

# Image Processing and Interface for Retinal Visual Prostheses

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**Abstract**— Controlled electrical stimulation of the retina can result in visual percepts in blind patients. In contrast to the over 100,000,000 photoreceptors in a healthy retina, even hundreds of pixels/electrodes of a retinal implant may restore low-resolution vision for unaided mobility and large print reading. We describe the real-time application of image processing techniques such as contrast and brightness enhancement, grayscale histogram equalization, edge detection, and grayscale reduction, to enhance visual perception provided by a retinal implant. We discuss schemes for reducing the amount of data transmitted wirelessly to the implant, as well as the interface between the external imaging unit and retinal implant.

## I. INTRODUCTION

A healthy retina has over 100 million photoreceptors. However, psychophysical tests have estimated that this number may be reduced to hundreds or thousands (e.g., 32 x 32 electrode arrays) of individual pixels in order to restore low-resolution vision that would enable a blind person to attain unaided mobility and large print reading, two important quality of life indicators. Scientific and technological barriers to realization of an effective visual prosthesis with thousands of stimulating channels are listed below:

- Development of image processing schemes such as real-time contrast and edge enhancement for effective stimulation enhancement and data reduction
- Development of a retinal, chip-driven electrode array with properties that permit efficient transfer of charge to the tissue
- Development of a more thorough understanding of the interaction of electrical current with the electrically and anatomically heterogeneous retina
- Development of learning algorithms that would allow blind patients to self-tune and fine-tune their individual retinal implant devices.

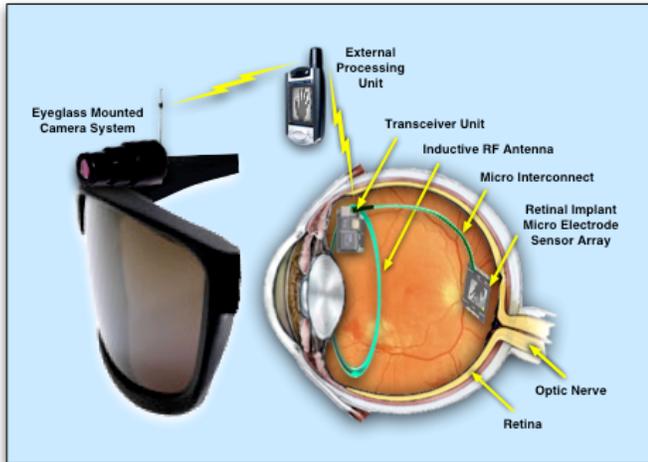
This paper will focus on the first bullet. Two possible approaches for retinal implants, an *epi-retinal* [1] and a *sub-retinal* [2], have been proposed and are currently being pursued [3]. In the sub-retinal approach, stimulating

electrodes are placed beneath the retina at the location of the retinal photoreceptor layer. In the epi-retinal approach the prosthetic device is placed on the surface of the retina to stimulate predominantly the retinal ganglion cell layer. Consisting of several subsystems, it is primarily divided into implanted and external components (Fig. 1). *External* components include a camera, image processing unit, and bi-directional telemetry. *Implanted* components include bi-directional telemetry, hermetically packaged electronics, and a multi-channel electrode array. The implanted electronics perform power recovery, management of data reception and transmission, digital processing, and analog output of stimulus current.

Previous studies for the epi-retinal implant have shown that controlled electrical stimulation of the retina results in visual percepts in blind patients. Humayun and his team recently reached an important milestone in the development of retinal prostheses with the implantation of an active stimulating device in a blind human [4]. The patient had reported vision loss for 50 years from retinitis pigmentosa (an inherited condition in which all photoreceptors are eventually lost) and had documented no light perception in the eye before implantation of the device. When the 16-electrode device (4 x 4 electrode matrix) was activated one week after implantation, the patient perceived spots at all 16 electrodes. Further testing demonstrated spatial discrimination between two electrodes that allowed the ability to discern gross movement of objects in the field of the patient's camera.

