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Image Analysis for Automatically-Driven Bionic Eye

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1. Introduction

In many fields such as health or robotics industry, reproducing the human visual system (HVS) behavior is a widely sought aim. Actually a system able to reproduce even partially the HVS could be very helpful, on the one hand, for people with vision diseases, and, on the other hand, for autonomous robots.

Historically, the earliest reports of artificially induced phosphenes were associated with direct cortical stimulation Tong (2003). Since then devices have been developed that target ùany different sites along the visual pathway Troyk (2003).These devices can be categorized according to the site of action along the visual pathway into cortical, sub-cortical, optic nerve ane retinal prostheses. Although the earliest reports involved cortical stimulation, with the advancements in surgical techniques and bioengineering, the retinal prosthesis or artificial retina has become the most advanced visual prosthesis Wyatt (2011).

In this chapter, both applications will be presented after the theoretical context, the state of the art and motivations. Furthermore, a full system will be described including a servo-motorized camera (acquisition), specific image processing software and artificial intelligence software for exploration of complex scenes. This chapter also deals with image analysis and interpretation.

1.1 Human visual sytem

The human visual system is made of different parts: eyes, nerves and brain. In a coarse way, eyes achieve image acquisition, nerves data transmission and brain data processing (Fig. 1).

The eye (Fig. 2) acquires images through the pupil and visual information is processed by retina photoreceptors. There exist two kinds of photoreceptors: rods and cones. Rods are dedicated to light intensity acquisition. They are efficient in scotopic and mesopic conditions. Cones are specifically sensitive to colors and require a minimal light level (photopic and mesopic conditions). There are three different types of cones sensitive for different wavelengths.

Fig. 3a shows the photoreceptors responses and Fig. 3b their distribution accross the retina from the foveal area (at the center of gaze) to the peripheral area. At the top of Fig. 3b, small parts of retina are presented with cones in green and rods in pink. This outlines that the repartition of cones and rods varies on the retina surface according to the distance to the

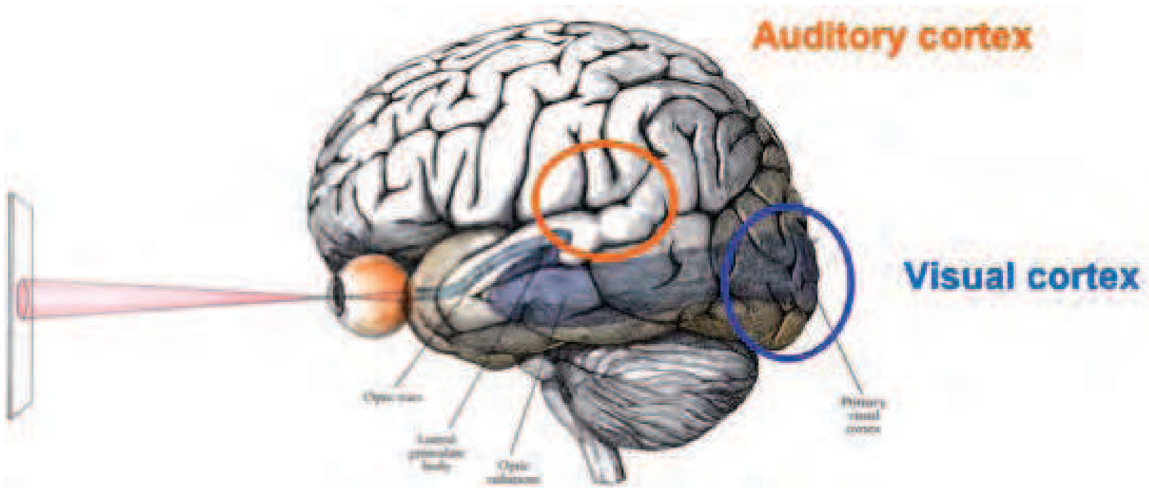


Fig. 1. Human visual system

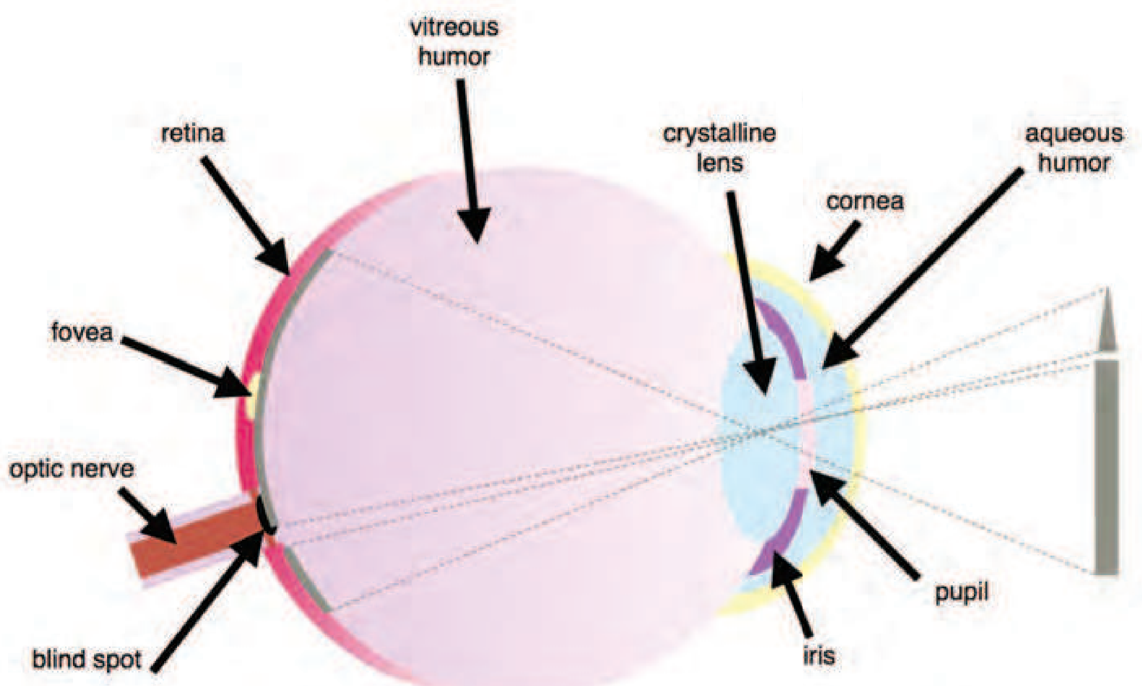
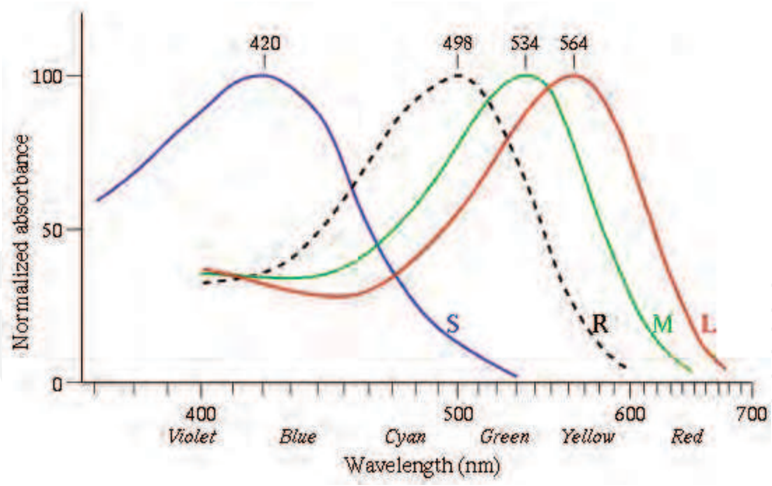


