Bio-Medical Materials and Engineering 26 (2015) S1257–S1263
DOI 10.3233/BME-151423
IOS Press

MEMS-based system and image processing strategy for epiretinal prosthesis

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Abstract. Retinal prostheses have the potential to restore some level of visual function to the patients suffering from retinal degeneration. In this paper, an epiretinal approach with active stimulation devices is presented. The MEMS-based processing system consists of an external micro-camera, an information processor, an implanted electrical stimulator and a microelectrode array. The image processing strategy combining image clustering and enhancement techniques was proposed and evaluated by psychophysical experiments. The results indicated that the image processing strategy improved the visual performance compared with direct merging pixels to low resolution. The image processing methods assist epiretinal prosthesis for vision restoration.

Keywords: Retinal prosthesis, MEMS, image processing, simulated prosthetic vision

1. Introduction

Visual diseases associated with retinal degeneration, including retinitis pigmentosa and age-related macular degeneration, result in severe visual loss with few therapeutic options for current clinical treatment. A number of retinal ganglion cells are spared following the loss of retinal photoreceptors, which provides the potential to restore vision by electrical stimulation of microelectrodes implanted near the retina [1]. Such electrically induced visual perceptions are called phosphenes. Multiple simultaneous phosphenes elicited by electrodes array convey limited but useful visual information to the blind and form the foundation for the current effort in visual reparation.

Neural prostheses have the potential to restore neural activity in patients suffering from a variety of sensory disorders. Among the prominent innovations are visual prostheses that are designed to provide artificial vision for the blind and result in increased quality of life. Image data is transmitted to a visual implant that applies pulse currents to the neural pathway via microelectrodes. From a technological perspective, prevalent retinal prostheses include two basic designs used for epiretinal and subretinal implants separately. The epiretinal implant is on the inner surface of retina and stimulates ganglion cells (RGCs) [2]. The corresponding approach depends on external data acquisition and processing based on a system including an external video camera, vision processor, and power supply connected to the implantable stimulator. The subretinal implant is under the transparent retina and replaces the

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degenerated photoreceptors [3], which utilize the high-resolution of remaining visual pathway and transform the light of the external images casting on the retina point by point into appropriate currents that are proportional to light intensity using photodiode arrays.

The size of retinal prostheses ranges from 10 × 6 electrodes array [4] to over 1500 microphotodiodes array [5]. But the number of implantable electrodes is limited with existing techniques, by which the perception formed is a low-resolution vision and far from the normal vision formed by ~150 million photoreceptor cells in human retina [6]. Thus, the prosthetic vision needs to be optimized to improve the efficacy of retinal prosthesis. Simulation of prosthetic vision with healthy individuals permits researchers to investigate the experience of prosthetic vision and behavior from the electrical stimulation. Boyle et al. studied image processing methods for recognition using simulated prosthetic vision, and found out some factors, such as resolution, contrast, gray levels, edge detection and importance extraction, that could help improve the object and scene understanding [7]. Van Rheede, et al. found that zoomed representation according to subject's eye gaze had better task performance than the full-field representation [8]. Parikh et al. evaluate the benefits provided by a saliency-based cueing algorithm to normally sighted volunteers performing visually guided tasks [9]. Their results showed that subjects' performance significantly improved in search tasks and when navigating unfamiliar environments. Li, et al. studied the performance of object recognition from different perspectives and proposed a wavelet-based method for edge detection [10]. Chang, et al. also implemented the enhanced edge information in facial representation and familiar people identification was facilitated in low-resolution prosthetic vision [11]. Wang, et al. proposed background-subtraction based strategies to extract the moving object for visual prosthesis, whose results indicated the effectiveness of computer vision algorithms [12].

Although different approaches of retinal prostheses utilize various neural interfaces over the visual pathway, they have the similar technical problems, such as low-power neural stimulator, visual information acquisition and processing, transcutaneous power and data transmission, and biocompatible micro-electrode array. In our approach, we proposed a signal processing system based on micro-electro-mechanical system (MEMS), which is integrated with a thin-film flexible microelectrode array, a wearable microcamera, an information processor, and the multichannel electrical stimulator. An image processing strategy combining image clustering and enhancement techniques was evaluated using simulated prosthetic vision.

2. Materials and method

2.1. Epiretinal approach to vision restoration

Current retinal prostheses can be divided into passive stimulation devices and active stimulation devices. Specifically, this means devices whose electrical stimulation patterns can be controlled an external system versus those that simply stimulate when light activates the implanted device and do not have an external information source. In subretinal approach, a passive device called a microphotodiode array is located behind the retina between the sclera and the bipolar cells where incident light is converted into graded electrical potentials that stimulate the bipolar cells to produce visual perceptions. Whereas the passive nature and low quantum efficiency of photodiodes necessitates the use of unrealistically bright lights in order to generate the necessary currents to stimulate bipolar cells.

