Retiner into three color planes (red, green and blue), corresponding to the light wavelengths activating different types of cones in retinas. Then, in a retina model, the function of bipolar cells is applied to color-contrast channels in the form of difference of Gaussians filters.

Retiner offers a variety of bio-inspired pre-defined filters, including spatial filters, as Gaussians (Eq. (1)), difference of Gaussians (Eq. (2)) and laplacian of Gaussians (Eq. (3)), each of them with a number of parameters that can be varied. Nevertheless, the user is not restricted to this catalog of filters. The experimenter can define and save his/her own filters in the form of any Matlab expres-

Fig. 3. A view of a window in a shiny day captured by a CMOS camera (upper-left), a logarithmic camera (upper-middle), and equalized view of the logarithmic image (upper-right). The three lower pictures show the result of applying a retina-like processing to its corresponding upper captures.

sion over the color or intensity channels.

$$G_{\sigma 1}(x, y) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp\left[-\frac{x^2 + y^2}{2\sigma_1^2}\right] \quad (1)$$

$$\begin{aligned} \mathrm{DoG} &= G_{\sigma 1} - G_{\sigma 2} \\ &= \frac{1}{\sqrt{2\pi}}\left[\frac{1}{\sigma_1} \mathrm{e}^{-(x^2+y^2)/2\sigma_1^2} - \frac{1}{\sigma_2} \mathrm{e}^{-(x^2+y^2)/2\sigma_2^2}\right] \end{aligned} \quad (2)$$

$$\mathrm{LoG} = \Delta G_\sigma(x, y) = \frac{x^2 + y^2 - 2\sigma^2}{\sigma^4} \mathrm{e}^{-(x^2+y^2)/2\sigma^2} \quad (3)$$

Natural retinas also detect and respond to temporal changes in the acquired images, as referred by Victor (1999). Retiner implements this temporal enhancement by remarking the differences between two or more consecutive frames of the video stream. To reduce noise, both frames are previously filtered trough a parameterized gaussian blurring. The program includes a foveated processing module (Fig. 4), which allows selecting a radius of a circular area, so that the periphery of it can be magnified by a factor, to remark the temporal enhancement in the surroundings.

Despite the limited "resolution" that can be transmitted in a neuroprosthesis system based on the present technology, our objective is to be able to send as much information as possible. So, there is not only a color-contrast and temporal enhancement, but it is also possible to include some other useful image features, such as stereo vision in order to provide knowledge about relative depth of objects in the scene. Thus, Retiner is being

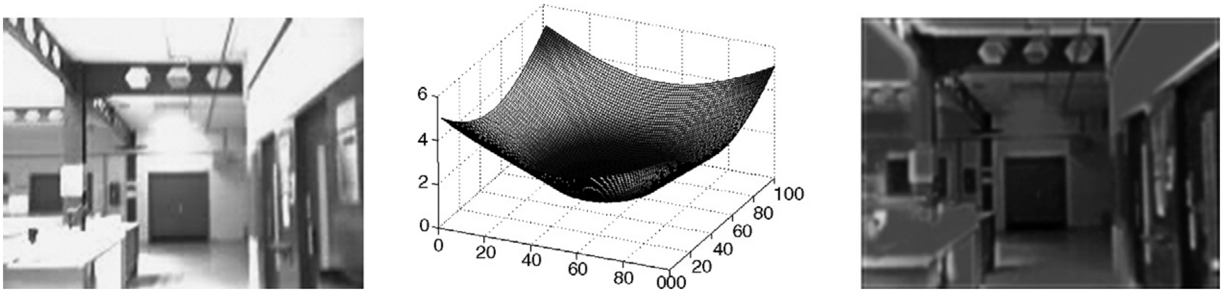

Fig. 4. A foveated processing, magnifying the temporal enhancement in the periphery of the source images. Borders due to motion are strongly remarked in the periphery.

extended with a stereo acquisition module, which grabs images from two cameras at the same time, and computes the disparity in the position of every pixel of both frames. This disparity is a clue to determine how distant is that point from the subject wearing the cameras. The smaller is the disparity, the farther is that point from the observer. This way, it is possible to include depth information (for example, by remarking the intensity of closer points) in the image sent to the microelectrode array.

All of the spatial and temporal filters mentioned above are applied over the acquired image in parallel. The result of every filtering is combined into a single “activity matrix”, in which the most relevant features in terms of color or motion contrast are represented with brighter pixels. The operator of Retiner can determine the way these elements are combined, so that some of the features can be given more relative relevance, if desired.

