Wearable Computer Vision Systems for a Cortical Visual Prosthesis

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Abstract

Cortical visual prostheses produce bionic vision by translating data from a headworn sensor into spatial-temporal patterns of electrical stimulation of a patient's Primary Visual Cortex (V1). The resulting bionic vision has low resolution, poor dynamic range and other limitations. These limitations are unlikely to change in the next decade due to the combined constraints of technology and biology as well as the slow process of medical device certification. This paper discusses ongoing research on Wearable Computer Vision Systems (WCVS) designed for two purposes: Improving the utility of bionic vision and non-invasive evaluation of visual prosthesis on sighted subjects using Simulated Prosthetic Vision (SPV).

1. Introduction

According to the World Health Organization, visual impairment and blindness affect 285 million people worldwide as of June 2012[1]. Ever since 1755, when LeRoy caused a blind man to see "flames passing rapidly downwards" by discharging a Leyden jar [11], electrical stimulation of the human visual pathway has been used to generate visual percepts. An implanted visual prothesis use an electrode array to stimulate the visual pathway to generate a spatial pattern of visual percepts called *phosphenes*, resulting in vision similar to a low resolution dot pattern.

Figure 1 illustrates the operation of a modern implanted visual prosthesis. An implant containing an array of electrodes is surgically placed at a point in the visual pathway past the diseased anatomy. While optic nerve implants have been clinically tested [5], the majority of current research effort is focused on retinal and cortical implants. This is because the retina and primary visual cortex (V1) are locations that give repeatable and predictable pattern of phosphenes with sufficient resolution to be of some benefit to a patient. Recent reports of clinical trials of implanted visual prothesis (retinal) are available from [9, 20].

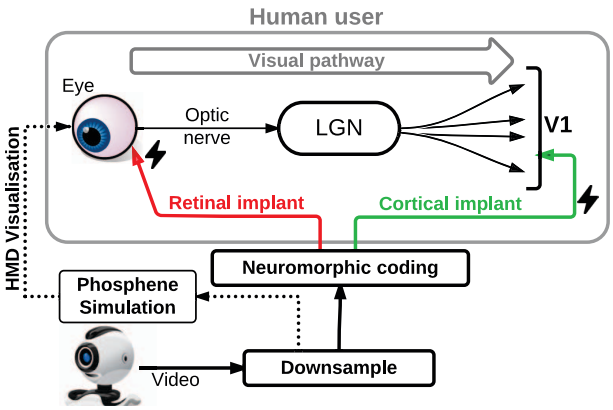


Figure 1: Operation of an implanted visual prothesis. The dashed path represents Simulated Prosthetic Vision, which is an non-invasive evaluation approach (Section 4.2).

Cortical implants may be able to address more causes of visual impairment than retinal implants as electrical stimulation occurs further *downstream* in the visual pathway. Also, the surface area of the human V1 is up to two orders of magnitude larger than the retina. This may allow more electrodes to be implanted thereby increasing the spatial resolution of the perceived *bionic vision*.

In the 1960's, Brindley and Lewin [1] were the first to develop a cortical visual prosthesis that can elicit multiple phopshenes at different locations in a patient's visual field. Unfortunately, bulky external electronics, large wireless transmitter-receiver coils, high stimulation currents and the lack of a portable camera prevented the system from becoming a practical visual prosthesis.

From the 1970's to 1990's, Dobelle developed cortical protheses that included a headworn camera and semi-portable stimulation electronics [6]. A recently published patient testimony suggests that the Dobelle device can provide useful bionic vision [16] despite the weight of the system and the transcranial connections to the cortical implant

[1] http://www.who.int/mediacentre/factsheets/fs282/en/index.html

via visible sockets on the skull. Dobelle's death in late 2004 put an end to his research and development.

2. MVG Cortical Visual Prosthesis

Monash Vision Group (MVG) was formed in 2010 by a Special Research Initiative of the Australian Research Council with the goal of developing a modern Cortical Visual Prosthesis.