Fig. 2. Human eye

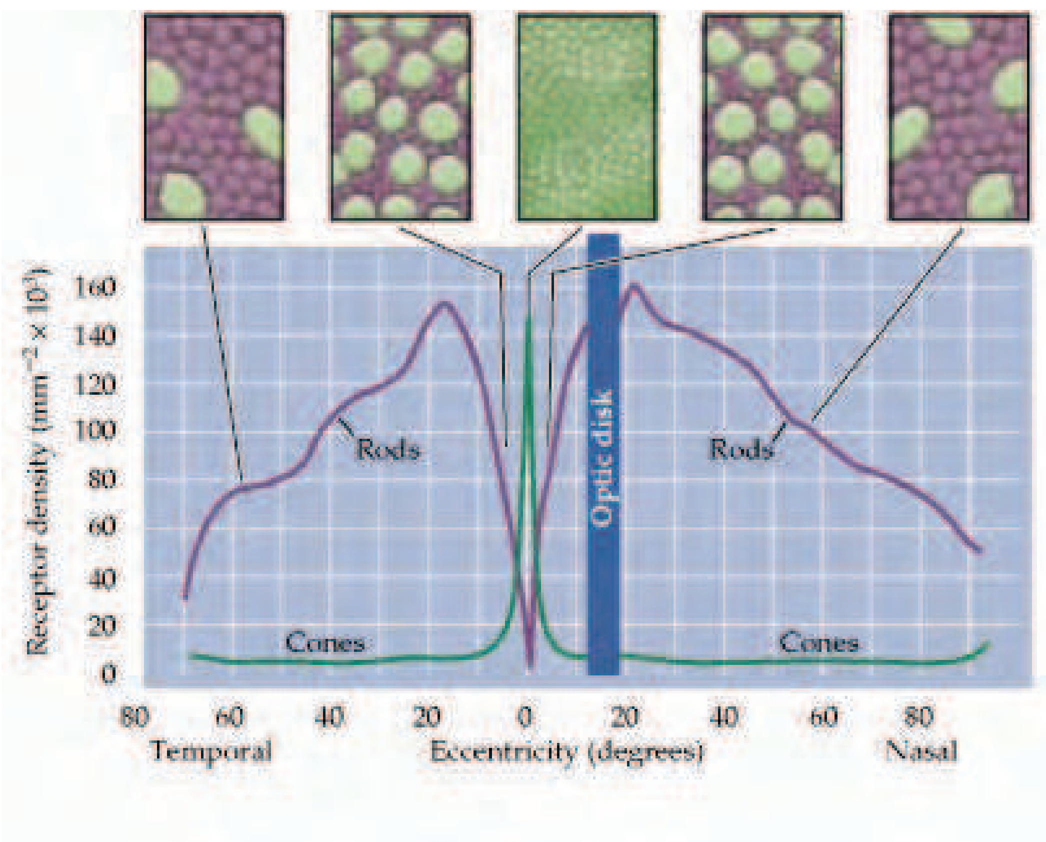
center of gaze. Most of the cones are located in the fovea (retina center) and rods are essentially present in periphery. Then light energy data are turned into electrochemical energy data to be carried to the visual cortex through the optic nerves. The two optic nerves converge at a point called optic chiasm (Fig. 4), where fibers of the nasal side cross to the other brain side, whereas fibers of the temporal side do not. Then the optic nerves become the optic tracts. The optic tracts reach the lateral geniculate nucleus (LGN). Here begins the processing of visual data with back and forth between the LGN and the visual cortex.

1.2 Why a bionic eye?

Blindness affects over 40 millions people around the world. In the medical field, providing a prosthesis to blind or quasi-blind people is an ambitious task that requires a huge sum of



(a) Rods (R) and cones (L, M, S) responses



(b) Rods and cones distribution accross the retina (from http://improveeyesighttoday.com/improveeyesight-centralization.htm)

Fig. 3. Rods and cones features

knowledge in different fields such as microelectronics, computer vision and image processing and analysis, but also in the medical field: ophtalmology and neurosciences. Cognitive studies determining the human behavior when facing a new scene are lead in parallel in order to validate methods by comparing them to a human observer's abilities. Several solutions are offered to plug an electronic device to the visual system (Fig. 4). First of all, retina implants can

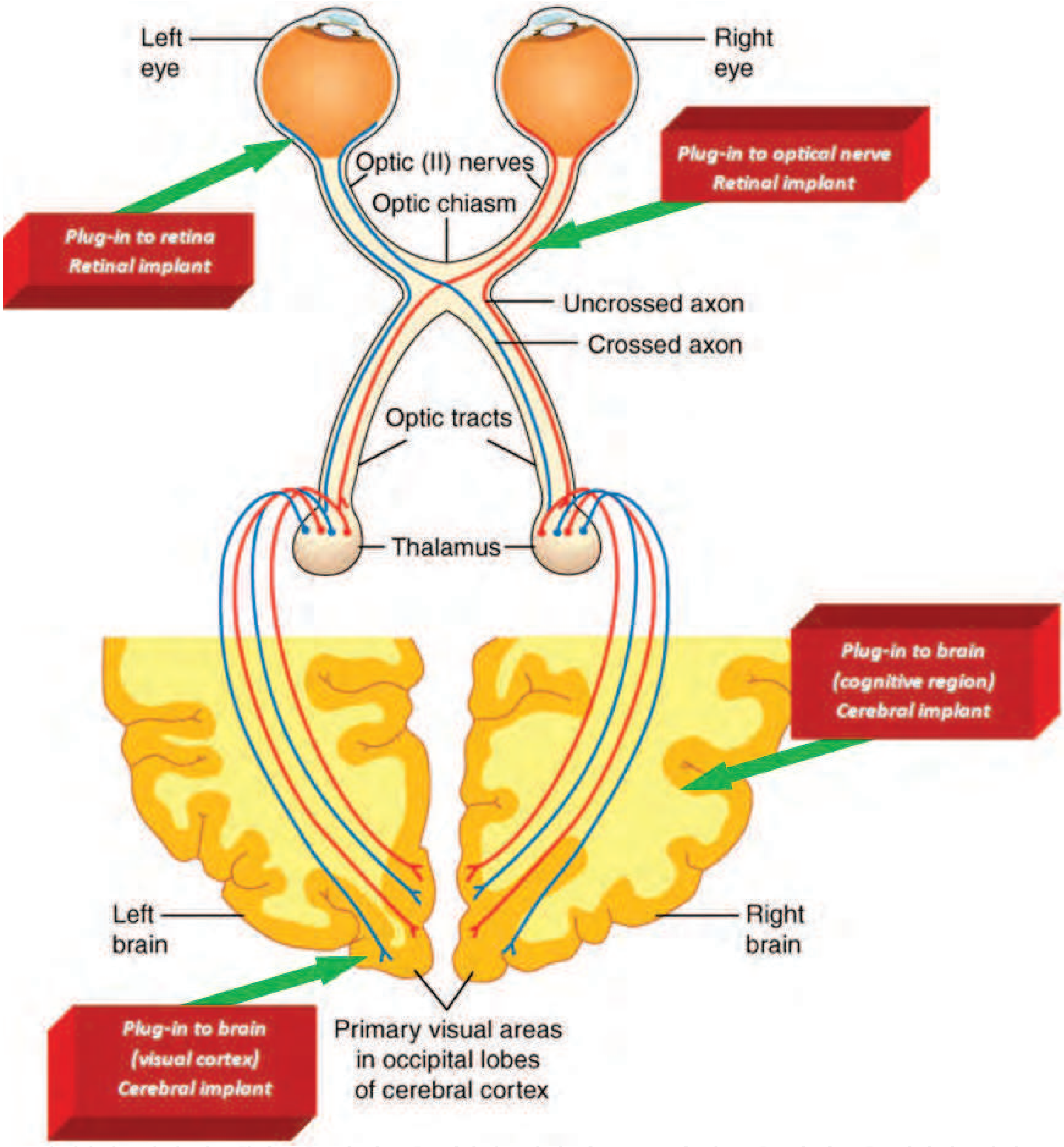


Fig. 4. Human visual system and solutions for electronic device plugins

be plugged either to the retina or to the optic nerve. Such a solution requires image processing in order to integrate data and make them understandable by the brain. No image analysis is necessary as data will be processed by the visual cortex itself. But the patient must be free of pathology at least at the optic nerve, so that data transmission to the brain can be achieved. In another way, retina implants can directly stimulate the retina photoreceptors. That means that the retina too must be in working order. Secondly, when either the retina or the optic nerve is damaged, only cerebral implants can be considered, as they directly stimulate neurons. In this context, image analysis is required in order to mimick at least the LGN behavior.

