Retinal Prosthesis to Aid the Visually Impaired*

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Abstract

In this retinal prostheis project, a rehabilitative device is being designed to replace the functionality of defective photoreceptors in patients suffering from Retinal Pigmentosa (RP) and Age-Related Macular Degeneration (AMD). An implantable intraocular unit receives power and signal via a telmetric inductive link with an extracoluar unit. The extraocular unit consists of a video camera and video processing board, a telemetry protocol encoder chip, and an RF amplifier and primary coil, while the intraocular unit consists of a secondary coil, a rectifier and regulator, a retinal chip with a telemetry protocol decoder and stimulus signal generator, and an electrode array. This paper describes the design and testing of the overall system components.

1. Introduction

Over 10,000,000 people worldwide are blind because of photoreceptor loss due to degeneraitve retinal diseases such as age-related macular degenration (AMD) and retinitis pigmentosa (RP). The retinal prosthesis under development is based on the concept of replacing photoreceptor function with an electronic device. In a healthy retina, the photoreceptors initiate a neural signal in response to light. Photoreceptors are almost completely absent in the retina of end-stage RP and AMD patients. However, cells to which photoreceptors normally synapse, (i.e. the next neuron in the signal path) survive at high rates [1]. Previous clinical studies have shown that controlled electrical signals applied to a small area of the retina with a microelectrode can be used to initiate a local neural response in the remaining retinal cells [1,2,3,4]. The neural response was perceived by otherwise completely blind patients as a small spot of light. When multiple electrodes were activated in a two dimensional electrode array, a number of small spots of light were perceived by the patients, which when viewed together formed an image representative of the pattern of active electrodes. In the experiments reported by Humayun [1], simple forms such as an english character or a matchbox have been perceived by human subjects when pattern electrical stimulation of the retina was invoked. When controlled pattern electrical stimulation of the remaining retinal neurons is coupled with an extraocular image acquisition and transmission system, it can allow blind patients to regain form vision of their environment as perceived by an extraocular vidoe camera. The basic concept is illustrated in Fig. 1.

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2. Evolution of Engineering Approaches

Our fist generation design consisted of the dual unit visual intraocular prosthesis, consisting of a photosensing, processing, and stimulus-driving chip for a 5x5 electrode array [5] . It was demonstrated that the chip was capable of delivering the requisite currents for retinal stimulation in humans, as were determined by clinical studies conducted on visually impaired patients with RP and AMD.

However, it became apparent that it would be to our advantage to have the video capture performed extraocularly, since extra image processing may be required before the retinal neurons are stimulated. Currently, we are developing a dual-unit prosthesis system which is conceptually illustrated in Fig. 1. The implantable intraocular unit receives power and video signal via a telemetric inductive link with the extraocular unit. The extraocular unit includes a video camera and video processing board, a telemetry encoder chip, and an RF amplifier and primary coil, while the intraocular unit consists of an intraocular secondary coil, a rectifier and regulator, a retinal chip with a telemetry protocol decoder and stimulus signal generator, and an electrode array. The system block diagram is shown in Figure 2, with the three fundamental blcoks being 1)external video camera and prcoessing 2) telemetric link, and 3) intraocular processing and stimulating unit.

The extraocular unit captures an external picture with a video camera and provides additional image processing whose output is further encoded with a specific data transmission protocol. Two categories of data, image and configuration, are distinguished by bit patterns in the transmission protocol. The data is processed by a pulse width modulation circuit (PWM) with amplitude shift key modulation (ASK). At this stage, the image/configuration data has been mixed with the carrier frequency of 1 MHz – 10 MHz. The modulated signal is then inductively transmitted to the intraocular unit, providing telemetric power and signal. The PWM modulated data signal is separated from the carrier by the filter in the intraocular unit. The filter design dictates the ratio of carrier frequency to that of the data rate. In our design, the data rate is 25–250 kbits/s. Constant DC power, independent of the data stream, is obtained from rectification and regulation of the carrier waveform. A digital signal is extracted from the PWM data signal by the telemetric protocol decoder within the intraocular unit, and it controls the generation of the current pulses which stimulate the retina via the electrode array.

