Introducing the Monash Vision Group's Cortical Prosthesis
AJ Lowery
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INTRODUCING THE MONASH VISION GROUP'S CORTICAL PROSTHESIS

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ABSTRACT

Monash Vision Group is developing a bionic eye based on implanting 7-11 small tiles into the visual cortex. Each tile has 43 active electrodes on its base, and a wirelessly powered electronic system to decode control signals and drive the electrodes with biphasic pulses. The tiles are fed with power and data using a common transmitting coil at the back of the patient's head. Sophisticated image processing, described in a companion paper, ensures that the user experiences maximum benefit from the small number of electrodes. This paper describes the progress in the first three years (2010-2012) of this four-year project.

Index Terms— Visual prosthesis, bionic eye, visual cortex, cortical implant, electrostimulation.

1. INTRODUCTION

The restoration of sight is a noble goal and has driven much innovative research [1-3]. The majority of effort has gone into developing retinal implants to replace damaged photoreceptors, by stimulating the ganglion cells with small electric currents that are related to the image received by a small camera, or by independent photodiodes located close to the electrodes. These retinal implants can only serve a proportion of the clinically blind population, and are particularly unsuitable for those who have lost their sight through traumatic injury or diseases in the eye or optic nerve.

The Visual Cortex offers another access point to the visual pathway [4-7]. In particular, the V1 region is the first area of the cortex that processes vision, and there is a reasonably consistent spatial mapping between the image received at the retina and where it is processed on the surface of the cortex, albeit with more surface area dedicated to central (foveal) vision than for peripheral vision. This distortion is actually an advantage, as images from the 1-mm^2 area of the fovea is processed by approximately 500-mm^2 of the cortex. Thus, for a given spacing of electrodes, we can obtain a 20× advantage in resolution over a retinal implant. Another advantage is that the V1 region lies mostly on the surface of the brain so is easily accessibly using a standard craniotomy, in which a piece of skull is removed by milling a narrow trench along its edges, for later replacement. The prostheses can then be attached to the brain.

In the early 1960's Brindley and Lewin [5] pioneered the stimulation of the surface of the visual cortex, firstly by exciting one electrode at a time, then by stimulating several electrodes. Each electrode was powered by a simple receiver coil and resonant capacitor, with a diode envelope detector – very similar to a 'crystal set' radio. The transmitters were arranged radially outside the skull, and were large and heavy, making movement impossible. Dobelle [7] use a wired approach, gain with surface electrodes, and with relatively simple signal processing from a large head-mounted camera. The last patients were implanted in the early 2000's.

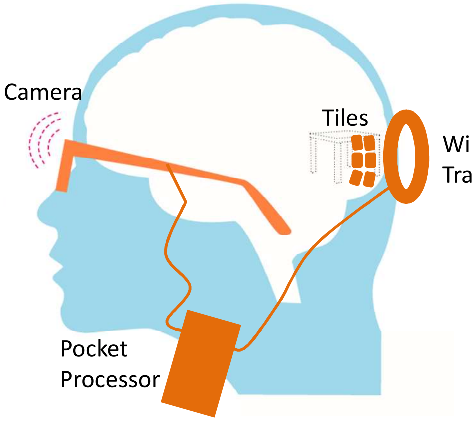

Fig. 1. Artistic impression of the Monash Vision Group's Bionic Vision System (Courtesy, Monash University).

We are developing cortical implants to the stage that they can be implanted in humans, especially as they offer a solution to traumatic eye damage due to explosions. This paper serves as an introduction to our bionic vision system, which is in development by a partnership between Monash University, Grey Innovation, MiniFAB and The Alfred Hospital, all located in South-East Melbourne, Australia.

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The group is truly multi-disciplinary and has drawn on the skills of analog and digital electronics engineers, robotic vision specialists, surgeons and ophthalmologists, physiologists, including experts in the human visual pathway and electro-stimulation, mathematicians, immunologists, materials and mechanical engineers, psychologists and people who are clinically blind. This paper will present the basis of cortical vision systems, and the technologies that we have used to overcome the challenges of developing a miniaturized electronic system. The paper takes an electrical engineering approach to a biomedical engineering problem.

2. MVG'S CORTICAL PROTHESIS

Our approach is to use penetrating electrodes, as we can greatly reduce the stimulation current by one or two orders of magnitude, compared with surface electrodes. The method of stimulation is to inject a negative current from an electrode inserted about 2-mm into the surface of the cortex. This is the input layer to the visual processing of V1. The current spreads away from the electrode, causing a voltage drop (a potential field) across the tissue surrounding the electrode [8]. This tissue comprises neuronal cell bodies, with dendrites as inputs and axons as outputs.