1.3 Why now?

The development of biological implantable devices incorporating microelectronic circuitry requires advanced fabrication techniques which are now possible. The importance of device stability stems from the fact that the microelectronics have to function properly within the relatively harsh environment of the human body. This represents a major challenge in developing implantable devices with long-term system performance while reducing their overall size.

Biomedical systems are one example of ultra low power electronics is paramount for multiple reasons [Sarpeshkar (2010)]. For example, these systems are implanted within the body and need to be small, light-weighted with minimal dissipation in the tissue that surrounds them. In order to obtain implantable device, some constraints have to be taken into account such as:

- The size of the device
- The type of the technology (flexible or not) in order to be accepted by the human body
- The circuit consumption in order to optimize the battery life
- The performance circuit

The low power hand reminds us that the power consumption of a system is always defined by five considerations as shown on Fig.5:

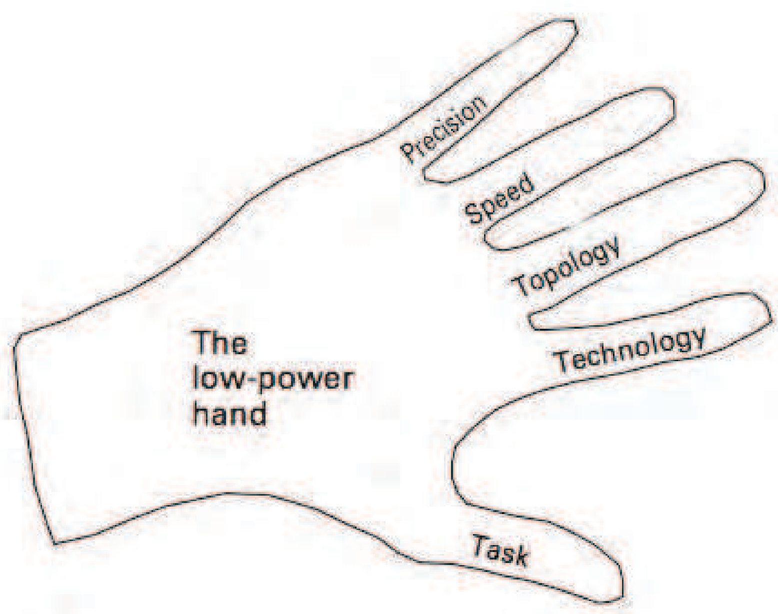


Fig. 5. Low power Hand for low power applications

2. State of the art: Overview

Supplying visual information to blind people is a goal that can be reached in several ways by more or less efficient means. Classically blind people can use a white cane, a guide-dog or more sophisticated means. The white cane is perceived as a symbol that warns other people and make them more careful to blind people. It is also very useful in obstacle detection. A guide-dog is also of a great help, as it interprets at a dog level the context scene. The dog is trained to guide the person in an outdoor environment. It can inform the blind person and advise of danger through its reactions. In the very last decades, electronics has come to reinforce the environment perception. On the one hand, several non-invasive systems have been set up such as GPS for visually impaired [Hub (2006)] that can assist blind people with orientation and navigation, talking equipment that provides an audio description in a basic way for thermometers, clocks or calcultors or in a more accurate way for audio-description that gives a narration of visual aspects of television movies or theater plays, electronic white canes [Faria (2010)], etc. On the other hand, biomedical devices can be implanted in an invasive way, that requires surgery and clinical trials. As presented in Fig. 4, such devices can be plugged at different spots along the visual data processing path. In a general way the principle is the same for retinal and cerebral implants. Two subsystems are linked, achieving data acquisition and processing for the first one and electrostimulation for the second one. A camera (or two for stereovision) is used to acquire visual data. These data are processed by the acquisition processing box in order to obtain data that are transmitted to the image processing box via a wired or wireless connection (Fig. 6). Then impulses stimulate cells where the implant is connected.

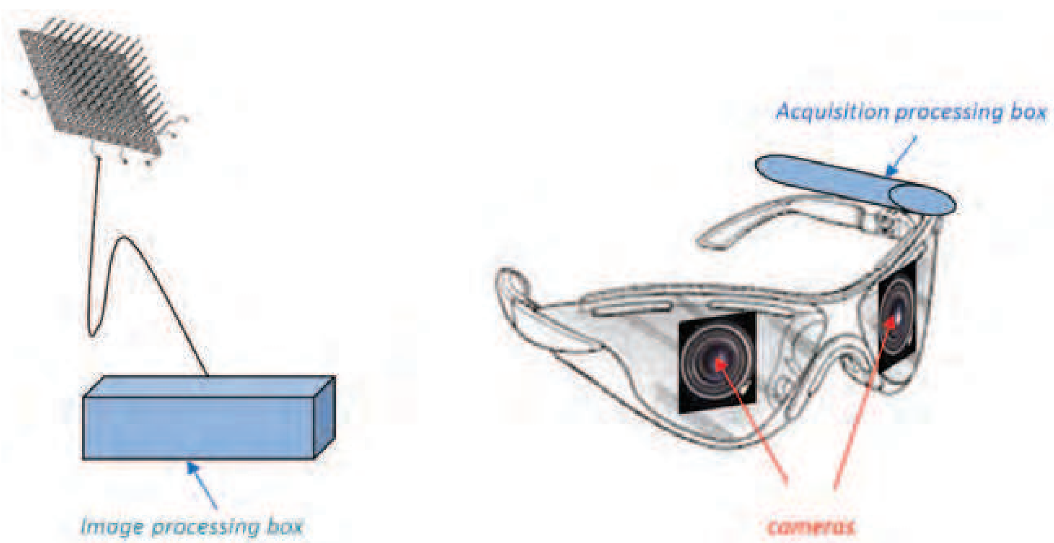


Fig. 6. General principle of an implant

2.1 Retina implant

For retinal implants, there exist two different ways to connect the electronic device: directly to the retina (epiretinal implant) or behind the retina (subretinal implant). Several research teams work on this subject worldwide. The target diseases mainly are:

- retinitis pigmentosa, which is the leading cause of inherited blindness in the world,
- age-related macular degeneration, which is the leading cause of blindness in the industrialized world.

2.1.1 Epiretinal implants

The development of an epiretinal prosthesis (Argus Retinal Prosthesis) has been initiated in the early 1990s at the Doheny Eye Institute and the University of California (USA)[Horsager (2010)Parikh (2010)]. This prosthesis was implanted in patients at John Hopkins University in order to demonstrate proof of principle. The company Second Sight[1] was then created in the late 1990s to develop this prosthesis. The first generation (Argus I) has 16 electrodes and was implanted in 6 patients between 2002 and 2004. The second generation (Argus II) has 60 electrodes and clinical trials have been planned since 2007. Argus III is still in process and will have 240 electrodes.

VisionCare Ophtalmic Technologies and the CentralSight Treatment Program [Chun (2005)Lane (2004)Lane (2006)] has created an implantable miniature telescope in order to provide central vision to people having degenerated macula diseases. This telescope is implanted inside the eye behind the iris and projects magnified images on healthy areas of the central retina.

2.1.2 Subretinal implants

At University of Louvain, a subretinal implant (MIVIP: Microsystem-based Visual Prosthesis) made of a single electrode has been developped [Archambeau (2004)]. The optic nerve is directly stimulated by this electrode from electric signals received from an external camera.