Figure 2 shows an overview of the core components in the MVG device. Images from a headworn camera are sent to the *Pocket Processor*, which is a portable computer with additional custom electronics. Camera images are *down sampled* to match the spatial resolution of the cortical implant, which is capable of generating several hundred phosphenes. The down-sampled image is then encoded as stimulation instructions, which are sent to the implanted electrode tiles via the wireless link. Each tile decodes the relevant signals and stimulates individual electrodes as instructed. Note that the wireless link provides both data and power to the implanted tiles. An animated video walkthrough of the MVG device is available online[2].

MVG's cortical prosthesis improves upon previous cortical devices in multiple ways, including:

- Wireless power & data link to electrodes lowers post-surgery risk by allow hermetic seal of skull.
- Reconfigurable electrode tiles with custom ASIC provide surgical flexibility and post-surgery adjustment.
- Denser intra-cortical penetrating electrode arrays with lower stimulation currents, providing higher bionic vision resolution.
- **Portable electronics that use computer vision to improve the bionic vision provided to the patient.**

The last bolded improvement is enabled by the steady progress of Moore's Law since the devices produced by Dobelle in the 1990's. One might ask: "Why not just send the camera image directly to the patient's visual pathway?". We shall explore this question in Section 3 below.

3. Limitations of Bionic Vision

3.1. Spatial Resolution of Phosphene Pattern

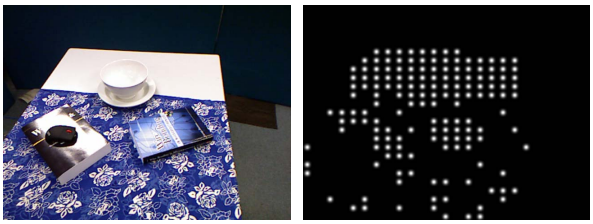
Retinal and cortical prostheses produce bionic vision by electrical stimulation of the visual pathway. When activated, each implanted electrode can produce a brightly lit dot called a *phosphene*. An array of electrodes produces bionic vision consisting of a pattern of phosphenes similar to the dot pattern of a sports stadium scoreboard. The working assumption is that one working implanted electrode equals one phosphene or "pixel" in the bionic vision image[3].

The number of implanted electrodes is constrained by the local spread of electrical charge, biological anatomy, medical safety concerns and technical limitations of electrode fabrication. As of September 2013, state-of-the-art retinal devices have between 60[4] and 1500[5] electrodes [22]. Patient reports of the Dobelle cortical implant suggest up to 100 working electrodes [16]. The MVG cortical prosthesis will allow up to 473 implanted electrodes.

3.2. Dynamic Range of Phosphene Intensity

To make matters worst, the dynamic range of phosphenes is very limited. While there is limited clinical evidence of producing phosphenes of different intensities in retinal implants [8], there is little evidence that one can achieve more than on-off phosphene activation in cortical implants such as the MVG device. In combination with the limited spatial resolution, the resulting bionic vision is expected to be similar to a low resolution binary dot pattern.

Figure 3 shows an idealized simulation of bionic vision resulting from a 25 by 25 electrode array (625 phosphenes). The input image is *down sampled* by averaging pixel patches. Otsu's method [17] is used to binary threshold the patch averages. Electrodes are activated for patches that are above the threshold. In Figure 3b, lit phosphenes are visualised using a symmetric 2D Gaussian function, following the recommendation in the detailed review of Simulated Prosthetic Vision and patient reports by Chen *et al* [3].



(a) Input (b) Bionic Vision

Figure 3: Simulation of a 25x25 binary phosphene pattern.

Given the limited spatial resolution and dynamic range of bionic vision, it is clear that a direct representation is insufficient and *too lossy* to clearly represent real world scenes. Specular reflections, shadows, textures of various scales and the low *visual bandwidth* of bionic vision all contribute to the poor results shown in Figure 3b. While image

[2] http://youtu.be/v9Ip8j3eca8

[3] Coordinated activation of electrodes may increase the number of phosphene but this has yet to be clinically proven

