Cortical Visual Neuro-Prosthesis for the Blind: Retina-Like Software/Hardware Preprocessor

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Abstract- **This paper describes the implementation of a software/hardware (Sw/Hw) retina-like preprocessor designed for the study of bio-inspired visual processing schemes, and for experimentation in the development of a cortical visual neuro-prosthesis.**

The goal is to obtain, in a near future, an integrated artificial retina for a visual neuro-prosthesis prototype able to stimulate efficiently an array of intra-cortical implanted microelectrodes.

The Sw/Hw platform presented is highly programmable and reconfigurable as required for experimentation, providing real-time video processing and neuromorphic stimulation. But its implementation is also devised to be finally mapped into fully portable hardware, particularized for each implanted blind individual.

Keywords - **artificial retinas, neural processing and coding, visual neuro-prostheses, reconfigurable computing, visual impairment and rehabilitation**

I. INTRODUCTION

The work here described is part of the European project CORTIVIS (Cortical Visual Neuro-prosthesis for the Blind, QLK6-CT-2001-00279) [1], within the European program "Quality of Life and Management of Living Resources", started in January, 2002. Several neuro-physiologists, physicians, physicists and computer and electronic engineers from 8 european institutions, including a biotechnology company, participate in this multidisciplinary project.

The CORTIVIS consortium has as main goal the development of a visual neuro-prosthesis acting at the cortical level, having as main target people suffering a total vision loss caused by accident or illness. The problem stated is complex, and nowadays there are many laboratories world-around working on similar lines, evaluating prosthesis that interface to different centers in the visual pathway (retina, optic nerve and primary visual cortex) [2].

Unlike cochlear prostheses, which have reached a high degree of success, currently being a valid surgical option for rehabilitation in many cases of deafness, visual prosthesis have certain added handicaps, causing a delay in its development. These problems are not only technical challenges, due to the high number of stimulation electrodes needed to produce a visual perception with useful resolution, but also surgical difficulties, as long as it must be implanted on the closest centers to the brain, so they are less reachable, and with higher risks in case of bio-incompatibility.

Definitely, we face a challenge that is difficult to overcome, but in which small advances provide a big hope for blind people (in an increasing number everyday due to accidents and the progressive ageing of population), since vision is the human sense that provides us with most information in daily life. We may need a time, maybe 5 to 10 years, to reach a maturity on this field similar to the current one in cochlear implants.

Among the tasks planned in CORTIVIS, there is an implementation of a bioinspired visual-information processing system that must work in real time (that is, at a rate that can provide almost continuous visual perception), and able to produce neural stimuli similar to those received by the primary visual cortex of a sighted person. This system will be initially employed for animal experimentation and development of the whole electronic system of the prosthesis. At the end, it must be capable of being integrated into an specific chip, customizable for each patient.

Fig. 1 shows a schematic view of the organization of the whole system, that includes a bioinspired visual information processing block (artificial retina), an output coding block that puts the retina output in the form of pulses that can be modulated with different cadences and temporal lags, and whose projection onto the electrode matrix must be fully reconfigurable. Although image projections from the retina to the primary visual cortex are said to be "retino-topic", that is, two points that are close in the visual scene project onto neighbor locations on the visual cortex, it presents folds and irregularities that may have the projection distorted [3]. These deformations would depend on the patient and on the specific implant site, and can be artificially corrected by an adecuate mapping of the destination addresses of pulses coming from the artificial retina.