In the late 1980s, Dr. Joseph Rizzo and Professor John Wyatt performed a number of proof-of-concept epiretinal stimulation trials on blind volunteers before developing a subretinal stimulator. They co-founded the Boston Retinal Implant Project (BRIP). The collaboration was initiated between the Massachusetts Eye and Ear Infirmary, Harvard Medical School and the Massachusetts Institute of Technology. The mission of the Boston Retinal Implant Project is to develop novel engineering solutions to restore vision and improve the quality-of-life for patients who are blind from degenerative disease of the retina, for which there is currently no cure. Early results are actually a reference for this solution. The core strategy of the Boston Retinal Implant Project [2] is to create novel engineering solutions to treat blinding diseases that elude other forms of treatment. The specific goal of this study is to develop an implantable microelectronic prosthesis to restore vision to patients with certain forms of retinal blindness. The proposed solution provides a special opportunity for visual rehabilitation with a prosthesis, which can deliver direct electrical stimulation to those cells that carry visual information.

The Artificial Silicon Retina (ASR)[3] is a microchip containing 3500 photodiodes, developed by Alan and Vincent Chow. Each photodiode detects light and transforms it into electrical impulses stimulating retinal ganglion cells (Fig. 8).

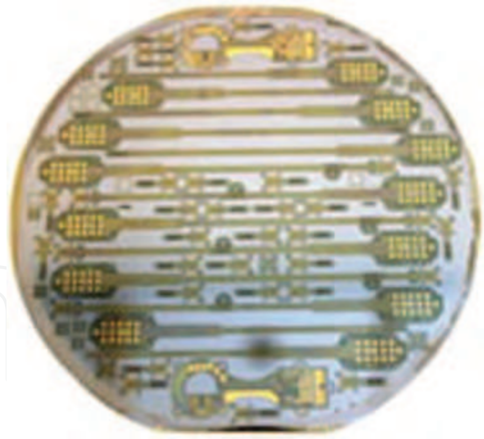
In France, at the Institut de la Vision, the team of Pr Picaud has developed a subretinal implant [Djilas (2011)]. They have also set up clinical trials.

As well, in Germany [Zrenner (2008)], a subretinal prosthesis has been developed. A microphotodiode array (MPDA) acquires incident light information and send it to the chip located behind the retina. The chip transforms data into electrical signal stimulating the retinal ganglion cells.

In Japan [Yagi (2005)], a subretinal implant has been designed at Yagi Laboratory[4]. Experiments are mainly directed to obtain new biohybrid micro-electrode arrays.

[1] 2-sight.eu/
[2] http://www.bostonretinalimplant.org
[3] http://optobionics.com/asrdevice.shtml
[4] http://www.io.mei.titech.ac.jp/research/retina/

(a) Silicon wafer wit flexible polyalide iridium oxide electrode array



(b) Close up of a flx circuit to which IC will be attached

Fig. 7. BRIP Solution

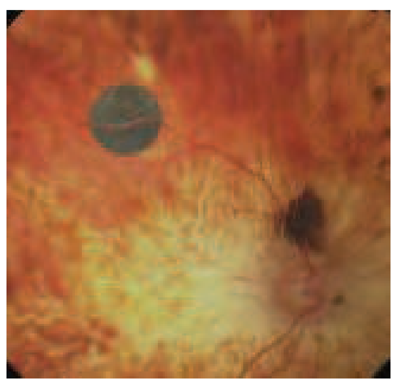


Fig. 8. ASR device implanted in the retina

At Stanford University, a visual prosthesis[5] (Fig. 9) has been developed [Loudin (2007)]. It includes an optoelectronic system composed of a subretinal photodiode array and an infrared image projection system. A video camera acquires visual data that are processed and displayed on video goggles as IR images. Photodiodes in the subretinal implant are activated when the IR image arrives on retina through natural eye optics. Electric pulses stimulate the retina cells.

In Australia, the Bionic Vision system[6] consists of a camera, attached to a pair of glasses, which transmits high-frequency radio signals to a microchip implanted in the retina. Electrical impulses stimulate retinal cells connected to the optic nerve. Such an implant improves the perception of light.

2.2 Cortex implant

William H. Dobelle initiated a project to develop a cortical implant [Dobelle (2000)], in order to return partially the vision to volunteer blind people [Ings (2007)]. His experiments began in the early 1970s with cortical stimulation on 37 sighted volunteers. Then four blind volunteers

[5] http://www.stanford.edu/ palanker/lab/retinalpros.html
[6] http://bionicvision.org.au/eye

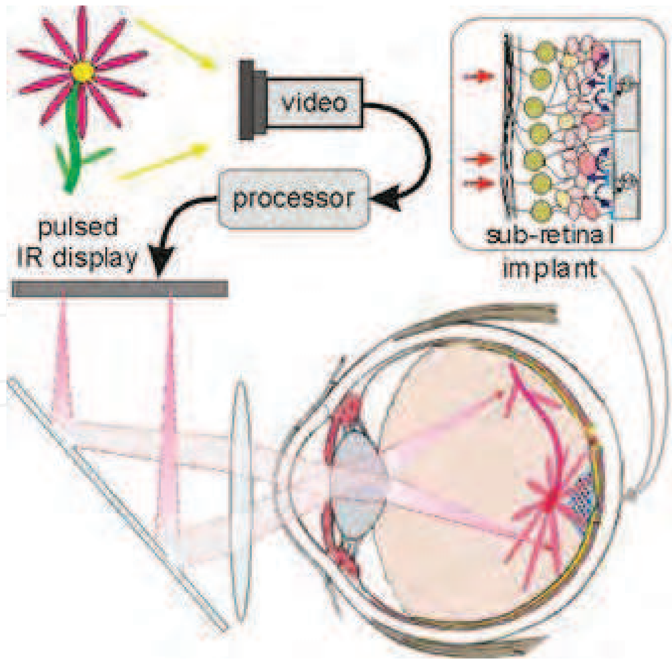


Fig. 9. Stanford University visual prosthesis

were implanted with permanent electrode arrays. The first volunteers were operated at the University of Western Ontario, Canada. A 292 $\times$ 512 CCD camera is connected to a sub-notebook computer in a belt pack. A second microcontroller is also included in the belt pack and it is dedicated to brain stimulation. The stimulus generator is connected to the electrodes implanted on the visual cortex through a percutaneous pedestral. With this system a vision-impaired person is able to count his fingers and recognize basic symbols.

In Canada, the research team of Pr Sawan [Sawan (2008)] at Polystim Neurotechnologies Laboratory[7] has begun clinical trials for an electrode array providing images of 256 pixels (Fig. 10). Such images are not very accurate but they allow the patient to guess shapes. Furthermore clinical trials have proved that it was possible to directly stimulate neurons in the primary visual cortex.