The stimulation caused by this potential field is mainly of the axons [9]. An axon can be considered as an insulating tube filled with conducting ions. Through the membrane forming the tube are voltage-gated channels and ion pumps. The ion pumps maintain a high concentration of potassium within the axons, which causes a potential across the axon's membrane – the resting potential, which is around -70 mV. If this potential can be made less negative, voltage-gated sodium channels will open, causing a huge increase in (ionic) permeability for sodium which has a high-concentration outside the axon. This causes the membrane potential to move positive, creating an 'action potential'. This spike then propagates along the axon to neighboring voltage-gated channels, causing them to open. Thus, if we can alter the membrane voltage at any part along the axon, we can get the channels to open, and the axon to transmit a 'false' message along itself to neurons. This occurs if there is a sufficient transient longitudinal field gradient imposed along the axon [8]. Typically 50 μA pulses of 100 μs duration will cause a visual sensation. Normally a pulse of the opposite polarity is then applied to discharge the charge around the electrode, which can cause biocompatibility problems if too much charge accumulates.

Because we are penetrating the cortex, we can get reasonably localized stimulation around each electrode, thus each electrode generally gives rise to a separate visual sensation, or *phosphene*, which appears as a grey or colored disk. We are placing our electrodes at a spacing of approximately 1 mm, for a variety of reasons including reducing mechanical damage to the brain. Thus, we expect to be able to implant in the order of 300-500 electrodes, in groups of 43. This, of course, is far fewer than the typical resolution of the eye, which may have 1-2 million 'pixels'. Fortunately, computing power and miniaturization of computing devices has come a long way in the last 10 years. This has enabled extremely-sophisticated image processing methods to be proposed and implemented in pocket-sized devices, to extract the most important features from the camera's high-resolution image. This work will be presented in a companion paper [10].

3. PROTHESIS AS A COMMUNICATIONS SYSTEM

The signal flow of the system can be likened to an early television system. A relatively high-resolution camera converts images into electrical signals. These are then processed by the electronics in the studio to make them suitable for transmission to many users in the home. The key is to make the home appliance cheap and reliable, so that it will be adopted by many consumers. On the other hand, the electronic processing in the studio can be complex and so less reliable, as it will be serviced by expert technicians. Thus, complexity is best placed in the studio, by designing the transmitted waveforms so they are easy to decode.

In a wireless prosthesis, the same rules apply: the camera and external signal processing can be complex and so less reliable – for they can be replaced without surgery; the implants have to be simple and extremely reliable – for replacement requires a craniotomy to access them in our case. In early cochlear implants, ingenious signaling formats were used to minimize the complexity of the implants, similar to the framing of 1950's raster-scan TV systems. Because digital logic has shrunk significantly in the last 20 years, we can use far more sophisticated signaling formats, with error correction. The communications data rate is considerably reduced by only occasionally setting up the currents and pulse durations that will be applied to each electrode when they are commanded to turn on; this means that only a 1-bit command (not including the error correction overhead) is required to turn on a particular electrode, rather than tens of bits. Of course, the stimulation is limited to 'on and off' rather than a greyscale in this version of the project. To perform this processing and implement the registers that store the settings, we have designed a 500,000-transistor mixed-signal ASIC to fit inside each of the implant tiles.

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A second likeness to a communications system is the power budget. Unlike television, we must supply power to the implants via a wireless link, sufficient to cause axonal stimulation. Unfortunately, every device between the battery and the axon being stimulated causes a loss in power, with the greatest proportional losses being across the wireless link, and between the electrode and the cytoplasm of the target axons. The wireless link can be improved by using resonant transmitters and receivers and reducing resistive losses within these, and by increasing the mutual inductance between the transmitter and receiver coil. The electrode loss can be improved by designing the electrode to produce a controlled electric field around it with a high derivative sufficient to drive currents along the axon's cytoplasm, to invoke an action potential [9].

4. ELECTRONICS

4.1. Camera and Image Processing

High-resolution miniature digital cameras are cheap and plentiful, thanks to hand-held computing devices, so will not be discussed further. The high-resolution image from the camera is fed to a custom-designed Pocket Processor (Fig. 2), which applies a number of signal processing techniques, such as transformative reality, to extract the most useful features from the image. The pocket processor has been designed for long battery life and ergonomics. It has six buttons as controls, and a single port for connection to the camera and the wireless transmitter using a Y-shaped lead. The single port ensures that it cannot be connected to a power source and used at the same time, for safety. Much of the size of the pocket processor is the battery. Rather than having a removable battery, we use a rechargeable high-capacity Lithium-Polymer battery. Each recipient will be provided with two Pocket Processors, so that one can be charged while the other is used.

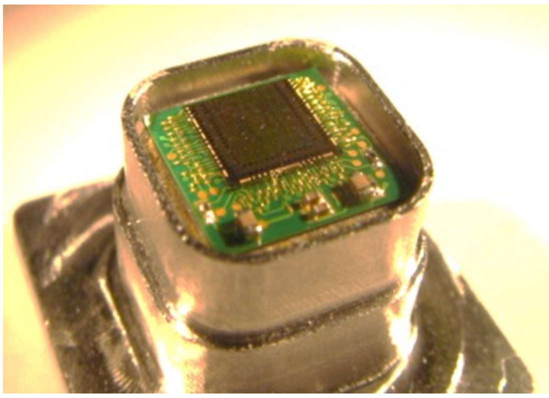

Fig. 2. Computer-generated image of the Pocket Processor (Courtesy, Grey Innovation).