Finally, an integrated telemetry system must be developed in order to transmit the electric pulses to the electrode stimulator. The experiences that are planned in this project will start by using the Utah micro-electrode array [4], although other matrices could provide similar results of stimulation (Utah's array employs silicon micro-electrodes

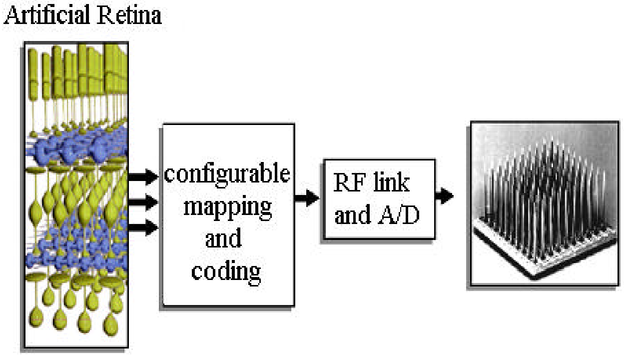

Fig. 1. Functional blocks of the cortical visual neuro-prosthesis.

separated about 400 micrometers from each other, like the distance existing between neighbor cortical columns in the human visual system).

The work described here refers to the first two blocks in Fig. 1. The processing features we are incorporating in these blocks have as a goal to provide the electrode array with the biggest amount of useful information that is possible (with a quite limited number of electrodes) for visual perception.

The functional organization of the retina model we consider for implementation is summarized in the next Section II. Section III describes the current programmable Sw/Hw implementation of the configurable and parameterized retina model in a PC with a FPGA based accelerator board. Section IV introduces a preliminary approach to the neuromorphic output coding module. Section V shows some experimental results and Section VI is a conclusion.

II. RETINA MODEL

As it is known, a biological retina consists of several specialized neuron layers. Far from a simple transducer of light into electrical neural pulses, a retina performs a locally-computed spatio-temporal contrast enhancement function, and a very efficient compression of visual information. These tasks are essential to provide our visual system with a high adaptation capability to very different lighting conditions, a high noise immunity, and to efficiently communicate the retina with the next center in the visual pathway (the LGN) by means of a reduced number of optic nerve fibers.

At the output layer of a human retina there are spiking ganglion cells with different transient responses and receptive fields (sustained ON_center-OFF_surround and OFF_center-ON_surround, and ON-OFF transient cells), as well as different chromatic sensibilities [5,6,7].

Color information is essential for our visual perception in everyday life since all around us uses color cues to attract our attention and to easily differentiate spatial patterns.

In the application we try to cope with, it is not practical to put chromatic information in separate channels of an array with a very restricted number of electrodes. Instead of this, we try to artificially increase the activity of those electrodes whose receptive field is stimulated by specific color channels.

Fig. 2 shows the architecture of the retina model we consider for implementation. The input images are processed by a set of separate filters (intensity contrast and color opponent filters, temporal differentiation, etc.) that enhance specific features of the captured visual information. The output of these filters is combined to produce an output map we call "information figure". The next stage reduces the information figure array to the resolution of the electrode matrix, with the option of defining specific receptive field shapes and sizes. Finally, a mapping and neuromorphic coding (into output pulses that will be sent to each electrode) is carried out.

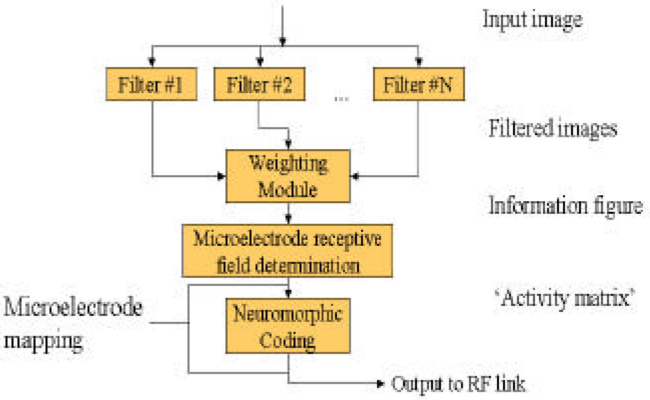

Fig. 2. Schematic view of the blocks that implement the retina processing

III. RETINER

Retiner is the name of the hardware/software environment for testing retina models we are working on. Its software front-end has been implemented using MATLAB [8].

The main purpose of Retiner is to describe and simulate the retina processing. Through a set of parametrized filters and characteristics (which are very close to the hardware constraints for a digital implementation) we obtain a retina portable model that can be translated into a hardware description for automatic synthesis.