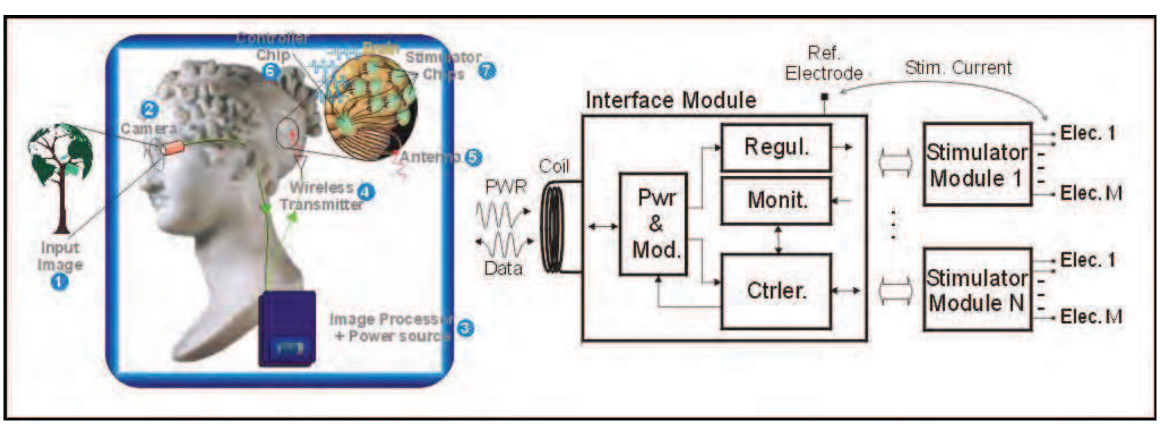


Fig. 10. Principle of Polystim Laboratory visual prosthesis

[7] http://www.polystim.ca

3. Bionic eye

Such a system has to mimick several abilities of the human visual system in order to make visual information available for blind people. The system is made of a camera acquiring images, an electronical device processing data and a mechanical system that drives the camera. Outputs can be provided on cerebral implants, in other words, electrodes matrices plugged to the primary visual cortex. When discovering a new scene the human eye processes by saccades and the gaze is successively focused at different points of interest. The sequence of focusing points enables to scan the scene in an optimized way according to the interest degree. The interest degree is a very complex criterion to estimate because it depends on the context and on the nature of elements included in the scene. Geometrical features of objects as well as color or structure are important in the interest estimation (Fig. 11). For example, a tree (b) is of a great interest in a urban landscape whereas a bench (a) is a salient information in a contryside scene. In the first case, the lack of geometrical particularities and the color difference make the tree interesting. In the second case the structure and the geometrical features of the bench make it interesting in comparison to trees or meadows.

Several steps are carried out successively or in parallel to process data and drive the camera. First of all a detection of points of interest is achieved on a regular image, in other words, on an image usually provided by a camera. One of the points best-scoring with the detector is chosen as the first focusing point. Then the image is re- sampled in a radial way in order to obtain a foveated image. The resulting image is blurred according to the distance to the focusing point [Larson (2009)]. Then a detection of points of interest is achieved on the foveated image in order to determine the second focusing point. These two steps are repeated as many times as necessary to discover the whole scene (Fig. 12). This gives the computed sequence of points of interest. In parallel a human observer faces the primary image while an eye- tracker follows his eye movements in order to determine the observer sequence of points of interest, when exploring the scene by saccades [Hernandez (2008)]. Afterwards the two sequences will have to be compared in order to quantify and qualify the computer vision process, in terms of position and order.

4. Circuit and system approach

4.1 Principle and objective

The proposed solution is based on Pr. Sawan research [Coulombe (2007)Sawan (2008)]. The implementation is a visual prosthesis implanted into the human cortex. In the first case, the principle of this application consists in stimulating the visual cortex by implanting a silicium micro-chip on a network of electrodes made of biocompatible materials [Kim (2010)Piedade (2005)] and in which each electrode injects a stimulating electrical current in order to provoke a series of luminous points to appear (an array of pixels) in the field of vision of the sightless person [Piedade (2005)]. This system is composed of two distinct parts:

- The implant lodged in the visual cortex wirelessly receives dedicated data and associated energy from the external controller. This electro-stimulator generates the electrical stimuli and oversees the changing microelectrode/biological tissue interface,
- The battery-operated outer control includes a micro-camera which captures the image as well as a processor and a command generator. They process the imaging data in order to:
  1. select and translate the captured images,

(a) Bench in a park

(b) Tree in a town

Fig. 11. Image context and points of interest

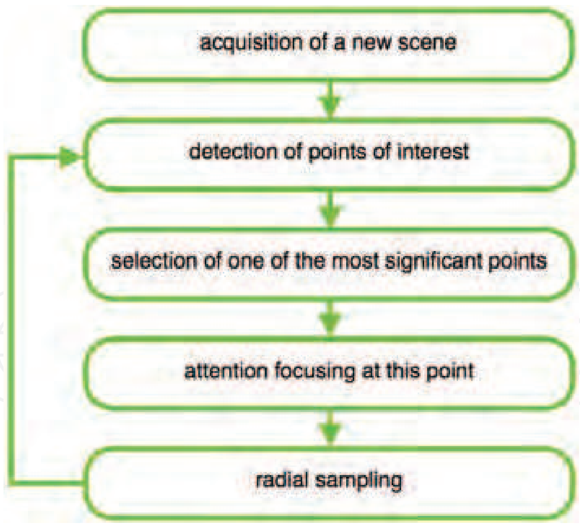


Fig. 12. Scene exploration process

2. generate and manage the electrical stimulation process
3. oversee the implant.

The topology is based on the schematic of Fig. 13.

An analog signal captured by the camera provides information to the DSP (Digital Signal Processor) component. The image is transmitted by using the FPGA which realizes the first Image Pre-processing. A DAM (Direct Access Memory) is placed at the input of the DSP card in order to transfer the preprocessing image to the SDRAM. The DSP realizes then the image processing in order to reproduce the eye behavior and a part of the cortex operation. The LCD screen is added in order to achieve debug of the image processing. In the final version, this last one will be removed. The FPGA drives two motors in two axes directions (horizontal, vertical) in order to reproduce the eye movements. We will know focus on the different components of

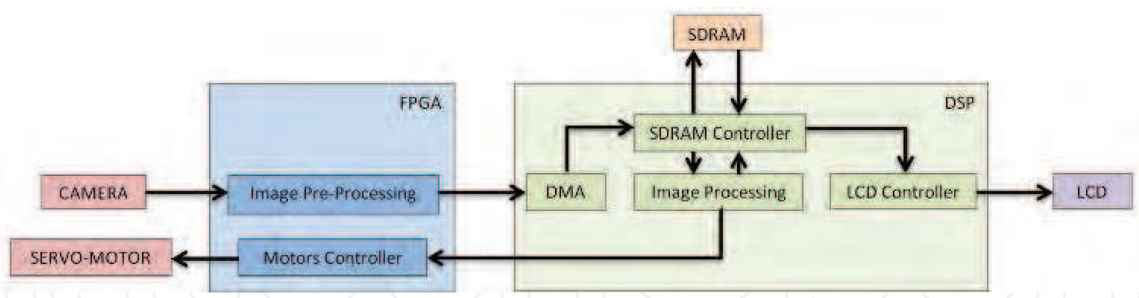


Fig. 13. Schematic principle of bionic eye

this bionic eye topology.

4.2 Camera component

With the development of the mobile phone, the CMOS camera became more compact, lower powered, with higher resolution and quicker frame rate. As for biomedical systems, the constraints tend to be the same, this solution retained our attention. Indeed, for example, Omnivision has created a 14 megapixel CMOS camera with a frame rate of 60 fps for a 1080p frame and a package of 9 mm $\times$ 7 mm. In this project, we have retained a choice of a 1.3 megapixel camera at a frame rate of 15 fps for mainly two reasons: the package who is easy to implement and the large number of different outputs thanks to the internal registers of the camera. The registers allow us to output a lot of standard resolutions (SXVGA, VGA, QVGA etcÉ), the output formats (RGB or YUV) and the frame rate (15 fps or 7.5 fps). These registers are initialized by the I2C controller of the DSP. This allows a dynamic configuration of the camera by the DSP. The camera outputs are 8 bits parallel data that allow a datastream up to 0, 3 Gb/s with 3 control signals (horizontal, vertical and pixel clocks). For the prototype we output at a VGA resolution in RGB 565 at 15 fps.

In order to reproduce of the eye movement, two analog servo motors have been used (horizontal and vertical) mounted on a steel frame and controlled by the FPGA.