Concurrent designs of the various component blocks in Fig. 2 are being pursued in this project. Detailed description of the design and testing of a chip which accommodates the telemetry function, protocol receiver, and current driver can be found in the paper [6]. The chip serves as a flexible current waveform generator and it could potentially determine the optimum of stimulus waveforms via implanted experiments. The chip provides the charge-balanced current with a biphasic waveform (annode phase first followed by a cathode phase) as shown in Fig. 1.

3. Intraocular and Extraocular Units, and Telemetric Link

The system will be composed of two units, an extraocular and an intraocular one, as shown in Fig. 1 and 4. The two units are connected by a telemetric inductive link, allowing the intraocular unit to receive both power and a data signal from the extraocular unit.

The extraocular unit includes a video camera and video processing board, a telemetry protocol encoder chip, and an RF amplifier and primary coil, while the intraocular one consists of an intraocular secondary coil, a rectifier and regulator, a retinal chip with a telemetry protocol decoder and stimulus signal generator, and an electrode array, pictured in Fig. 5.

3.1 Extraocular Unit: Video Camera and Video Processing Board

The portion of the prosthesis which is exterior of the eye consists of an image acquisition device, and image processing device, and a power and data delivery sub-system serving the implanted retinal stimulator. The power and data link to the interior electronics is implements inductively through an external and implanted coil which couple through air. This subsystem is further discussed in the section on inductive link design and implementation.

A number of image acquisition devices, or mini-cameras, are available and suited to this application. Integrated camera have so matured that it is now possible to have photo-sensors and most or all of the support electronics integrated on a single microchip. The bulk of most mini-cameras now consists in the lens assembly. CCD cameras have represented the dominant implementation of electronic camera to date. Now CMOS cameras represent a power-efficient alternative for portable applications such as the retinal prostheis. Some CMOS camera provide image output in the form of a BW analog or composite color analog video signal in the NTSC or similar format. Digital image processing hardware digitizes this video signal with using an A/D converter for further processing. However, digital B/W and color CMOS cameras have now begun to appear which have the A/D conversion co-integrated with the image sensor on a common CMOS microchip. The retinal prosthesis uses a color camera of this type.

The role of the image processing device is to prepare digital data in images provided by the camera for delivery to the retinal stimulator. The stimulator accepts instructions on generating bi-phasic stimulation pulses. The image processing device transmits this data to the stimulator. A block diagram of the image processing electronics is shown in Fig. 4. The format and protocol of data provided to the stimultar is discussed in the section on chip functionality. An FPGA/EPLD (Field Programmable Gate Array)/(Electrically Programmable Logic Device) represents is the heart of the system. An FPGA is a digital device which is programmable as is a microprocessor except that highly-parallel algorithms or hardware needed for concurrent processing can be exploited via an FPGA whereas this is more difficult with a single processor. Any vision algorithms needed prior to data delivery to the stimulator can be described in a hardware description language. The FPGA allows its flexible architecture to be configured to implement this custom hardware.

Three SRAM memories serve as frame bufffer on the board to support the storage of images delivered via the camera. Two SRAMs support dual-buffered video, whereby a current image in transit from the camera can be stored, while a prior image can be simultaneously processing from a second memory. Once the camera has completed delivery of a transit image, the roles of the memories are reversed, such that the new image is processed while a new image is stored in the alternate RAM. A third frame buffer is available for intermediate computations as may occur in algorithms such as spatial convolution. Three separates SRAMs are available for arbitrarily re-ordered readout of stored images during processing.

An 8-bit pipeline A/D converter is available on the board to support cameras which provide only analog video. Low bandwidth communication with the board is possible via an integrated RS232 transceiver. Higher bandwidth links such as PCMCIA, USB, or firewire can also be integrated into the architecture as future extensions.

The camera can be fitted to glasses to be worn by the individual. The image processing board can be worn is a shirt pocket or clipped on a belt. Batteries (not addressed here) are relatively heavy compared with the camera and image processor. These can be integrated into a waist-belt. Thus a portable and ergonmic prototype for the prosthesis can be acheived.