According to the block diagram depicted in Fig. 2, Retiner includes:

A) Photoreceptors: modeled after a camera sensor (preferably a logarithmic response camera), take the input from the image acquisition device and extract the three color channels (red, green and blue). A gain factor can be specified for every individual channel as well as a global gain. At the moment, the software allows acquisition of still images in most digital formats, webcams compatible outputs with Video for Windows and video streams in AVI format.

B) Ganglion modules (filters): perform filtering operations over the input channels to extract or enhance relevant features of the scene. In the current implementation, three filters have been considered:
   a. ML vs S: Yellow vs Blue, performed by a difference of gaussians (DoG) as the shown in Fig. 3.
   b. LS vs M: Red vs Green, another DoG.
   c. LMS: an achromatic filter, implemented as a laplacian filter.

   The ML vs S filter contribution is a DoG between the average of the green (M) and red channel (L), and the blue channel (S), where M, L and S stand for medium, large and short wavelength of light.Filter *b* is analogous to the first one, but using different color channels.

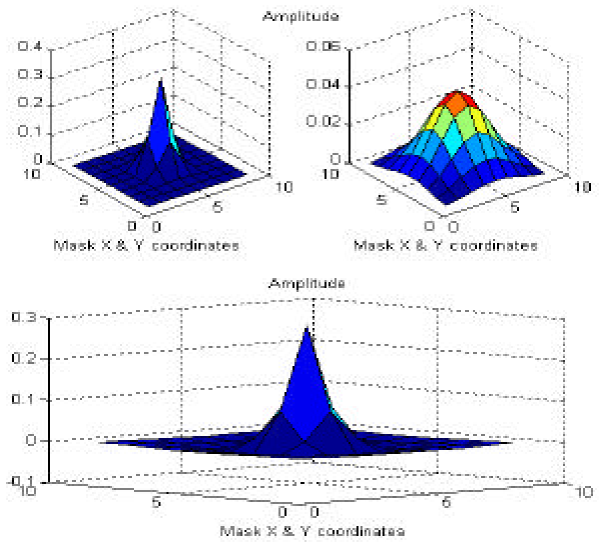

Fig. 3. Example of mask used to implement a 2D DoG filter.

C) Weighting module: that produces a user defined weighted sum of the three filter outputs. Any intermediate result (filter outputs and information figure) can be observed and saved to an image or video file.

D) Electrode output configuration: allows selecting the number of electrodes in the stimulator matrix. The weighted filtered output will result in an assignation or mapping to a limited number of electrodes. The value assigned to an electrode has been computed by averaging the value in the pixels in its receptive field. At the moment the receptive field area is fixed, but it will be configurable for every electrode. An approximation to the "cortical integration" or the induced image the stimulation of electrodes would invoke in a implanted individual can also be displayed as an output (see example in Section V). This integration consists in a custom blurring of the microelectrodes output. The mapping will be made to be reconfigurable, so that every output can be redirected to the convenient electrode.

This flexibility will be useful in the case of damaged electrodes or adaptation to specific individual features, avoiding surgery in any case.

Regarding the input of the system a problem arises when using conventional CCD and CMOS camera sensors, which have a linear response to light intensity. This feature can be a problem in visual scenes in which a high contrast exists. If an image presents areas of darkness and very brilliant zones, essential information at the entry point of our system will be lost, as most exposed pixels will get saturated. We would be missing important features of the scene.

To overcome this disadvantage, a logarithmic response camera is being used. The response of this camera is distributed so that it is never saturared. With this camera, we are able to acquire scenes in which a brilliant source of light (even the sun) appears together with simple non-brilliant objects (see Fig. 4 for a comparison).

Fig. 4. A view of a window in a shiny day. CCD camera (left) gets saturated, losing details that can be observed with a logarithmic camera (right).

IV. NEUROMORPHIC CODING

The output of the activity matrix, highlighting relevant information in the input image, must be coded into neural-like pulses. The neuromorphic coding module is in charge of this task. The output of this stage will feed the radio-frequency link that goes to the microelectrode array.