4.3 FPGA (Field-Programmable Gate Array) component

The FPGA realizes two processes in parallel. The first one consists in controlling the servo motor. The FPGA transforms an angle in pulse width with a refresh rate of 50 Hz (Fig. 13). The angle is incremented or decremented by two pulse updates during the signal of a new frame (Fig. 15). For 15 fps a pulse is 2 degrees for a use at the maximal speed of the servo motor (0.15s @ 60ą).

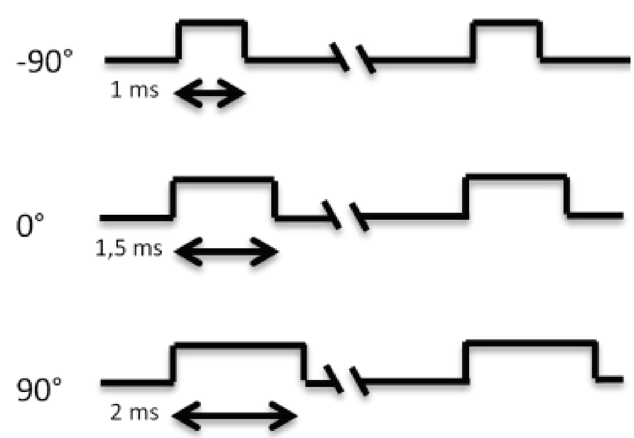


Fig. 14. Time affectation of the pulse width

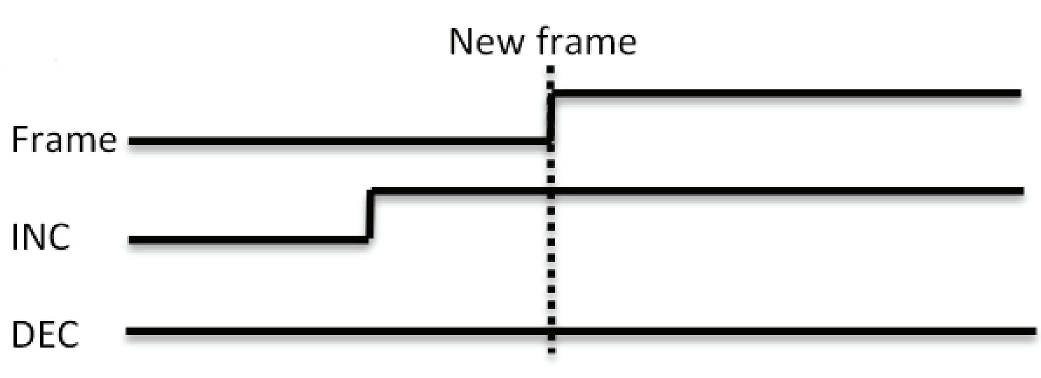


Fig. 15. New frame: increment/decrement signal

The second process is the image preprocessing. This process consists of the transformation of 16 bits by pixel image with 2 clocks by pixel into 24 bits by pixel image with one clock by pixel. For this, we divide the pixel clock by two and we interpolate the pixel color with 5 or 6 bits to a pixel color with 8 bits.

4.4 DSP (Digital Signal Processor) component

For a full embedded product, we need a core that can run a heavy load due to the image processing in real-time. This is why we focus our attention on a DSP solution and precisely on the DSP with an integrated ARM core by Texas Instrument, in fact the OpenCV library[8] is not optimized for DSP core (the mainline development of openCV effort targets the x86 architecture) but it has been successfully ported to the ARM platforms[9]. Nevertheless, several algorithms require floating-point computation and the DSP is the most suitable core for this thanks to the native floating point unit (Fig. 16).

Function Name	ARM9™ (ms)	ARM Cortex-A8 (ms)	C674x DSP (ms)
cvCornerEigenValsandVecs	4746	2655	402
cvGoodFeaturestoTrack	2040	1234	268
cvWarpAffine	82	37	17
cvOpticalFlowPyrLK	9560	5240	344
cvMulSpecturm	104	69	11
cvHaarDetectObject	17500	8217	1180

Fig. 16. Operation time execution

Moreover, the parallelism due to the dual-core adds more velocity to the image processing (Fig. 17). And finally, we use pipeline architecture for an efficient use of the CPU thanks to the multiple controller included in the DSP. The first controller used is the direct memory access controller that allows to record the frame from the FPGA to a ping-pong buffer without the use of the CPU. The ping-pong buffer allows to record the second frame to a different address. This enables to work on the first frame during the record of the second frame without the problem of the double use of a file.

OpenCV Function	ARM Cortex™-A8 with NEON (ms)	ARM Cortex-A8 with C674x DSP (ms)
cvAdaptiveThreshold	85.029	33.433
cvHoughLines2D	2405.844	684.367
cvCornerHarris	666.928	168.57
cvDFT	594.532	95.539

Fig. 17. Dual Core operation time execution

The second controller used is the SDRAM controller that controls two external 256 Mb SDRAM. The controller manages the priority of the use of the SDRAM, the refresh of the SDRAM and the signals control. The third controller used is the LCD controller that allows to display the frame at the end of the image processing in order to verify the result and presentation of the product. This architecture offers a use of the CPU exclusively dedicated to the image processing (Fig. 18).

[8] www.opencv.com
[9] www.ti.com

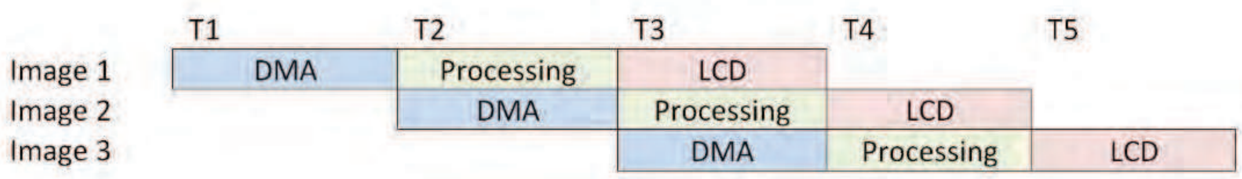


Fig. 18. Image processing

4.5 Electronic prototype

A prototype has been realized, as shown in Fig. 19. As introducted before, this prototype is based on : (i) a camera (ii) a FPGA card, (iii) a DSP card and (iv) a LCD screen.

Its associated size is 20*14*2cm. This size is due to the use of a development card. We choose respectively for the FPGA and DSP cards a Xilinx[10] Virtex 5 XC5VLX50 and a spectrum[11] digital evm omap l137. But on these two cards (FPGA, DSP), we just need the FPGA, DSP, memories and I/O ports. Indeed, the objective is to validate the software image processing. The LCD screen on the left of Fig19 is added to see the resulting image. This last one will not be present on the final product. For the test of the project, we choose a TFT sharp LQ043T3DX02.

So, the objective size for the final product is first of all a large reduction by removing the obsolete parts of these two cards (80%) and then by using integrated circuit solution. The support technology will be standard 0.35μm CMOS technology which provides low current leakage [Flandre (2011)] and so consumption reduction.

An other advantage of using this technology is the possibility to develop on the same wafer analog and digital circuits. In this case, it is possible to realize powerful functions with low consumption and size.