3.2 Intraocular Unit: Telemetric Retina Chip and Electrode Array

3.2.1. Chip Functionality

Fig. 5 shows the functional blocks of the implantable prototype retina chip, which is the heart and soul of this retinal prosthesis. The chip operates in two modes, configuration and run mode. The Amplitude Shift Key (ASK) demodulator receives the ASK envelope from the rectifier output, and generates the digital pulse width modulated signal to the clock and data recovery circuit. In this circuit, data and clock signal are recovered by a Delay Locked Loop (DLL) and a decoder circuit. The synchronization circuit detects a syncword and starts the chip into configuration mode. In this mode, the timing generator circuit is then configured to generate signals controlling the timing and the current control circuit is set up to control the amplitude of biphasic current pulses. This information is then used to control the current drivers and the current demultiplexers of the 20 electrode stimulator circuits. Once the configuration process is completed, the chip automatically starts the run mode. With multiplexing, the 20 electrode stimulators drive the configured biphasic current pulse through the 10x10 electrode array. The details of each block are described in this section.

3.2.2 Electrode Array

The final design of the MARC device is largely contingent upon the material chosen for the electrode array. If the electrode array is fabricated upon a polyimide material, then the possibility for creating connecting ribbon cables upon the polyimide exists. One may also solder-bump chips or chip carriers to the polyimide, and one could fabricate an RF coil upon the polyimide. On the other hand, if the electrode array is fabricated upon a silicon or silicone gel substrate, as shown in Fig. 6, then interconnecting ribbon cables will have to be wirebonded to the processing chips and the electrode arrays. The final design depends upon currently evolving technologies and methods of packaging chronic implants. An advantage of the silicon-gel electrode array pictured in Fig 6 is that it has been demonstrated to work in over ten clinical studies [1].

3.2.3 Telemetric Link

There have been numerous analyses and approaches to the design and fabrication of magnetic transcutaneous links[7,8,9,10]. These studies have attempted to both accurately characterize and maximize the coupling efficiency and displacement tolerance in the design of the transmitting and receiving coil circuits. Because axial, lateral, and angular misalignment of the two coils leads to changes in the coupling efficiency, efforts have been made so as to make the transmission of energy via RF less sensitive to coupling displacements. The primary coil of the retinal prosthesis, pictured in Fig. 3, will be driven by a Class E driver, similar to that which was developed by [11] and [12]. The Class E driver uses a multi-frequency load network, takes advantage of the impedance transformation inherent to the network, and is a switched-mode resonant driver; with the active device acting as a switch. The Class E point, or Class E mode, is characterized by voltage and current waveforms which are 180 degrees out of phase, and thus P=IV dissipation in the primary coil is kept to a minimum. This results in nearly zero power loss in the switch. The Class E amplifier would be less taxing on an external battery, which could be made smaller, and a circuit board is currently being fabricated for the amplifier.