[4] http://2-sight.eu/en/home-en

[5] http://retina-implant.de/en/patients/technology/

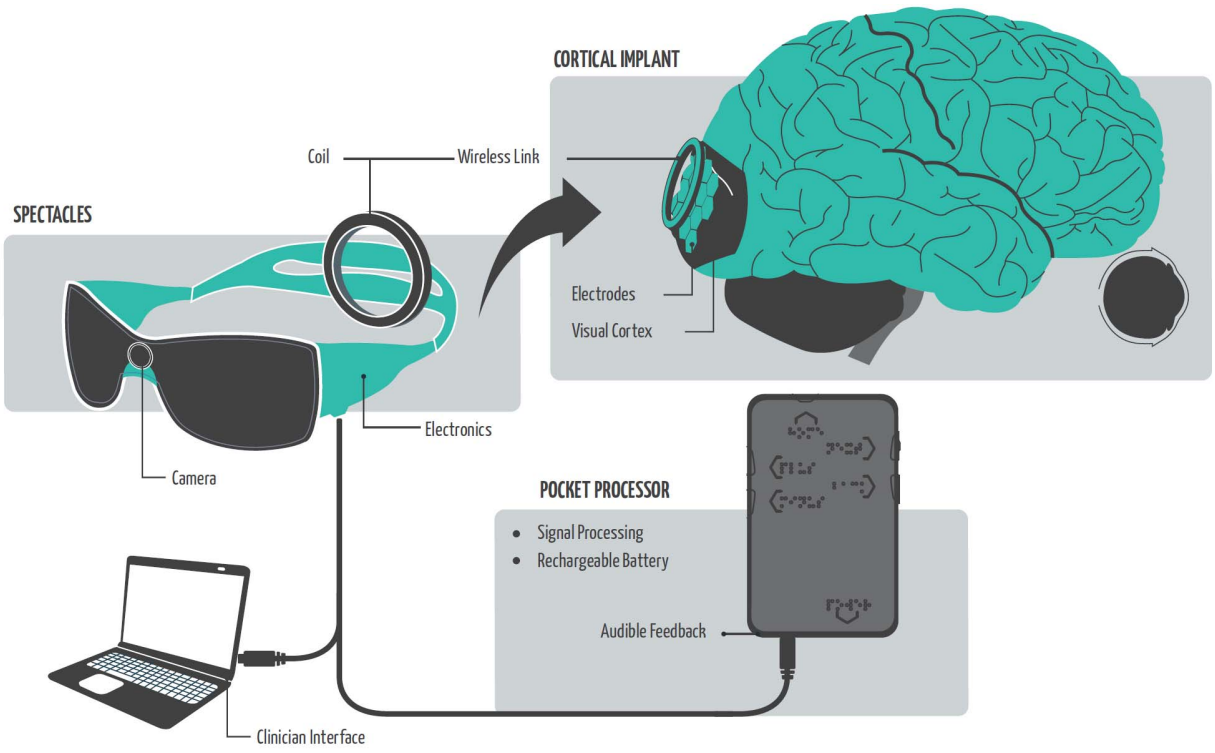


Figure 2: Overview of the MVG Cortical Visual Prosthesis.

processing such as edge detection may help, there is a need for more sophisticated computer vision approaches that can make the most of bionic vision despite its limitations.

3.3. Frame rate and Field of View

Observations from retinal implant patients[6] and Simulated Prosthetic Vision trials at MVG suggest that camera movement is an important strategy when using an implanted visual prosthesis. By moving the camera, patients and test subjects seem to improve their effective spatial resolution and obtain subtle 3D cues through motion parallax. The benefit of camera movement seems related to the *frame rate* of bionic vision. Trials performed by MVG have shown that navigation performance is lowered significantly when bionic vision frame rate is reduced to below 4Hz [10].

Clinical results from retinal implants show that frame rates between 5 to 15Hz can be achieved in practice [20]. Patients with cortical implants have reported frame rates of around 10Hz [16]. These results imply that the signal processing sub-system in a prosthesis must be able to process video images at 10Hz or more, ideally with low latencies, to maximise the benefits of camera movement.

As of September 2013, visual prostheses have quite limited Field of View (FOV). Retinal implants usually achieve a diagonal FOV of 15 to 20 degrees [9, 20]. The MVG cortical implant will span between 5 to 10 degrees of the visual field depending on the number of implanted tiles and the patient's visuotopic map. See Section 3.4 for more details.