The model implemented is a simplified version of an integrate-and-fire spiking neuron [9]. The neuron accumulates input values coming from its receptive field until it reaches a threshold. Then it fires and discharges the accumulated value. We also include a leakage term, to make the accumulated value diminish for low or null input values.

Fig. 5 shows the spike or pulsed output obtained by the coding module in response to input activity pulses of different amplitude and duration. We can observe the effects of the leakage factor and the thresholding in the middle trace of the same figure. The more intense is the input value and the longest it is sustained, we will obtain longer spike trains.

This part of the model has been developed with a XILINX [10] blockset for SIMULINK [8], that allows to easily build and test hardware models and, after testing, generate automatically VHDL code for synthesis.

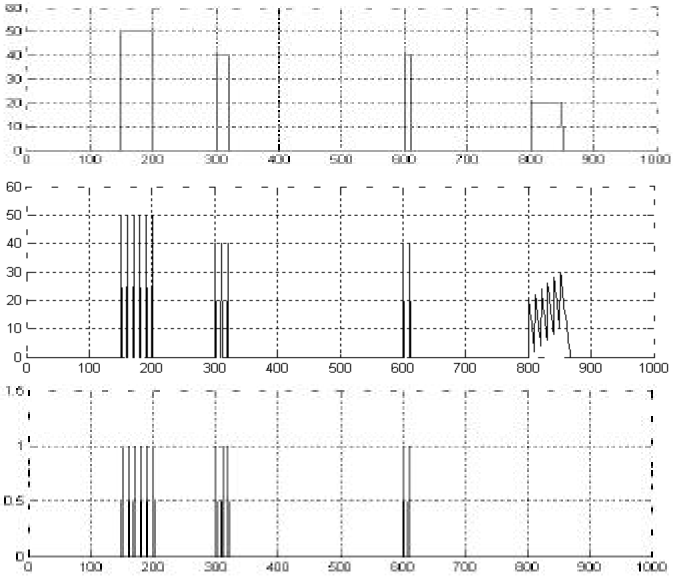

Fig. 5. Successive values of a microelectrode activity (top). Integration values (middle). Pulse-coded output (bottom).

V. RESULTS

As an example of the results that can be obtained by using the retina model, some figures of retinal processing have been included.

The scenes shown in Fig. 6 have been acquired with a resolution of 160x120 pixels. The image of the hand is finally coded with a resolution as low as 16x16 electrodes, and yet the main object in the scene is well represented, thanks to the contribution of the three filters, specially the LS vs. M filter. The activity level in every electrode is represented by the pixel value in the middle image. Each pixel corresponds to an electrode in the stimulator matrix. The figure at the bottom is an approximation of image integration which would be performed by the visual cortex from the discrete number of electrodes. This integration occurs as the electrode stimulates not only its insertion point, but also (decreasing gradually with distance) its neighbor area. The second image is more complex, as some details exist in the image background and foreground. Again, the main features of the input scene are represented at the output. In this case, a 20x20 microelectrode matrix is assumed.

VI. CONCLUSIONS

We have presented a Hw/Sw environment for developing and testing a cortical visual neuro-prosthesis for the blind. We have concentrated on the visual processing front-end, which consists of a bio-inspired retina model. Performing a bio-inspired pre-processing on the visual information we transmit to the neuro-stimulator is essential in order to: *(a)* trying to put into the signal arriving each electrode the biggest amount of "usable information" that is possible for visual perception, *(b)* getting the maximum independency of lighting conditions and, *(c)* with the appropriate inter-spike timing at different electrodes, facilitating higher level perceptive tasks (like visual feature binding) and the learning or adaptation of implanted individuals.

The current platform contains a high flexibility retina model, allowing to easily add or modify any parameter or component. This way, the medical researchers of the CORTIVIS project, will be able to find the optimal parameters when testing with real patients.