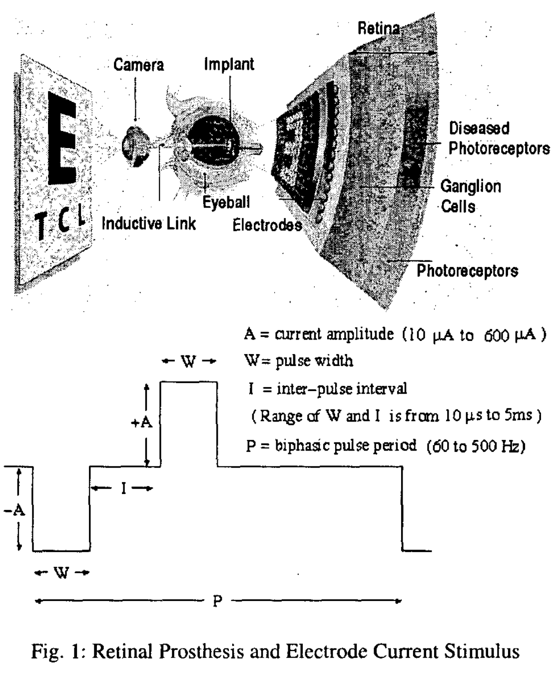


Fig. 1: Retinal Prosthesis and Electrode Current Stimulus

4. Conclusion

A retinal prosthesis system has been engineered in accordance with groundbreaking clinical data regarding retinal stimulation by electronic means. Its architecture contains two separate units: a front-end extraocular image-processing mounted on glasses, and the intraocular current stimulator device to be implanted within the eyeball. Data and power transfer between the units is accomplished via inductive coupling. The prototype implantable device is capable of recovering data and power and generating a flexible stimulus waveform with the requisite characteristics for retinal stimulation. The next step towards an artificial retinal prosthesis will be to develop the fourth generation MARCs which will be capable of driving a 25x25 electrode arrays, and testing the devices for short periods within a human. The implications of this research may extend beyond this immediate project, as contributions are made to the overall field of chonically implanted prosthetic devices, telemetric monitoring and control, and hermetic packaging. The observations and clinical and engineering experiments performed should lend insight into the actual functioning of the human retina. The feedback gained by these studies should provide a vehicle for further understanding of the retinal/vision/perception process. It is expected that a chronically-implanted retinal prosthesis will be realized in a few years.

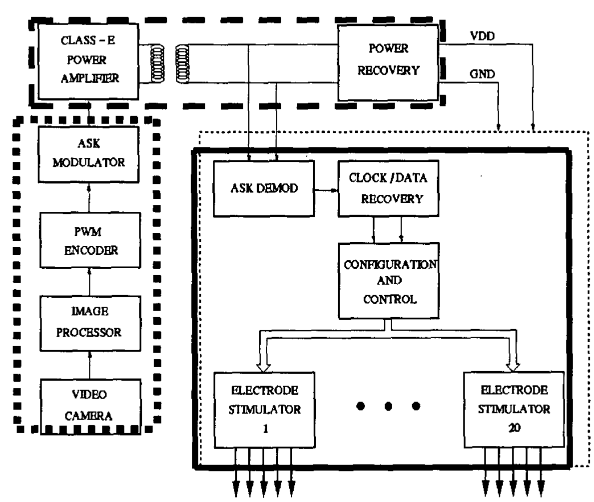


Fig. 2 System Block for Prosthetic Device

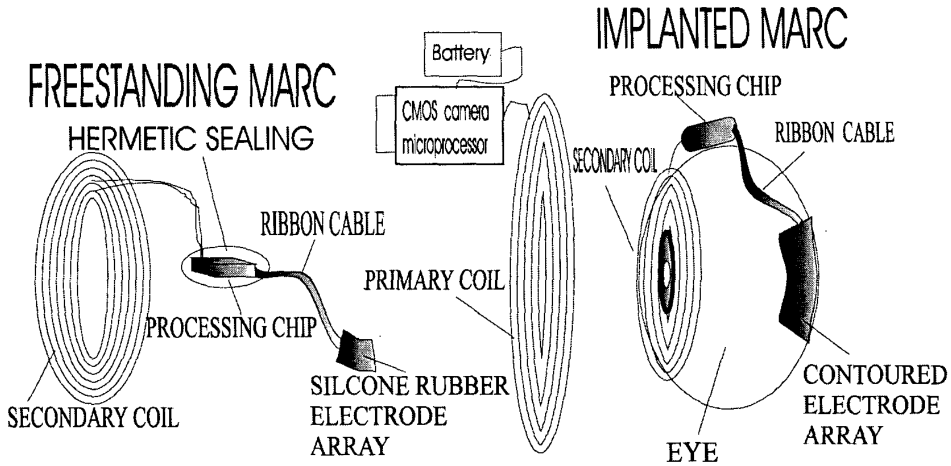
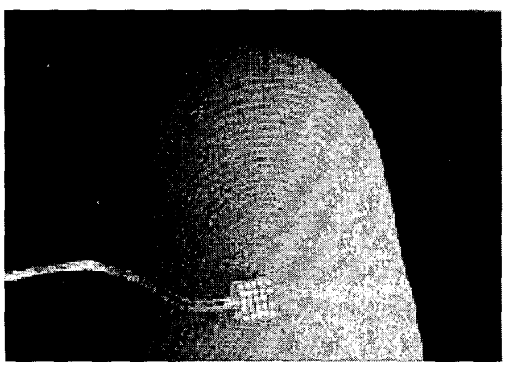


Fig 3: General design and RF coil configuration of Multiple Unit Artificial Retina Chipset (MARC) system. Secondary coil may also be implanted intraocularly.