3.4. Irregular Phosphene Patterns

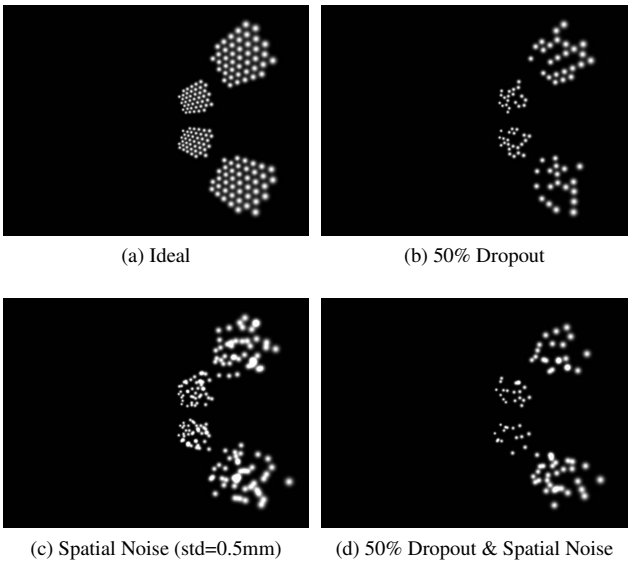
Irregular phosphene patterns are caused by a combination of visuotopic mapping, electrode dropouts and spatial noise. The first is specific to cortical implants while the other two occur in all implanted visual prostheses.

Visuotopic maps related regions of the visual cortex, such as the primary visual cortex V1, with regions of the visual field. For example, human visuotopic maps show that a spatially linear grid of electrical stimulus applied to V1 will result in a non-linear phosphene pattern in a patient's visual field. The mapping is roughly *log-polar* where central *foveal* vision are mapped to larger regions of V1 near the occipital lobe. The review by Schiller and Tehovnik [19] provides extensive illustrations of visuotopic maps.

Figure 4 contains simulations of fully-lit phosphene patterns for the MVG prosthesis where 4 *tiles* (electrode arrays) have been implanted into V1 on the left visual cortex. Note that the left cortex is *wired* to the right visual field. The tiles are placed as close together as possible, radiating out from the occipital lobe (foveal region). Each tile contains 43

[6]Discussion with Second Sight CEO Dr. Greenberg

electrodes and has a small padding area around their outer edge due to the manufacturing process. The padding can be seen as gaps between groups of phosphenes in Figure 4a. The large butterfly-shaped phosphene pattern is caused by the implant locations of tiles, which avoids the calcarine sulcus (large crevice in the visual cortex).



(a) Ideal (b) 50% Dropout

(c) Spatial Noise (std=0.5mm) (d) 50% Dropout & Spatial Noise

Figure 4: Simulations of phosphene patterns from MVG cortical prosthesis using 4 implanted tiles.

Mathematically, the phosphene patterns were generated using the Monopole model [18].

$$z = \exp(\frac{w}{k}) - a \tag{1}$$

$$m = \frac{E + a}{k} \tag{2}$$

The simulations in Figure 4 were generated with parameter values of $k = 15$ and $a = 0.7$. The variable w represents spatial positions on the cortical plane (flattened surface of V1) as the complex number $w = x + iy$. The result z is a complex number representing the spatial position of phosphenes in the visual field. E is the Eccentricity (degrees radiating from center of the visual field). m is the Cortical Magnification, which increases the size of phosphenes that are further away from central vision.

Figure 4 also shows simulations of dropouts and spatial noise. Dropouts occur when implanted electrodes fail to activate nearby neurons in a way that elicits phosphenes. A dropout rate of 50% means that half of the electrodes are not functional, which is quite a high number considering dropout rates reported in literature [23, 9]. Spatial noise is a normally distributed random shift in the spatial position of each implanted electrode on the cortical plane. This represents uncertainties about electrode location and deviations of a patient's visuotopic map from ideal models.