3.3. *A variety of receptive fields*

The amount of photoreceptors converging into a ganglion cell varies depending on the location in the retina Hubel (1988). It is known that receptive fields are smaller in the center and wider in the periphery. This means better spatial resolution in the fovea, and better response to temporal changes in the surroundings. This aspect also can be modeled in Retiner, which allows defining receptive fields with different and even variable sizes and shapes, like rectangles, ellipses, or circles. An example of a receptive field definition similar to biological retinas is shown in Fig. 5.

3.4. *Translation to neuromorphic encoding*

The last step in the processing is a neuromorphic coding, that is, the translation of the above mentioned “activity matrix”, which is represented in intensity, into a spike frequency encoding, according to the way it is done by ganglion cells. The model followed to implement this neural encoding is a simple leaky integrate-and-fire spiking neuron (Fig. 6) Gerstner and Kistler (2002). Retiner lets the tuning of several parameters of this model, like the threshold to fire an event, the leakage term, or the resting membrane potential of the model neuron.

The result of this translation from intensity levels into pulse frequency is recorded for every channel, corre-

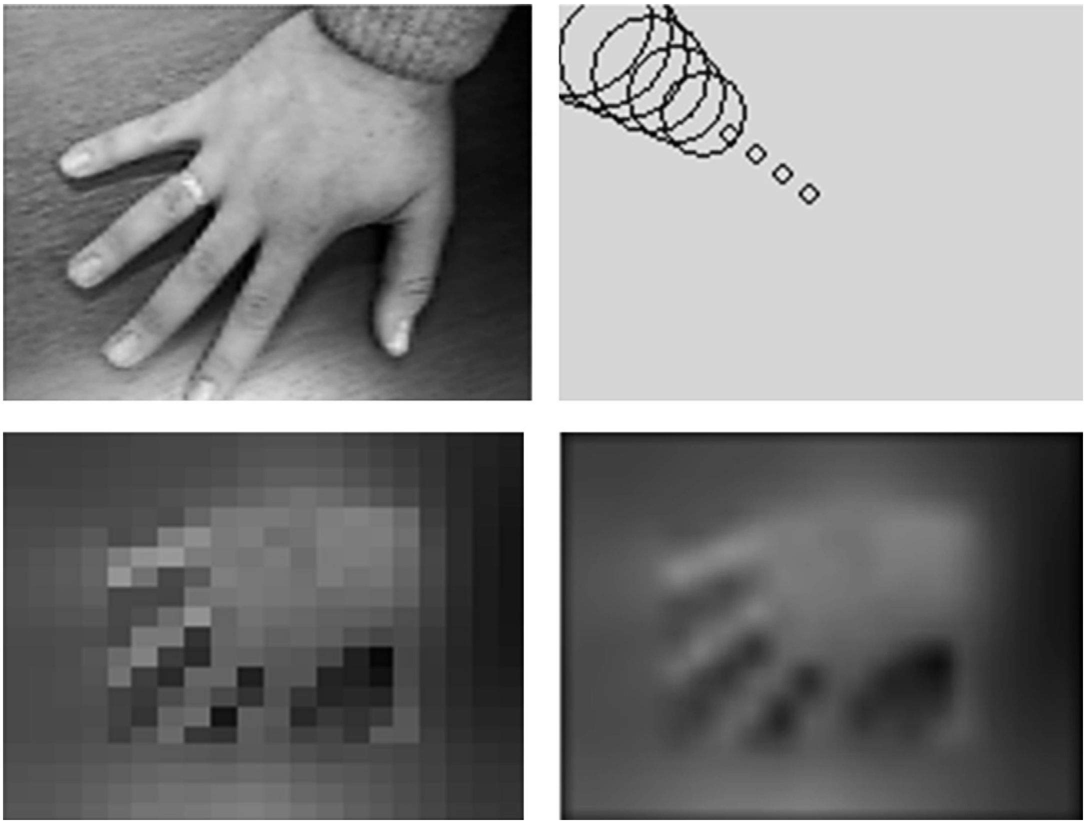

Fig. 5. Receptive field definition with higher resolution in the center than in the periphery (upper-right). The effect of this distribution applied to the upper-left image is shown in the lower-left picture, and its biological approximation (lower-right).