## II. IMAGE PROCESSING

The human retina is not a mere receptor of photonic information, but performs significant image processing due to its layered neural network structure. The precise processing of information from the photoreceptor layer to the optic nerve is not fully understood. The current state-of-the-art and near future epi-retinal implants provide only tens of electrodes, thereby allowing only for a very limited visual perception (pixelization). Therefore, it is crucial to enhance this limited perception by means of image processing. Clearly, the relatively high resolution of the external video



**Figure 1.** An intraocular retinal prosthesis will use an external microelectronic system to capture and process image data and transmit the information to an implanted microelectronic system. The implanted system would decode the data and stimulate the retina with a pattern of electrical impulses to produce a visual perception.

camera for a retinal implant carrier is not immediately suitable for the stimulation of the retina via the retinal implant chip and its electrodes. Rather, an “intelligent downscaling” (pixelization) of the camera image has to be performed that attempts to preserve the content of the image as much as possible. Since tens of pixels/electrodes allow only for a very crude approximation of the about 10,000 times higher optical camera resolution, the preservation of contrast differences and transitions, such as edges, becomes very important as opposed to picture details such as texture.

As an example consider a slightly darker grayish hand (see III) in front of a grayish wall, or a slightly off-white door within an otherwise white wall. This poses an almost impossible task for a retinal implant carrier to master in terms of autonomous mobility. However, using appropriate image processing modules this task becomes feasible even for a 4 x 4 electrode retinal implant carrier, as can be seen from the following: 1) pixelization (via averaging of the gray values of the pixels of the original camera image that feed into one resulting pixel for the electrode array) of the camera image down to the dimensions of the electrode array has to be performed, possibly displaying the door with only one pixel column; 2) contrast/brightness enhancement and/or grayscale histogram equalization has to be applied in order to let the door appear almost black as opposed to the white wall. Neither the texture of the white wall nor the texture of the door itself is in first order important for the retinal implant carrier in order to safely navigate through the door. However, the fact that the formerly invisible door appears now as a black one-pixel-wide column in the 4 x 4 pixel matrix enables the patient to aim for the black column and eventually find his way through the door safely.

In another instance, image processing can also significantly reduce the amount of data, i.e., data rate, to be transmitted to the retinal implant chip. As far as state-of-the-art retinal implants are concerned, the creation of color impression is not attainable as of yet. Therefore, a first reduction of the data rate is achieved by converting the color camera image to a gray-scaled image with a range of 256 grayscale values (8 bit per pixel). A second (obvious) major data reduction occurs during the pixelization process. Once the above mentioned image processing modules have been employed, a third stage of data reduction can be achieved by reducing the 256 grayscale values (8 bit resolution) to a lower number that still is sufficient to adequately represent the pixelated image, e.g., 32, i.e., 5 bits, or even lower (see III).

In a third instance, image processing can further reduce the amount of data to be transmitted by performing real time edge detection with subsequent binary gray scaling to reduce the data transmission to one bit (on/off) per pixel only.

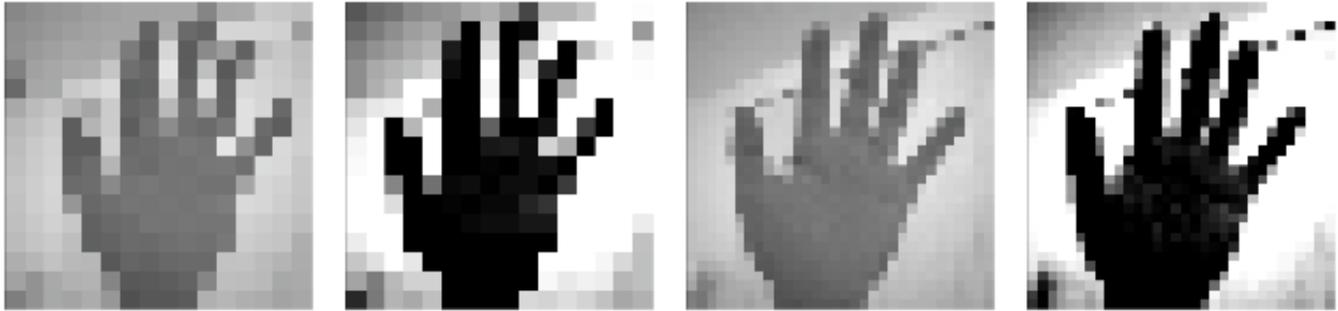
### III. IMAGE PROCESSING RESULTS

We have created a software package, the *Artificial Vision Simulator (AVS)* (full details provided in [5]), that interfaces with Firewire (IEEE 1394) cameras and presents the captured video stream in a user-defined pixelization, mimicking the visual perception with a retinal implant electrode array, on both a computer monitor and a head-mounted display. The software package comprises numerous efficient image manipulation and processing algorithms/modules [6, 7] that have been developed to modify the captured video stream in *real time* (30 fps) such as:

- Video pixelization to simulate the vision provided by a retinal implant electrode array
- Contrast and brightness correction/enhancement
- Grayscale histogram equalization for luminance control under severe contrast and brightness conditions
- Reduction of available (user-defined) grayscale levels
- Edge detection.