4. A Wearable Computer Vision System (WCVS) for Cortical Visual Prostheses

The combination of headworn camera and pocket processor, as shown in Figure 3, forms a Wearable Computer Vision System (WCVS) designed specifically for a Cortical Visual Prosthesis. Recall from Section 2 that this is a key improvement in the MVG system when compared to past devices. Given the limitations of bionic vision detailed in Section 3, it should now be clear *why* we cannot directly represent the visual world (or camera image) using bionic vision. Instead, we shall perform computer vision to mediate and improve the bionic vision provided to the patient.

4.1. Transformative Reality

In early 2011, the author conducted focus group sessions with low vision technology users, engineers and assistive technology trainers at Vision Australia[7] to identify *use cases* of bionic vision. By identifying common and desirable use cases, appropriate computer vision approaches can be selected and applied to improve bionic vision.

The following use cases were chosen as targets for computer vision improvement as they are desirable to low vision users and difficult to perform using traditional assistive aids such as the white cane or guide dog.

1. Navigation in cluttered spaces, such as small indoor areas where a cane or guide dog are inconvenient.

2. Object detection and recognition, including above-ground surfaces like table tops where cane use is inappropriate.

3. Detecting and interacting with people.

Revisiting Figure 3, we continue with our assumption of bionic vision consisting of a 25 by 25 binary phosphene pattern in a linear grid. We ignored the limitations detailed in Subsection 3.4 to make the problem more tractable. Moreover, discussions with primate vision experts suggest that the effect of irregular phosphene patterns can be reduced with learning, which is difficult to quantify using Simulated Prosthetic Vision experiments on sighted subjects.

The remainder of this section summarizes published research[14, 15, 12] on *Transformative Reality* (TR). TR is also the subject of a patent application [13] (at PCT stage).

[7] http://www.visionaustralia.org/

4.1.1 What is Transformative Reality?

Transformative Reality (TR) is a three-step process:

1. Sense the world around the patient using **visual and non-visual** sensors. Use a combination of headworn sensors that is the best for a use case.

2. **Build models in real time** from sensor data. The patient selects a **TR mode** that represents a subset of models.

3. **Render** the models as bionic vision, using **symbolic representations** to make the most of the limited visual bandwidth of bionic vision.

The core idea of TR is to provide multiple modes of representation of the world around a user, modelled using data from multiple sensing modalities. Essentially, TR mediates the real world to the patient by rendering the world as limited bionic vision, much like an Augmented Reality system where the augmented content is shown without being overlaid over the real world.

The following TR modes were implemented in C++ and runs in real time (>10FPS) on the Wearable Computer Vision Systems designed for Simulated Prosthetic Vision shown in Section 4.2. Each TR mode is designed to address one use case in the list at the start of Section 4.1.

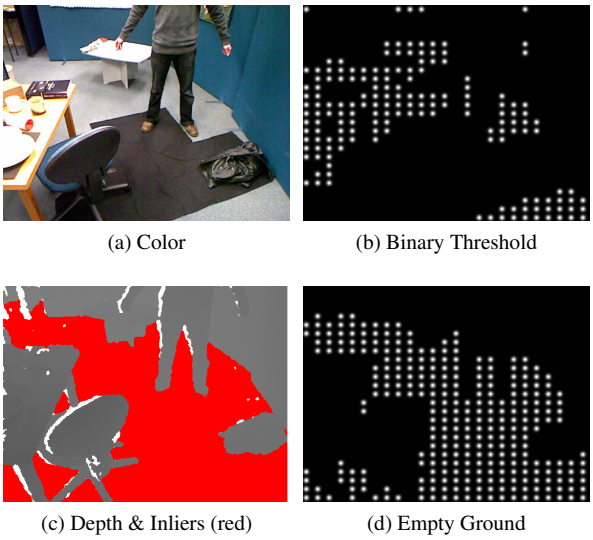
As it is difficult to convey moving imagery in a static medium, especially moving *bionic vision* imagery, **the reader is highly encouraged to view an online video of TR running in real time on headworn sensor data**[8] .