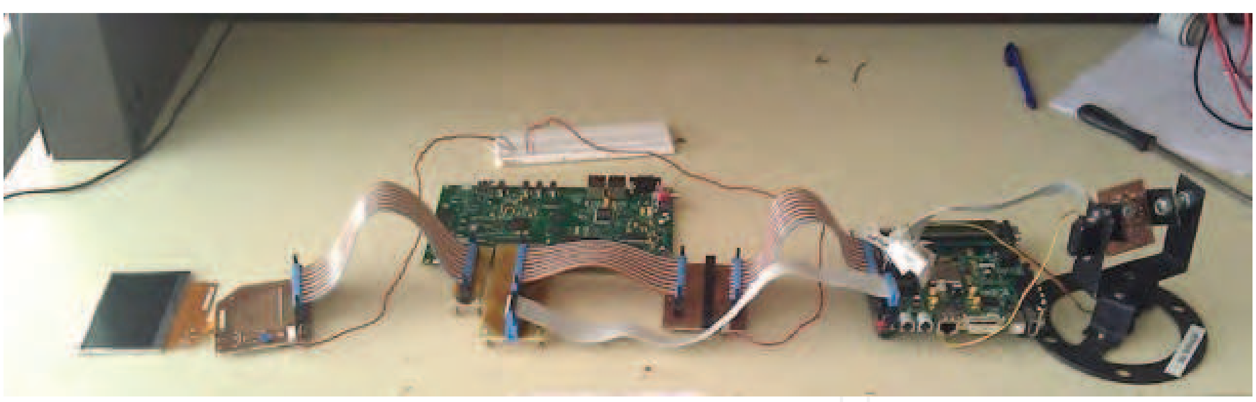


Fig. 19. Bionic Eye prototype

5. Image processing and analysis

The two main steps in HVS data processing that will be mimicked are focus of attention and detection of points of interest. Focus of attention enables to direct gaze at a particular point. In this way, the image around the focusing point is very clear (central vision) and becomes more and more blurred when the distance to the focusing point increases (peripheral vision).

[10] www.xilinx.com
[11] www.spectrumdigital.com

Detection of points of interest is the stage where a sequence of focusing points is determined in order to explore a scene.

5.1 Focus of attention

As a matter of fact, the role played by cones in diurnal vision is preponderant. Cones are much less numerous than rods in most parts of the retina, but greatly outnumber rods in the fovea. Furthermore cones are arranged in a concentric way inside the human retina [Marr (1982)]. In this way focus of attention may be modelized by representing cones in the fovea area and its surroundings. The general principle is the following. Firstly a focusing point is chosen as the fovea center (gaze center) and a foveal radius is defined as the radius of the central cell. Secondly an isotropic progression of concentric circles determines the blurring factor according to the distance to the focusing point. Thirdly integration sets are defined to represent cones and an integration method is selected in order to gather data over the integration set to obtain a single value. Integration methods can be chosen amongst averaging, median filtering, morphological filtering such as dilation, erosion, closing, opening, and so on. Then re-sampled data are stored in a rectangular image in polar coordinates. This gives the encoded image. This image is a compressed version of the original image, but the compression ratio varies according to the distance to the focusing point. The following step can be the reconstruction of the image from the encoded image. This step is not systematically achieved as there is no need of duplicating data to process them [Robert-Inacio (2010)]. When necessary it works by determining for each point of the reconstructed image the integration sets it belongs to. Then the dual method of the integration process is used to obtain the reconstructed value. When using directly the encoded image instead of the original or the reconstructed images, customized processing algorithms must be set up in order to take into account that data are arranged in a polar way. In this case a full pavement of the image is defined with hexagonal cells [Robert (1999)]. The hexagons are chosen so that they do not overlap each others and so that they are as regular as possible. A radius sequence is also defined as follows:

This hexagonal pavement is as close as possible to the biological cone distribution in the fovea. Furthermore data are taken into account only once in the encoded image because of non-overlapping.

Fig. 21 illustrates the type of results provided by previous methods on an image of the Kodak database[12] (Fig. 21). Firstly Fig. 21 shows the encoded image (on the right) for a foveal radius of 25 pixels and with hexagonal cells. The focusing point is chosen at $(414, 228)$, ie: at the central flower heart. Secondly the reconstructed image is given after re-sampling of the original image. In the following, the hexagonal pavement is chosen to define foveated images as it is the closest one to the cone distribution in the fovea.

5.2 Detection of points of interest

The detection of points of interest is achieved by using the Harris detector [Harris (1988)]. Fig. 22 shows the images with the detected points of interest. Points of interest detected as corners are highlighted in red whereas those detected as edges are in green. Fig. 22 illustrates the Harris method when using a regular image (a), in other words, an image sampled in a rectangular way, and a foveated image (b).

[12] http://r0k.us/graphics/kodak/

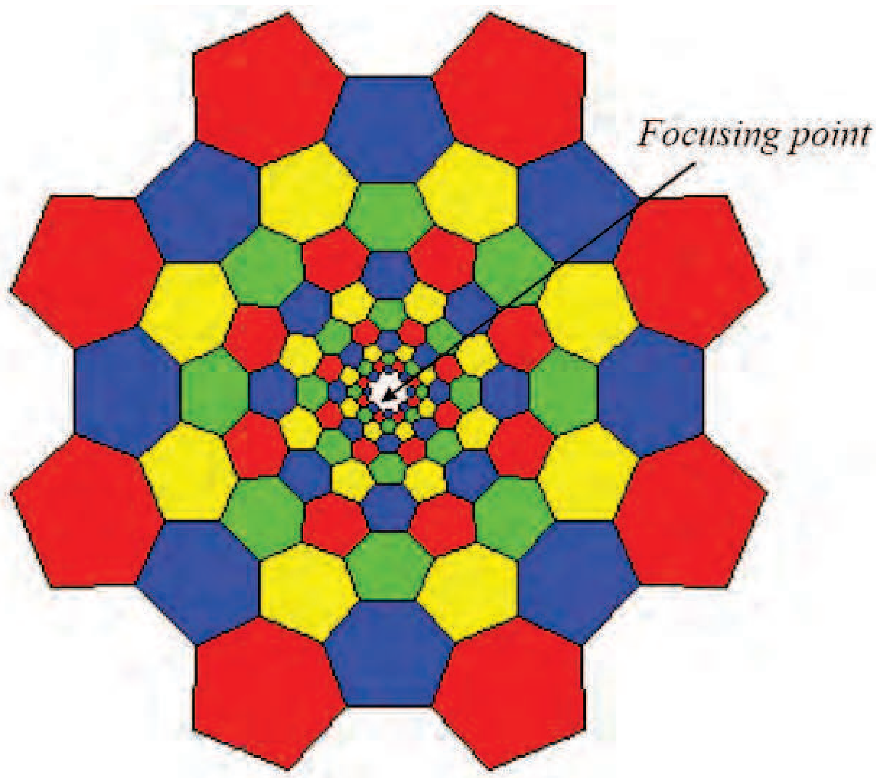


Fig. 20. Hexagonal cell distribution.

5.3 Sequence of points of interest

Short sequences of points of interest are studied: the first one has been computed and the second one is the result observed on a set of 7 people. Fig. 23 shows the sequences of points of interest on the original image of Fig. 21a and Table 1 gives the point coordinates. Sequences are made of points numbered from 1 to 4. The observer sequence in white goes from the pink flower heart to the bottom left plant, whereas the computed sequence in cyan goes from the pink flower heart to the end of the branch. Another difference concerns the point in the red flower. The observers chose to look at the flower heart whereas the detector focused at the border between the petal and the leaf. This is explained by the visual cortex behavior. Actually the detector is attracted by color differences whereas the human visual system is also sensitive to geometrical features such as symmetry. In this case the petals around the heart are quite arranged in a symmetrical way aroud the flower heart. That is why the observers chose to gaze at this point. In this example the computed sequence is determined without computing again a new foveated image for each point of interest, but by considering each significant point from the foveated image with the central point as focusing point. Furthermore for equivalent points of interest the distance between two consecutive points is chosen as great as possible in order to cover a maximal area of the scene with a minimal number of eye movements.

Table 1 gives the distance between two equivalent points from the two sequences. This distance varies from 8 to 32.249 with an average value of 18.214. This means that computed points are not so far from those of the observers. But the algorithm determining the sequence must be refined in order to prevent errors on point order.

