A MOEMS architecture for a bionic retina

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Abstract:

In this paper we show, based on the biological characteristics and functions of the retina, that a **MOEMS** circuit is suitable for the design of a bionic retina. Such a circuit is a matrix of optical (photoreceptors and lenses), electrical (neural processor), and mechanical (micro pump) elements. We first determine interactions between them using results from neurobiology and cognitive studies of vision. We then define the global modular architecture of the **MOEMS** circuit, , and a general bus structure for future design an simulation.

I INTRODUCTION:

Provided that the optic nerve is not damaged, an artificial retina implant can restore sight to blinds[6][7][8].

Such a retina is bionic and processes visual information, in order to replace a defective retina within the human body. Optobionics, Sandia Labs and USC, have designed artificial retina implants, but only to replace the retina's damaged photoreceptor cells, not the whole retina.

The past two decades, VLSI vision chips have been designed to become components of future intelligent systems, and have often been limited (due to cost , complexity, and size) to specific military and industrial applications. It is however important to notice that their designers have been inspired by the biological, physical, neural, and functional characteristics of the human, and vertebrate eye..

Just as a biological retina does, they detect light, visible wave lengths, flow motion, and movements. At first sight, and from a functional point of view, they only need an interface to the human optic nerve to become bionic retinas implants. Such an interface should be electrochemical (micropump), for the optic nerve is stimulated by electrochemical signals.

Thus the whole structure of a bionic retina, should comprise an optical part, an electrical part and a mechanical part. MOEMS circuits seem to be most appropriate for such realizations, since there is a need for an optical sensor, digital processing, and electrochemical stimulation (using micro-pumps) on the same implant.

Our initial approach considers the bionic retina as a matrix of basic photoreceptor, and processor cells. In each basic cell, a photoreceptor converts light to an electrical signal and transmits it to a neural processor that generates a stimulation of an optic nerve fiber, using an electrochemical interface.

A first step in the design of the artificial retina is its behavioral simulation. It is therefore necessary to determine the circuit modules, their functions, interactions, and interconnection between them.

In this modular approach, modules are considered to be the matrix cells, and sub-modules are the elements within a basic cell. The purpose of this paper is to determine, based on the retina functional study, interconnections between cells, and interactions within cells elements.

This paper will be organized as follows:

An overview of existing MEMS partitioning and architectures is given. Then the study of the biological retina and the vision mechanism is presented to deduce a physical model of the bionic retina .

Last the retina's characteristics are used to determine a global internal architecture for the bionic retina..

II MEMS PARTITIONNING AND ARCHITECTURES:

In their design methodology, MEMS systems can be described in three basic representations, behavioral, structural, and physical. Each representation has several levels of top down functionality in the design process (fig ?).

The 'specifications' step shows the objective of the MEMS circuit, functions to be realized, and the modules to be implemented (sensor part, processing part, and actuator part).

The step 'interfaces' shows the overall architecture of the MEMS circuit, its input and output signals, and its internal bus structure (interactions and interconnections between modules, and sub-modules …).

The 'partitioning step' decides how much of the system will be on the chip (one chip solution, or multichip solution) .

Our concern in this paper is with these three steps in the top down design methodology.

In order to prepare the behavioral simulation , using a VHDL-ams tool, of the bionic retina, we

show in fig(1) and fig(2), some possible architectures, and partitioning. This will help us choose the configuration that suits best the structure of our bionic retina. By combining information given in this section, with the results of the study of the vision biological , neural, and cognitive mechanisms, we will be able to define our global bionic retina architecture.

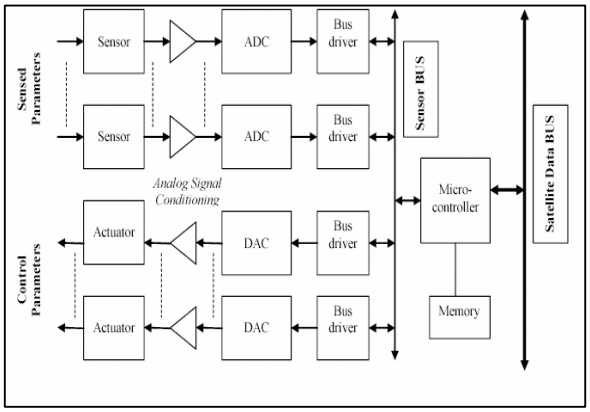

Fig 1-a: Distributed interconnection architecture
Advantage: modularity, interchangeability
Requirements: internal sensor bus