4.1.2 TR Mode - Empty Ground

Figure 5 shows the Empty Ground TR mode, which enables navigation in cluttered indoor environments by visualising obstacle-free patches of the ground plane. The mode operates by performing real time plane detection using data from a headworn depth camera and accelerometer. Plane fitting is performed using RANSAC [7] with the search space constrained by the direction of gravity sensed using the accelerometer. RANSAC inliers, shown in red in Figure 5c, are rendered as contiguous regions of lit phosphenes. Preliminary Simulated Prosthetic Vision experiments suggest that the Empty Ground TR mode provides more utility for indoor navigation than a vision-only approach such as adaptive binary thresholding.

4.1.3 TR Mode - Structural Edges

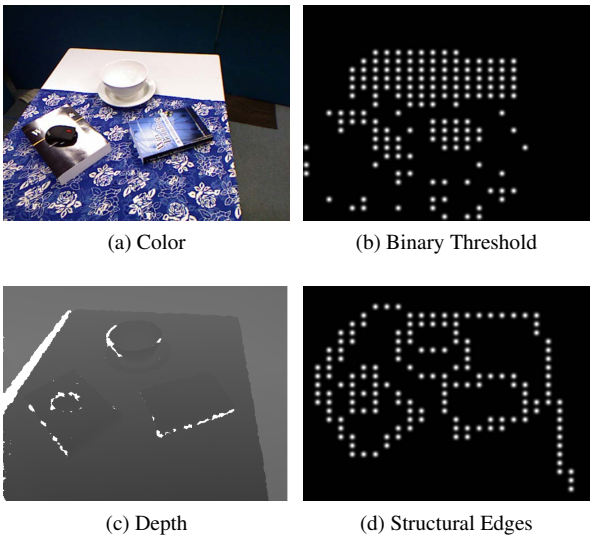
Figure 6 shows the Structural Edges TR mode, which is designed for object detection. It also allows crude object recognition based on shape outlines. Instead of using a color camera, a headworth depth camera is used to reduce the visually complicated scene in Figure 6a into the textureless depth image in Figure 6c. Non-planar regions in the depth image, detected using a local PCA operation applied to inverse depth pixel patches, are represented as lit phosphenes in the bionic vision output. Preliminary Simulated Prosthetic Vision experiments suggests that Structural Edges provide a much clearer and more useful representation of objects in a scene than vision-only approaches.



(a) Color (b) Binary Threshold

(c) Depth & Inliers (red) (d) Empty Ground

Figure 5: Transformative Reality - Empty Ground.



(a) Color (b) Binary Threshold

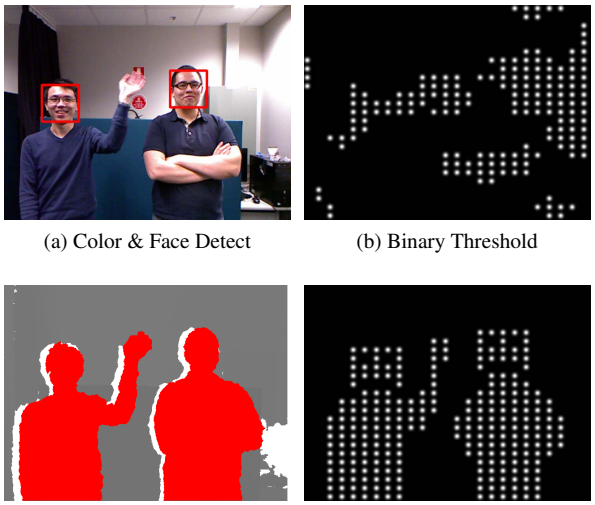
(c) Depth (d) Structural Edges

Figure 6: Transformative Reality - Structural Edges.

[8] http://youtu.be/J30uYYkDApY

4.1.4 TR Mode - People Detection

Figure 7 shows the People Detection TR mode, which uses color and depth images from a headworn RGB-D sensor. Faces are detected in the color image using a Viola-Jones detector [21]. The depth of the face is measured using the depth camera. A simple depth segmentation is performed by thresholding for a contiguous blob of depth pixels below each detected face. Again, Simulated Prosthetic Vision experiments suggest an improvement in the ability of subjects to detect nearby people compared with vision-only approaches such as binary thresholding or intensity-based edge detection.