Fig. 2 shows the visual perception of a hand with a gray-resolution of 8 bits per pixel as generated by the Artificial Vision Simulator software package for a patient wearing a 16 x 16 electrode retinal implant with and without image enhancement as well as the four times higher resolved visual perception of the same hand with a 32 x 32 electrode retinal implant with and without image enhancement. In both cases the contrast was enhanced to bring out the hand in the otherwise fairly low-contrast scene.

Fig. 3 demonstrates the effect of grayscale histogram equalization (left image): instead of a more or less



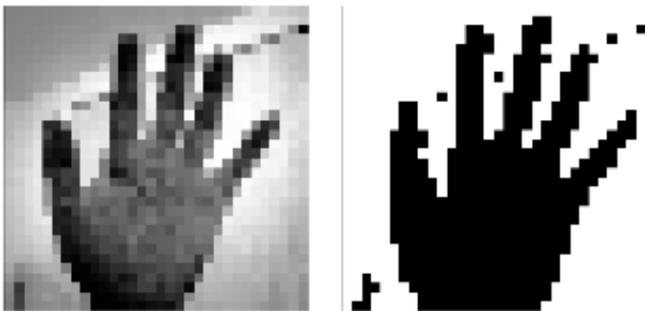
**Figure 2.** Visual perception of a hand with a gray-resolution of 8 bits per pixel, generated with the *Artificial Vision Simulator* software package for a 16 x 16 electrode retinal implant *without* image enhancement (1<sup>st</sup> image); 16 x 16 electrode retinal implant *with* image (contrast) enhancement (2<sup>nd</sup> image); 32 x 32 electrode retinal implant *without* image enhancement (3<sup>rd</sup> image); 32 x 32 electrode retinal implant *with* image (contrast) enhancement (4<sup>th</sup> image).

homogeneously gray hand or dark gray hand in the case of contrast enhancement, the hand appears to be more plastic, i.e., three dimensional, revealing more texture. The right image of Fig. 3 demonstrates how a data reduction without a significant image content loss can be accomplished by reducing the gray-resolution from 8 bits per pixel (256 gray shades) to 1 bit per pixel (black/white) in real time.

#### IV. INTERFACE BETWEEN IMAGING UNIT AND IMPLANT

In the visual prosthesis system the interface between imaging unit and retinal implant consists of two digital controllers: an external one and an implanted internal one.

The external controller receives the manipulated camera input for each pixel after the image processing described below. The ultimate goal is to conserve the power dissipation in the implant. With a close evaluation of the bi-directional telemetry unit, our study also shows that the overall system energy efficiency can be optimized if the stimulation pixel sequence as well as image processing techniques stated in this paper such as image averaging and enhancing are chosen. Thus this external unit also has an embedded intelligence to provide an optimal stimulation sequence based on each image in addition to the image processing. The controller essentially acts as a parallel-to-serial converter. During the parallel-to-serial conversion, the



**Figure 3.** Visual perception of a hand generated with the *Artificial Vision Simulator* software package for a 32 x 32 electrode retinal implant with image enhancement – grayscale histogram equalization (left); 32 x 32 electrode retinal implant with data reduction by converting the 8 bit per pixel gray-scaled image to a binary (1 bit per pixel) image (right).

controller can also set the order of the stimulation of the individual electrodes. The stimulus data will consist of anodic amplitude, cathodic amplitude, anodic phase width, cathodic phase width, and interphase delay. The stimulus data for all the electrodes can be serially arranged in one data packet with header and error detection codes without any address bits; this requires the minimum uncompressed data rate since the electrodes are addressed in a preset fashion.

Fig. 4 shows two data packets – configuration data and image data used for communication between the external and implant unit for a 60 output retinal prosthetic system [8]. The image data consists of stimulus information arranged for 60 drivers. The configuration data consist of packets that are sent occasionally to set the maximum stimulation currents and stimulation profiles. This can be automatically set up with a human interface mechanism shown in Fig. 5 [8]. Both data packets have a CRC signature and checksum for error detection.