An alternative approach is epiretinal prosthesis. Compared with the subretinal approach, the

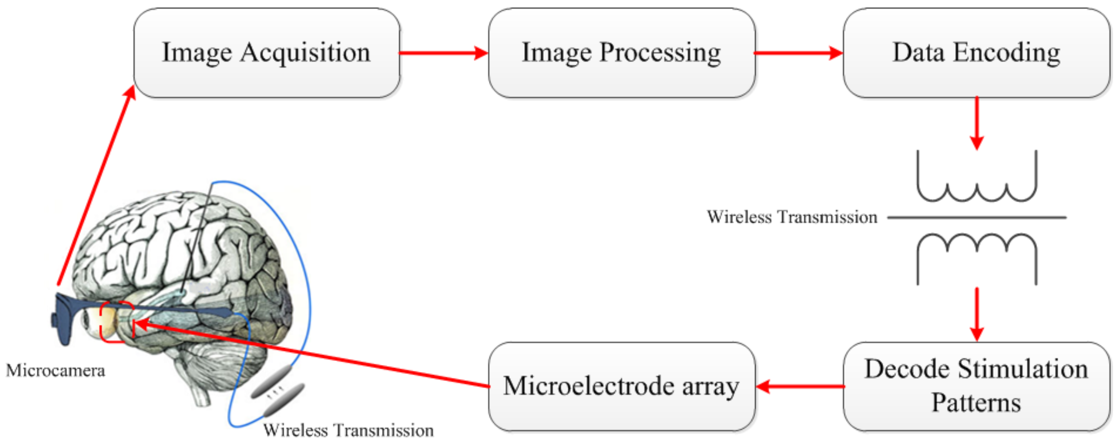

Fig. 1. Schematic drawing of epiretinal approach.

epiretinal approach places the stimulating implant on the inner retina. An epiretinal implant is an active device that provides current pulses to stimulate the RGCs, which need external power and transmission systems. As is shown in Figure 1, the acquired images are processed, encoded and transmitted into the implant wirelessly. The implanted stimulator decodes the stimulation patterns and drives the microelectrode array.

2.2. Hardware system

The hardware system of epiretinal prosthesis consists of external devices at the transmitter side and MEMS-based internal devices at the receiver side. At the transmitter side, video images are captured by an external micro-camera and optimized in the image processing unit. The image and command data is encoded and modulated by the transmitting unit. Systems power and data are delivered inductively via a telemetry system. At the receiver side, the implant coils are connected to the electrical stimulator. The data is demodulated and decoded to drive the microelectrode array. The components of hardware system are shown in Figure 2.

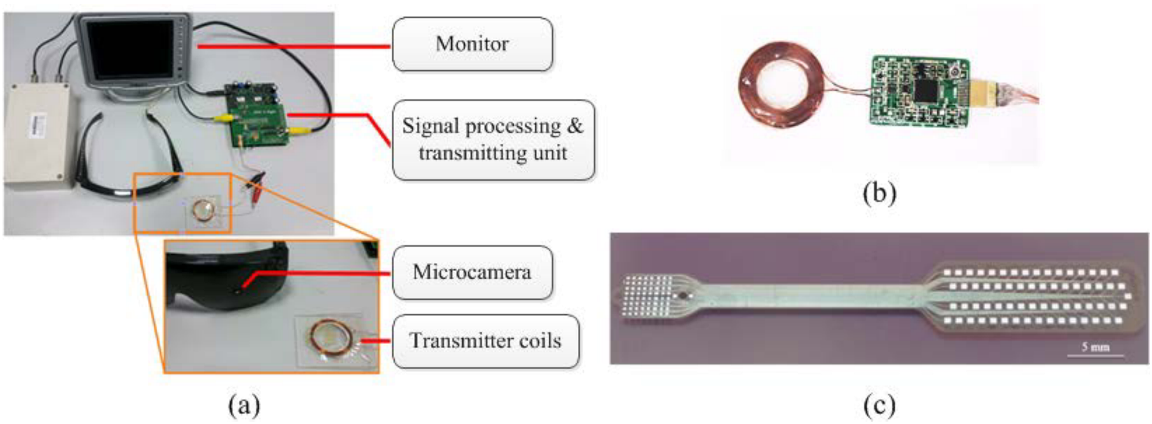

Fig. 2. The components of hardware system: (a) external devices; (b) electrical stimulator; (c) microelectrode array.