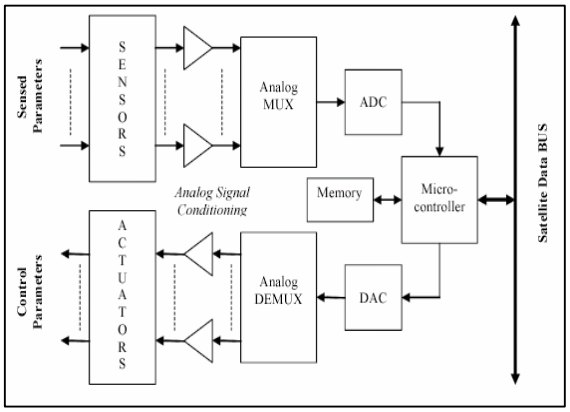

Fig 1-b : Classical interconnection architecture
Advantage: available microcontrolers and DSP's with internal memory, and digital interface capabilities
Disadvantage: no modular solution

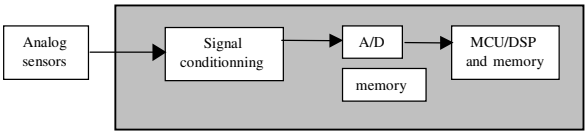

Fig 2-a: sensor alone, MCU/DSP with analog interface, Analog signal processing and MCU/DSP hybridisation

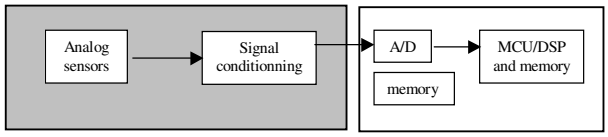

Fig 2-b: sensor and signal conditionning integration, MCU/DSP with alnalog interface, no digital direct integration.

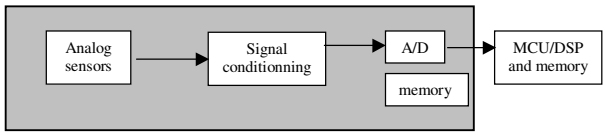

Fig 2-c: sensor and signal conditionning integration, and digital output interface , digital direct integration

III BIOLOGICAL RETINA, AND VISION MECHANISMS.

The vision is a series of processes leading to the mental representation of the external world. It uses optical (eye), electrochemical (retina, optical nerve, brain), and cognitive (brain) functions. In this section, only a brief description and sight information relevant and useful to the choice of the moems architecture , are given.

III 1 The eye anatomy and function:

The eyeball (fig3) is an organ that focuses a visual scene on the retina where real processing begins.

The cornea and lens focus light, coming from objects, onto the retina photoreceptors, which

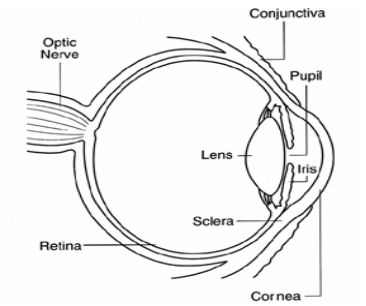

Fig 3 Simplified anatomy of the eye

absorb, process, and convert it into electrochemical signals that are transmitted to the brain via the optic nerve.

III 2 The retina

The retina is a neural tissue which lines the back of the eye[5] Its main function is the capture of light signals, and their conversion into neural messages carrying to the brain, color, position and contour and movement detection, information. The retina is in fact, an extension to the brain, to which it is connected through the optic nerve.

The structure of the retina shows three cell layers:

- The photoreceptors: they are of two types:

- the cones; responsive to colors in bright conditions; they are used in fine detail, and day sight, and are classified into three types: red, blue, and green sensitive. Cones are spread throughout the retina, with a greater concentration in the center area called the macula.

- The rods: responsive in low light conditions, they function in dim light and at night. They are also used in peripheral vision, and are found with a higher density in the peripheral area of the retina.

- The photo-pigment cells: they absorb color, and generate, by a shape change, events that lead to a change in the electrical state of the rods, and cones.