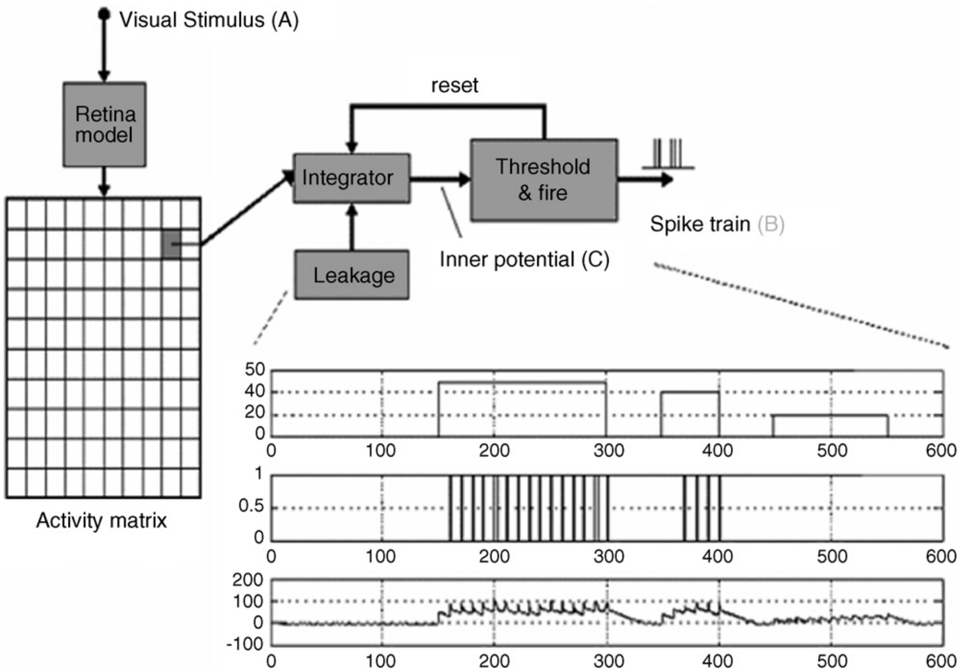

Fig. 6. Leaky integrate-and-fire spiking neuron model, showing the response to a stimulus, for a given component of the activity matrix (see Fig. 2).

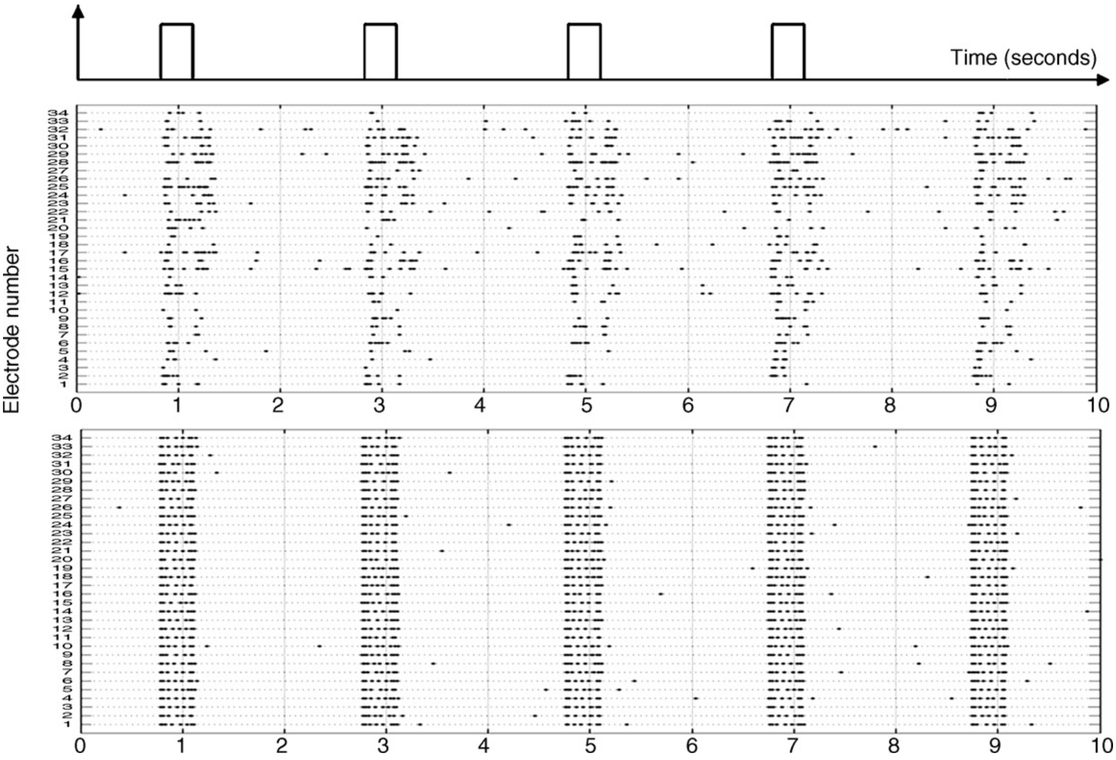

Fig. 7. Full-field flashing stimulation of a retina: (top) periodic stimuli flashes, (middle) in vivo recording from a rabbit retina, and (bottom) output of Retiner simulation for this stimulus.