(a) Color & Face Detect (b) Binary Threshold

(c) Depth Segmentation (d) People Detection

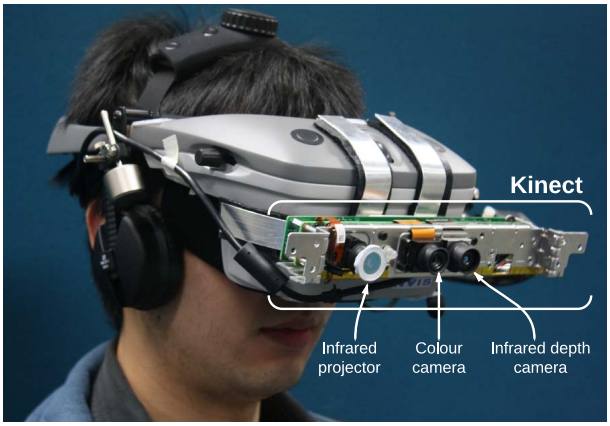
Figure 7: Transformative Reality - People Detection.

4.2. WCVS for Simulated Prosthetic Vision

Simulated Prosthetic Vision (SPV) was first used to estimate the number of electrodes (phosphenes) required for visual navigation using bionic vision [2]. In general, a SPV system is used to conduct psychophysics experiments that measure user task performance by simulating bionic vision in real time based on parameters selected by researchers. SPV systems are also an invaluable tool for prosthesis developers as well as the family and friends of potential patients as they provide a means by which bionic vision can be visualised for various usage scenarios on real world scenes.

SPV systems work by converting sensor data, such as imagery from a headworn camera, to a phosphene pattern, which is then presented to a human test subject via a Head Mounted Display (HMD) or another appropriate display. The underlying assumption is that improved task performance by sighted individuals using an SPV system correlates with similar improvements in implanted patients. A detailed review of SPV phosphene visualisations and psychophysics studies are available from [3, 4].

Since 2011, MVG has developed several SPV systems to evaluate the task performance of sighted subjects while they are presented with the bionic vision visualisations from various computer vision algorithms, including Transformative Reality modes. The SPV systems are Wearable Computer Vision Systems (WCVS) to allow the evaluation of mobility-based tasks such as indoor navigation. The HMD portion of the WCVS SPV systems, modified with headworn sensors, are shown in Figure 8. The WCVS SPV systems also include an laptop in a backpack running computer vision algorithms, phosphene visualisations and data logging processes.



(a) 2011

(b) 2012

(c) 2013

Figure 8: Wearable Computer Vision Systems (HMD) for Simulated Prosthetic Vision developed by MVG.

The size, weight and cost of the HMD have been significantly reduced from 2011 to 2013. The 2013 HMD consists of a PrimeSense Carmine 1.08 sensor (colour and depth) and a Vuzix VR goggle mounted within a ski mask for improved ergonomics; It costs around US$450 to construct. Work has begun to integrate the Pocket Processor of the MVG prosthesis directly into the SPV WCVS data path so that the final production software and external electronics can be tested using SPV psychophysics trials.

5. Discussion and Conclusion

The development of an implanted cortical visual prothesis is a difficult research problem with many challenges spanning materials science, surgical techniques, several engineering disciplines, ophthalmology and neuroscience. This paper has provided a summary of the subset of challenges related to the visual limitations of bionic vision. Wearable Computer Vision Systems (WCVS) can tackle these challenges by making better use of the limited visual bandwidth of bionic vision. WCVS are also an invaluable tool for Simulated Prosthetic Vision trials.

There are other challenges that must be tackled in relation to WCVS for cortical implants. Firstly, the WCVS must be robust and reliable enough to be used as a medical product, which is a common problem faced by non-vision prostheses such as the Cochlear implant. Also, the industrial design of the WCVS must be useable by patients with low vision or no vision who are often from older generations. Figure 9 shows several industrial designs concepts[9].