On the implant side, upon wirelessly receiving the data packets, they are serially shifted into the registers of the individual drivers. After the packet is completely shifted in, the computed values of CRC and checksum for the shifted data are compared against the signatures embedded in the packet. If the CRC and checksum signatures both match, then the configuration data are assumed to be error-free and are subsequently latched into internal registers allocated to the configuration data where they become resident and take effect. Otherwise, the data are ignored and subsequently overwritten as new packets are shifted into the implant IC. In this type of data format, the order of the electrode stimulation cannot be controlled by the external controller but only by the internal controller implanted in the eye that controls the micro-stimulator, the actual electrode array (Fig. 1). This is done by buffering the serial data into registers and sequencing the stimulation in an order that is preset or configured periodically. In another variation of the communication protocol, each driver's stimulation parameters can be transmitted as an independent data packet, which increases the data rate (since each data packet

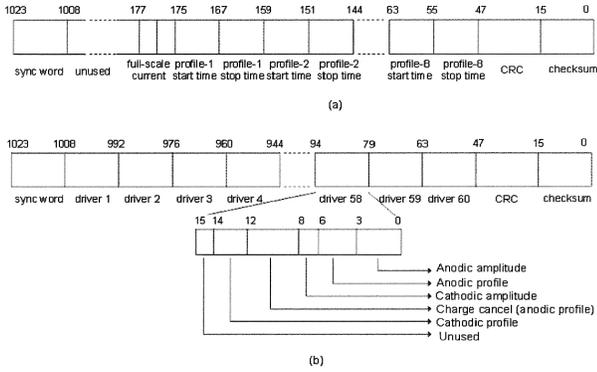


Figure 4. Packet protocol for (a) configuration data and (b) image data.

should be accompanied by the electrode address) but provides complete flexibility in regards to the order of stimulation. In this case, the order of the stimulation can be directly controlled by the external controller.

The internal controller can operate in a mode where buffering is not required. Each driver stimulates the electrode immediately after the data is loaded in its registers. The buffering feature can still be made available in this case, allowing the option of simultaneous stimulation of the electrodes. The current pulses to the electrodes are generated by the micro-stimulator. The stimulation data, which are in digital format, are converted to biphasic stimulus pulses through a driver circuitry, which consists of digital-to-analog converters, stimulus drivers and charge cancellation circuitry [9].

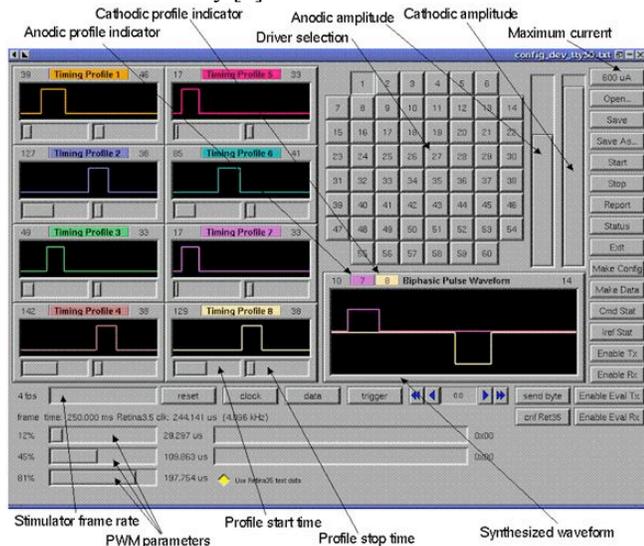


Figure 5. Interface between external imaging unit and retinal implant: The interface allows clinicians to set the stimulation parameters, including pulse amplitude, pulse duration, and inter-phasic delay, at each pixel level. The interface automatically assembles the parameter specifications into the proper protocol for data transmission.

## V. SUMMARY

We have shown that image processing can not only enhance the visual perception of a retinal implant carrier but, in addition, can provide means to simultaneously reduce the amount of data, i.e., data rate, to be transmitted to the retinal implant chip that controls the electrodes, which stimulate the retina. Furthermore, we have shown that image processing and retinal implant chip design are strongly coupled. This strongly coupled design provides a way to achieve optimal power efficiency for an epi-retinal implant. We are in the process of establishing psychophysical experiments with retinal implant carriers to evaluate the actual perception enhancement due to image processing.

## ACKNOWLEDGMENT

The work described in this publication was carried out at the California Institute of Technology and the University of California, Santa Cruz under support of the National Science Foundation Grant EEC-0310723.

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