The results obtained up to this moment correspond exclusively to spatial processing. In order to include the appropriate temporal processing in the model we must take into account that the temporal behavior of the biological retina is highly influenced by its working in a constantly moving eye. In any case, the signals sent to the implanted electrodes will be coded in a neuromorphic way (rate and timing of spikes). A communication scheme of address-event representation is being considered (in collaboration with another partner of the project) to finally send the output pulses, via a radio-frequency link, to the electrode matrix implanted in the primary visual cortex of the brain.

The need for prosthesis portability and real-time image processing implies the use of hardware for the final prototype. We are progressively moving from fully software to fully hardware implementation, without losing flexibility, as we employ reconfigurable hardware FPGAs (Field Programmable Gate Arrays).

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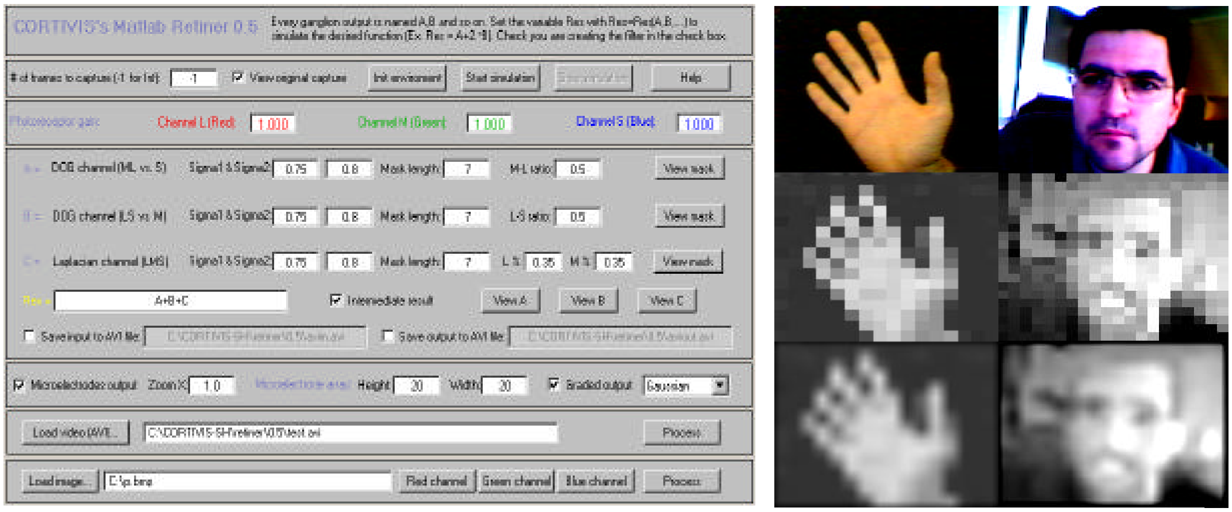

CORTIVIS's Matlab Retiner 0.5

Every ganglion output is named A,B and so on. Set the variable Res with Res=f(A,B,...) to simulate the desired function (Ex. Res = A+2*B). Check you are creating the filter in the check box

# of frames to capture (-1 for Inf): -1
☑ View original capture
Photoreceptor gain: Channel L (Red): 1.000 Channel M (Green): 1.000 Channel S (Blue): 1.000
A = DOG channel (ML vs. S) Sigma1 & Sigma2: 0.75 0.8 Mask length: 7 M-L ratio: 0.5
B = DOG channel (LS vs. M) Sigma1 & Sigma2: 0.75 0.8 Mask length: 7 L-S ratio: 0.5
C = Laplacian channel (LMS) Sigma1 & Sigma2: 0.75 0.8 Mask length: 7 L %: 0.35 M %: 0.35
Res = A+B+C
☑ Intermediate result
☐ Save input to AVI file
☐ Save output to AVI file
☑ Microelectrodes output Zoom X: 1.0
Microelectrode array: Height: 20 Width: 20
☑ Graded output: Gaussian
C:\CORTIVIS-SH\retiner\0.5\test.avi
C:\p.bmp

Fig. 6. Graphic user interface of RETINER (left), and experimental results (right; see text for details).