- The retinal neurons: or bipolar and ganglion cells. Their axons, which form the optic nerve fibers, are interconnected to each others (lateral connections), thus creating receptor fields. These receptor fields generate information about motion, contour, and shape, proving that the retina transmits not only color information to the brain, but also processed light information.

There are about 126000000 sensors (120000000 rods and 6000000 cones) to be connected to about 1000000 optic nerve fibers. Few cones converge onto retinal neurons to average their signals for better spatial resolution, and vision precision, whereas many rods (about 150) synapse onto the same target neuron, amplifying their signals, and enabling the brain to detect even small amount of light, but loosing in sight precision (movements are detected, and objects seen without being identified). The most precise vision is in the fovea where only cones are found whith a higher density, and where each cone is connected to one neuron.

III 3 Vision mechanism, and retinotopic map:

The visual field is defined as the view seen by both eyes when looking straight ahead. The visual information of the visual field, is mapped onto the retina of each eye, it then travels from retinal neural cells to the brain. It is mapped in an orderly, but not isotropic fashion, onto the neurons in different brain sections (retina, optic nerve, chiasma, thalamus, visual cortex) for appropriate processing. Every area of the visual field is mapped, not in proportion to its size, but rather to the density of sensory neurons.

- The visual pathway: An imaginary division of the retina into four quadrants, symmetric with regards to a vertical plan, parallel to the visual field, and an horizontal plan, both including the fovea, the following quadrants are defined:

Upper nasal, lower nasal, upper temporal and lower temporal. (fig 4) (what is nasal for one eye is temporal for the other).

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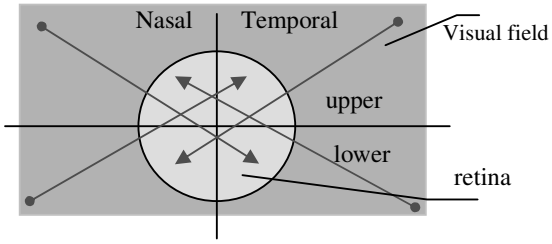

Fig 4 :Light incidence on the retina

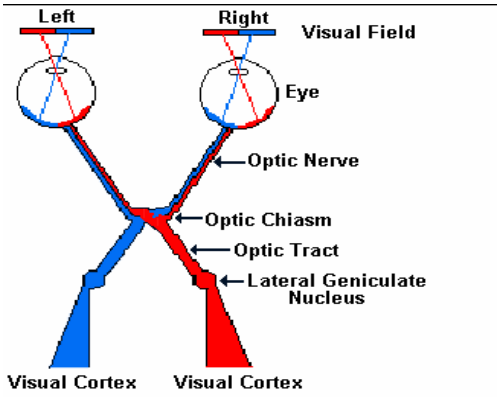

Fig5:visual pathway for temporal and nasal visual fields ; a similar pathway can be drawn for the upper and lower

Light signals issued from objects in the upper temporal side, go to the lower nasal quadrant of the retina, and those from the upper nasal go to the lower temporal quadrant of the retina and vice versa .

The retina photoreceptors take the converted and

processed information to optic nerve fibers in the same order. At the optic chiasma where the optic nerve of both eyes cross, information from the entire right field goes to the left occipital cortex, and all the left visual field information goes to the right(fig5)(and lower goes to upper, and upper goes to lower).

In every section of the brain where visual signals are processed, this topographic mapping is kept in an orderly manner with respect to the visual signals of the retina sections (fovea, macula, peripheral area) and to retina quadrants.

This mapping allows the brain to correctly process spatial information for 2D and 3D vision, as well as contour and shape and movement detection.

The retina functional characteristics, combined with the vision mechanisms information shall be used in the next section, in order to deduce our MOEMS global architecture.

IV THE BIONIC RETINA

The bionic retina to be conceived is a MOEMS implant, which will be interfaced with the optic nerve, to replace a defective retina.

This MOEMS circuit is a matrix of basic cells.

Considering that:

- **The retina's main function is the photo reception and processing of the visual field information**, each cell is made of a photoreceptor, an artificial neural processor, connected to an electrochemical actuator (fig 4), which will stimulate the optic nerve.
- **Cones and rods detect light in different ways**: the photoreceptors of the bionic retina are of three types: very high intensity color detectors(cones in the fovea), high intensity color detectors (cones in the macula and the peripheral retina), and low intensity color detectors(rods).