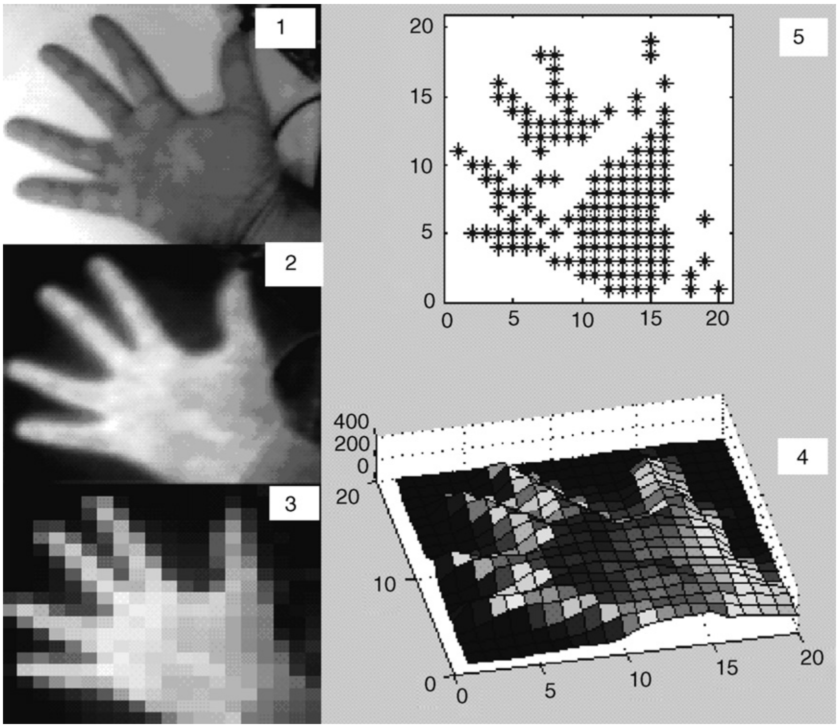

Fig. 8. Step-by-step example; snapshot of processing with Retiner: original scene (1), retina-like filtering (2), receptive field mapping (3), activity matrix (4) and spiking events (5), for a 20 × 20 electrode output.

sponding to an electrode, into a file that has the same format that those produced by the acquisition software employed in experiments with biological retinas (Neural Event Files (NEV files) from Cyberkinetics Inc.). This way, both Retiner-generated and experimentally recorded files can be opened for comparison, and allows to better tune the model to match them. Retiner includes a utility to select the electrodes to be displayed, for easier graphical analysis.

Fig. 7 presents a comparison between the neuromorphic-encoded responses to the same stimulus for a biological retina, versus a retina model simulated with Retiner.

In this figure, we show the response of a biological retina extracted from a rabbit (upper graph), when exposed to a periodic full field flash. The graph illustrates the spiking of ganglion cells recorded by means of a micro-electrode array, after noise cancellation and signal separation. We can observe that most electrodes record a spike train after the arrival of the stimulus. The lower graph is the response of an artificial retina to the same stimulus. This retina model was designed with the Retiner program.

This figure illustrates how Retiner is useful to design and simulate retina models, and that these models can be tested and compared against experiments with biological retinas, in order to adjust and refine them for better approximating the behavior of the natural system.

So this tool can be employed by neural engineers to create neuro-prosthetic devices, and test them, before implementing the prosthetic processor into a portable electronic system.

Fig. 8 depicts information obtained at several stages for a model simulation in Retiner. These steps include image acquisition, enhancement filtering, receptive field mapping, saliency map (activity matrix) and firing of events for every electrode reaching the threshold.

The whole retinal design platform runs on a PC with Matlab^{TM}. However, a prosthetic implementation of this artificial retina requires portability, real-time operation, low consumption, etc. A new feature is being incorporated to Retiner, so, once a retina model is defined and simulated, it can be automatically synthesized into a hardware description (in VHDL) (Martínez et al., 2005). Then, a digital programmable circuit (FPGA) can be configured to implement the retina model on a single chip.

4. Discussion

Retiner, intended to help neuroengineers to design and test retina models, has been described. This software allows the simulation of bio-inspired visual processing models in a flexible and highly parametric way, including acquisition from live video, definition of retina-like filtering, receptive fields, and neuromorphic encoding. The results of a simulation can be easily compared with biological recordings to adjust the model. The tool is able to synthesize automatically a circuit definition to create a portable device. This way, the same design framework facilitates us working from model definition and simulation up to real-time hardware implementation on a digital chip.

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