4.2. Wireless power and data link

The multiple implant tiles are powered and fed data through a single link. This is an inductive link, with a tuned resonating transmitter coil and resonating receiver coils within each implant (Fig. 3), separated by 1-2 cm. The resonances ensure that the power efficiency is maximized between the transmitter and receiver, even though the coupling (related to the mutual inductance) is very weak. This is very similar concept to the 'intermediate frequency transformers' in analog radio receivers. A downside of the resonance is that the bandwidth of the data signal is restricted, leading to slow rise and fall times of the data modulation. The 100 kbit/s data is amplitude-modulated onto a 5-MHz carrier.

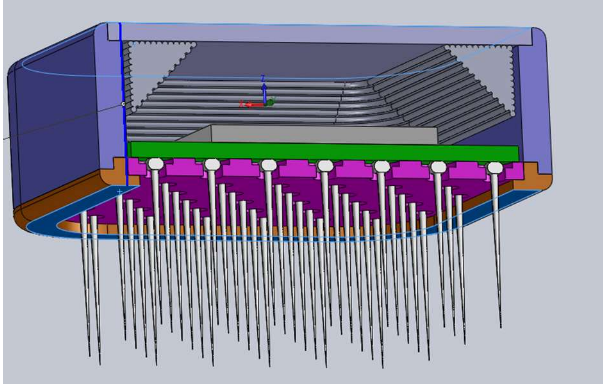

Fig. 3. Cross-section of the Implant Tile. The Wireless receiver coil sits at the top of the package. Size is 9 mm × 9 mm × 5 mm. (Courtesy, MiniFAB).

4.3. Implant Tile

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Each Implant Tile (Fig. 3) contains a receiver coil, which is tuned to the transmitter. A diode rectifier is used to extract power and its output smoothed and regulated to supply the ASIC. Another diode is used as an envelope detector for the modulation, and filtered using a short time-constant. The ASIC contains a thresholding AM receiver with error correction. The ASIC contains sufficient registers so that the pulse parameters for each electrode can be set individually via the wireless link. A brown-out detection circuit ensures that the link is reset if the registers lose power and become corrupted. The electrodes then can be commanded to produce a pulse (actually a bi-phasic pulse comprising a positive and negative pulse with settable timing and maximum currents). Each electrode driver contains a 5-bit DAC and a pair of current sources to drive the electrode with positive or negative currents. The ASIC is connected to the electrodes via a multi-layer distribution board, and early version of which is shown in Fig. 4.

Fig. 4. ASIC on distribution board in its assembly jig. The ASIC (black) is 4 mm × 4 mm. (Courtesy, MiniFAB).

5. IMPLANTATION

A key to the success of the project is developing the surgical technique. The aim is to implant the electrodes through a thin covering of the brain called the *pia mater*. This is like a thin plastic food wrapping: the brain being similar to butter. Thus, the electrodes need to be punched through the *pia mater* at a reasonable speed [11] otherwise the brain will simply move out of the way. Because each person's brain is slightly different, we will use high-resolution MRI to identify V1. Fig. 5 shows a typical image where the image processing has been asked to trace-out the visual pathways (red) that radiate out to V1 (bottom of image – back of head). During the procedure, stereotactic imaging can be used to inform the surgeon about the exact position of V1. The tiles will then be implanted, taking care to avoid major blood vessels. It is therefore likely that there will be gaps in the perceived image; however, scanning of the head, and the plasticity of the brain, may help produce a continuous image after patient training and testing. This aspect of the project will be presented in an accompanying ICIP 2013 paper "*Psychophysics testing of bionic vision image processing algorithms using an FPGA hatpack*" [12].

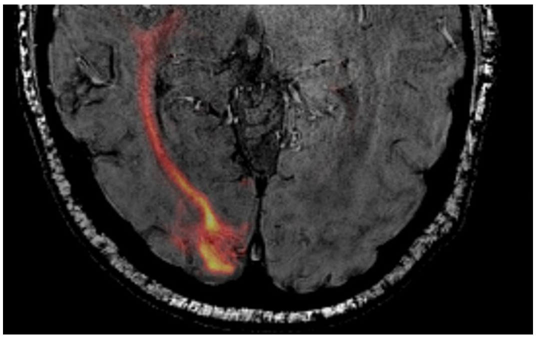

Fig. 5. Probabilistic optic radiation density tractography superimposed over an axial susceptibility weighted image, to trace visual pathways. The visual pathways to V1 are shown in blue. (Courtesy, Drs Richard Thomson and Jerome Mahler, The Alfred Hospital, Melbourne)

6. CONCLUSIONS

The project's aim has been to develop an end to end system that can evoke visual sensations in a human. At the time of writing, a complete system, from camera to electrodes has been developed and tested on the bench. In 2013 this system will be tested in preclinical trials, in preparation for human trials in 2014.

The project has been an inspiring example of how multiple disciplines can work together towards a common goal. All of the team learnt a vast amount about their colleagues' disciplines, and everybody has experienced detailed project planning. A particularly interesting cross-over has been the application of computer-vision techniques, intended for autonomous robots, to bionic vision. These will be discussed in detail in the paper: "*Going Beyond Vision to Improve Bionic Vision*" [10].

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