The photoreceptors will be made of buried triple junction[3], wave length sensitive photodiodes (red blue and green color detectors), and used in association with micro lenses[2] to reduce pixel size for better integration[4].

- **In the retinotopic map, every point of the visual field is mapped to the same corresponding visual cortex point**: spatial repartition, and density of the photoreceptors must correspond to the repartition of cones and rods and their functions in the retina. Photoreceptors must line the entire back of the eye for a better quality of the restored vision. The number of photoreceptors must be high enough and close to the number of the biological photoreceptors to insure high resolution sight, improving the implants developed in recent years[6] [7][8].
- **Retina neurons are connected laterally: to form receptor fields**, the basic cells neural processors must be interconnected to provide information on motion, shape , and contour detection.
- **Many receptors are connected to the same ganglion cell axon:** groups of artificial neural processors must be connected to the same actuator(fig 7).

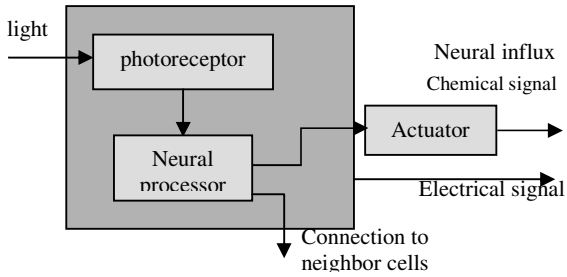

Fig 6 basic cell bloc diagram

V MOEMS ARCHITECTURE FOR THE BIONIC RETINA:

Several types of mems architectures exist. Depending on the context of their use, their different parts (sensors, processors, and actuators) can be integrated on the same chip, or partially or totally separated, and communication between parts will be organized for maximal efficiency. [1] shows standard mems partitioning, and integration, and different bus architecture and organization.

As seen in the previous section, in our case each actuator receives information from several neural processors. The number of neurons converging to the same actuator will depend upon the nature of the processor (cone like, or rod like), and the location of its photoreceptors cell in the implant (peripheral or central area of vision).

Neural processors connected to the same actuator, communicate through a common bus in order to process incoming data, to provide relevant motion, contour, shape information, in addition to local color information.

A distributed interconnection architecture (fig1-a), with a sensor alone partitioning (fig 2-a), characterize our bionic retina global architecture (fig 7).

Because the position of the incident light on the retina is important for its neural processing by the brain, the photoreceptors will line the back of the

eye and only the neural processors, and actuators, shall be integrated on the same chip.

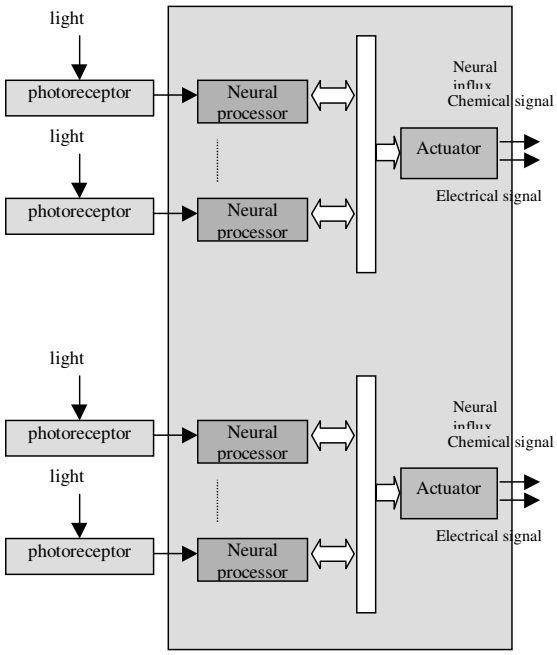

Fig 7 : Global architecture for a Moems bionic retina

V CONCLUSION

We have proposed a MOEMS architecture for a bionic retina. A modular design of the bionic retina can now be undertaken using Top down design model.

The next step will be the determination of each basic cell element inputs and outputs, and mathematical model, in order to simulate the different types of basic cells and a matrix of basic cells using a VHDL-ams tool.

Resolution, integration, encapsulation will be considered later, and will depend on the progress made in MEMS circuits technology.

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