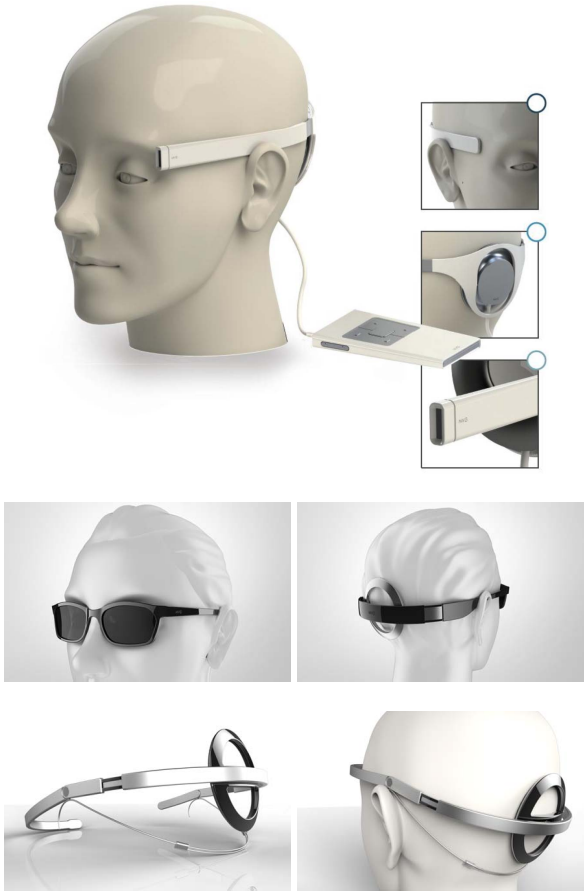


Figure 9: Design concepts by Prof. Mark Armstrong.

[9]Images courtesy of Monash Art Design & Architecture (MADA)

Both cortical visual prostheses and many WCVS have *a human in the loop*, which is a further challenge. Carefully designed psychophysics and human factors experiments are needed in order to improve and optimize system design; for patients in general as well as for individual patients based on his or her preferences.

To conclude, let us discussion the questions from the Call for Papers for the ICCV 2013 Workshop on WCVS[10]:

5.1. Which visual sensors should we use for a particular application?

Our research on Transformative Reality suggests that the broad answer is: Any combination of sensors that provides the data required for a particular use case - Including non-visual sensors. Our implementations thus far have focused on the use of RGB-D sensors together with inertial sensors. In practice, the flexibility of sensor choice may be constrained by cost and medical (or other) certification, which often requires early *lock in* of hardware choices. Having additional sensors may also increase the risk of device failure if the WCVS is not robust to individual sensor failure.

5.2. Where should I wear the visual sensor?

Head mounted is the de-facto standard in implanted visual prostheses. Interestingly, patients reports have suggested that a handheld camera or *eye-in-hand* configuration may be beneficial in some scenarios, such as driving [16].

5.3. Which visual tasks are suitable for the WCVS?

The low hanging fruits are application areas where there is an overlap between low vision patient demands and the capabilities of robust and fast computer vision approaches. The more ambitious goal is to provide the patient with a richer semantic understanding of the world by the inclusion of recognition approaches for places, activities, people and scenes as well as the use of contextual algorithms that predicts the patient's needs as they travel around the world. For example, as the patient walks into a room full of people, the WCVS can disable navigation mode and enable people detection mode and start performing gesture recognition.

5.4. What is the achievable performance?

The Transformative Reality WCVS systems we have built are able to run in real time and significantly improve upon a user's performance in real world tasks when compared against basic image processing operations such as adaptive binary thresholding. The Simulated Prosthetic Vision WCVS systems are able to perform real time simulations of bionic vision, which allows them to be used for a range of psychophysics evaluations.

The important performance metric here is actually the measurable capabilities of the patient (user) and their level

[10]https://sites.google.com/site/wwcv2013/call-for-papers

of comfort or pleasure while using the WCVS; not the capabilities of the WCVS in isolation. Patient performance in terms Orientation and Mobility (O&M) and Activities of Daily Living (ADL) while using the WCVS is a key performance metric; so much so that it is already included in the FDA's preliminary guidelines for retinal prostheses[11].

As with non-prosthetic WCVS, the main purpose of the WCVS in a visual prosthesis is to improve the user's capabilities without getting in the way.

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