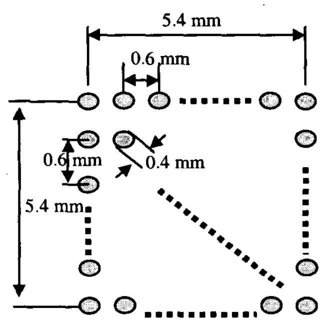


Fig 6: RF coil configuration of MARC system. Secondary coil may also be implanted intraocularly.

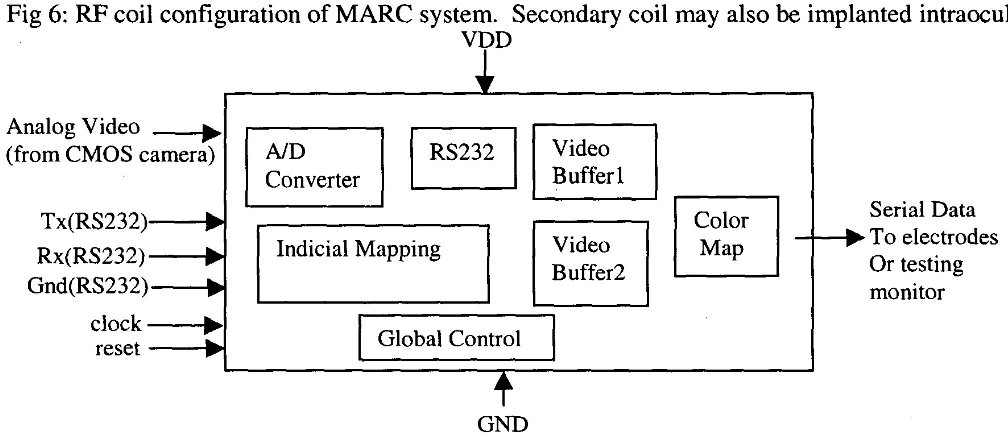


Fig 4: Block diagram of front-end MARC image acquisition system.

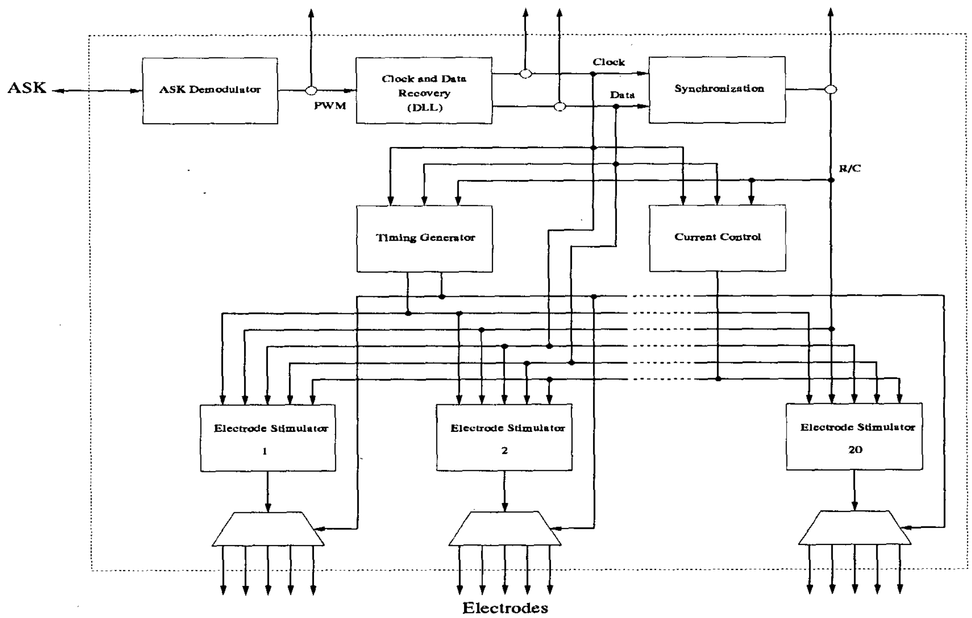


Fig. 5 Chip Block Diagram

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