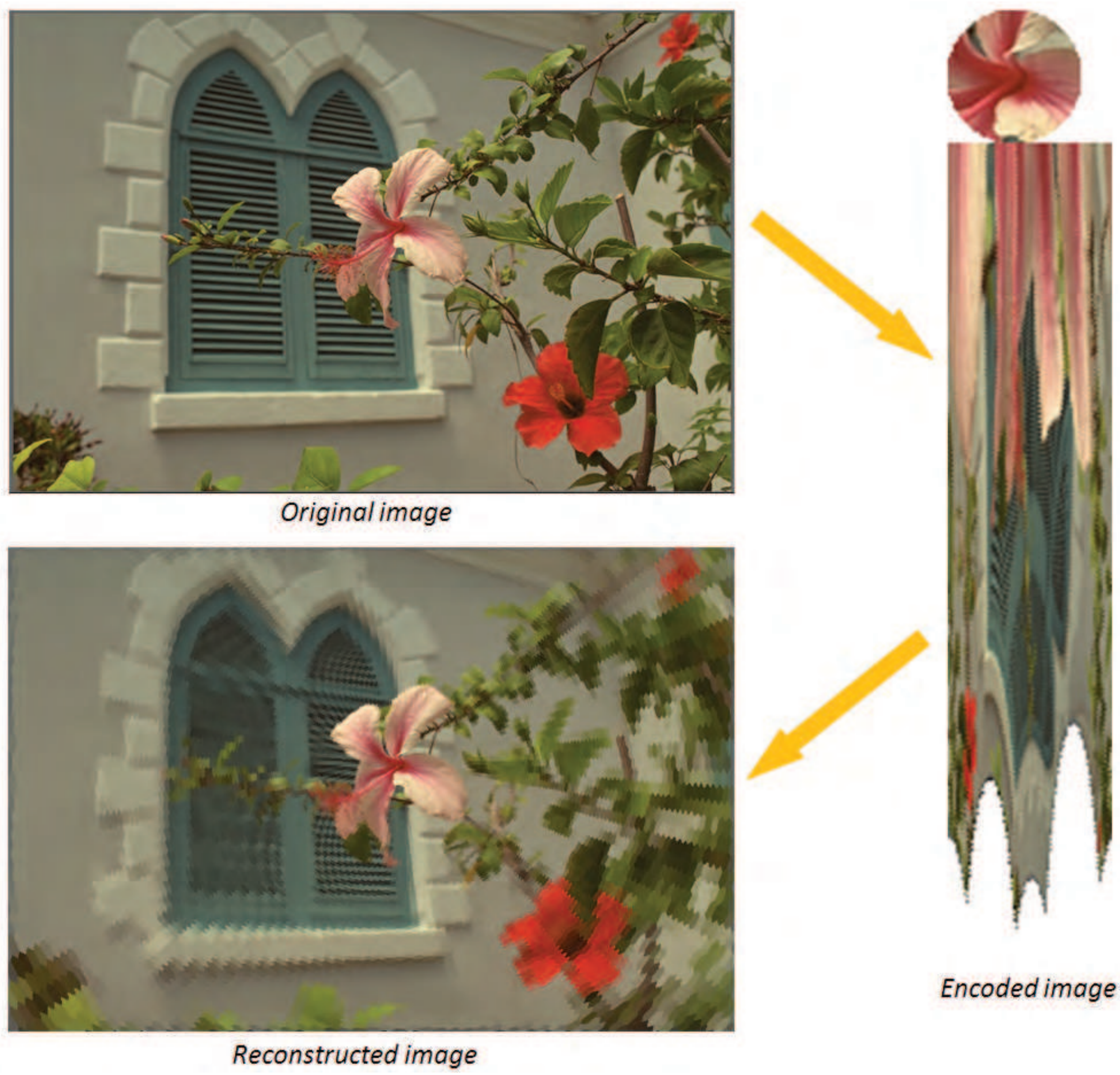


Fig. 21. Focus of attention on a particular image: from the original image to the reconstructed image, passing by the encoded image (foveated image)

Point Number	Regular Detection	Point Number	Foveated Detection	Distance
1	(191, 106)	1	(194, 114)	8.544
2	(279, 196)	2	(275, 164)	32.249
3	(99, 118)	4	(109, 103)	18.028
4	(24, 214)	3	(38, 215)	14.036

Table 1. Distances between points of interest.

6. Applications

There exist two great families of applications: on the one hand, applications in the biomedical and health field, and on the other hand, applications in robotics.

In the biomedical field, a system such as the bionic eye can be very helpful at different tasks:

- light perception,
- color perception,

(a) On a regular image (b) On a foveated image

Fig. 22. Detection of points of interest

(a) Observers' sequence (b) Computed sequence

Fig. 23. Sequences of points of interest

- contextual environment perception,
- reading,
- pattern recognition,
- face recognition,
- autonomous moving,
- etc.

These different tasks are achieved very easily for sighted people, but they can be impossible for visually impaired people. For example, color perception cannot be operated by touch, by hearing, by the taste or smell. It is a pure visual sensation, unreachable to blind people. That is why the bionic eye must be able to replace the human visual system for such tasks.

In robotics, such a system able to explore an unknown scene by itself can be of a great help for autonomous robots. For example AUV (Autonomous Underwater Vehicles) can be even more autonomous by being able to decide by themselves what path to follow. Actually, by mimicking detection of points of interest, the bionic eye can determine obstacle position and then it can compute a path avoiding them. Furthermore, application fields are numerous:

- in archaeology and exploration in environments inaccessible to humans,
- in environmental protection and monitoring,
- in ship hull and infrastructure inspection,
- in infrastructure inspection of nuclear power plants,
- in military applications,
- etc.

Each time it is impossible for humans to reach a place, the bionic eye can be used to make decision or help making decision in order to drive a robot.

7. Conclusion

In this chapter, the bionic eye principle has been presented in order to demonstrate how powerful such a system is. Different approaches can be considered to stimulate either the retina or the primary visual cortex, but all the presented systems use a separate system for image acquisition. Images are then processed and data are turned into electrical pulses stimulating either retinal cells or cortical neurons.

The originality of our system lays in the fact that images are not only processed but analyzed in order to determine a sequence of focusing points. This sequence allows to explore automatically a complex scene. This principle is directly inspired by the human visual system behavior. Furthermore foveated images are used instead of classical images (sampled at a constant step in two orthogonal directions). In this way, every image processing algorithm even basic has to be redefined to fit to foveated images.

In particular, an algorithm for detection of points of interest on foveated images has been set up in order to determine sequences of points of interest. These sequences are compared to those obtained from a human observer by eye-tracking in order to validate the computational process. A comparison between detection of points of interest on regular images and foveated images has also been made. Results show that detection on foveated images is more efficient because it suppresses noise that is far enough from the focusing point while detecting as well significant points of interest. This is particularly interesting as the amount of data to process is greatly decreased by the radial re-sampling step.

In future works the two sequences of points of interest must be compared more accurately and their differences analyzed. Furthermore the computed sequence is the basis for the animation of the bionic eye in order to discover dynamically the new scene. Such a process assumes that the bionic eye is servo-controlled in several directions.

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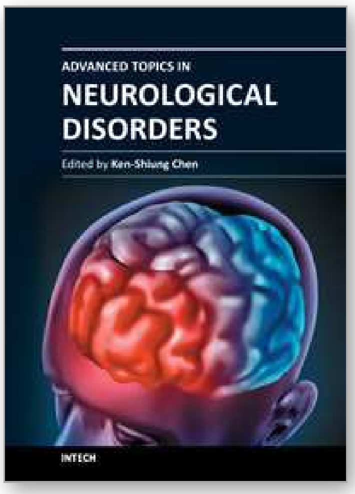

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This book presents recent advances in the field of Neurological disorders research. It consists of 9 chapters encompassing a wide range of areas including bioengineering, stem cell transplantation, gene therapy, proteomic analysis, alternative treatment and neuropsychiatry analysis. It highlights the development of multiple discipline approaches in neurological researches. The book brings together leading researchers in neurological disorders and it presents an essential reference for researchers working in the neurological disorders, as well as for students and industrial users who are interested in current developments in neurological researches.

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