The external part achieves the useful visual information and transforms it into stimulus signals according to the relationship between a phosphene map and retina. A wireless channel is used to transmit power and stimulus signals to implanted device and allows transmission without the infection risk. With control signals, the visual information is transformed to rapid biphasic electrical impulses for neuron depolarization without net charge transfer, which is finished by electrical stimulator. The electrical stimulator composes of three units: communication unit, processing and control unit, and stimulus driver unit. The encoded information and power are modulated and transmitted to the communication unit by radio frequency (RF) telemetry. The radio frequency signal will be demodulated and decoded by the processing and control unit after the power and data information are received. In addition, the processing and control unit is also responsible for monitoring and recording the state of electrode arrays, which is based on implemented logic circuit. The stimulus driver unit converts digital signals of stimulation patterns into analog signals by the digital analog converter (DAC). The output of DAC is biphasic current pulses and delivered to the multiple electrodes array by stimulus driver circuitry. All the functional units are integrated in a neuro-stimulus chip consisted of analogue-digital mixed application specific integrated circuit (ASIC) implanted with microelectrode array. To realize the in vivo stimulation, several important factors must be considered including biocompatibility, insertion trauma, and stimulation efficacy. The flexible microelectrode array is revealed in Figure 2(c). The 64 (8 × 8) stimulating electrodes covered a region of approximately 4.7 × 4.7 mm. Two 700 μm diameter holes were designed for the array stability in vivo, on which two 400 μm returning electrodes were placed. The 500 μm squares bonding pads were connected to the stimulating electrodes. The corners were curved to reduce the neural damage during implantation.

2.3. Image processing strategy

Epiretinal prosthesis designs utilize a micro camera placed on a head-worn frame. The image acquisition system, based on complementary metal oxide semiconductor (CMOS) technology and making use of the wide brightness operating range provided by the automatic gain control of these devices, have a resolution far exceeding the size of electrodes array. The image processing system selects a small region from the view of camera and adjusts the image resolution to the microelectrode array. The regions of brightness produced by a visual prosthesis should be constant across a range of brightness levels, and the ideal brightness levels should be consistent with the apparent brightness of objects as they appear to those with normal vision [13]. The spatial and grayscale resolution is adjusted to the requirements of the tissue interface by merging pixels to low resolution (MPLR).

The image processing model shown in Figure 3 applied image clustering and enhancement (ICE). The input image is processed by three methods including edge extraction, contrast enhancement and image clustering. Since the edge information plays a fundamental role in vision recognition and interpretation, edge extraction is a useful method of encoding and describing the main information in an image. The edge features are transformed to edge maps of electrode array resolution. Contrast affects the detection of image features and is known to be a fundamental early vision characteristic in human vision. The RGB image is converted to grayscale before contrast enhancement and the enhanced image is adjusted to the required resolution by MPLR. In the third method, the fuzzy c-means (FCM) clustering is used to partition different parts of the image and cluster the points of same part into regions. The edge extraction and contrast enhancement are applied to the clustered images. The weighted summation of all the results of three methods produces the output image. The weight coefficients are optimized with the adaptive network based fuzzy inference system.

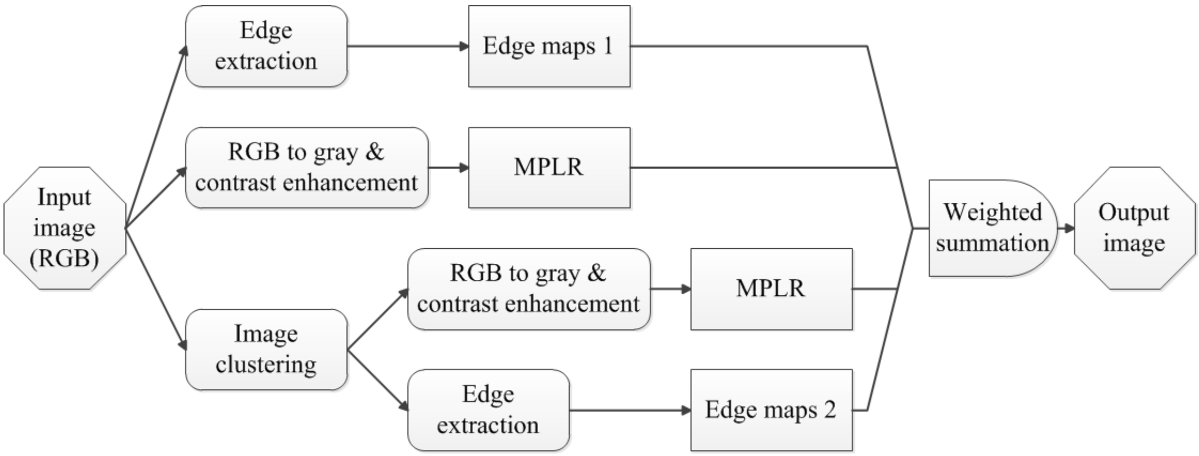

Fig. 3. Flow chart of the image processing strategy.

2.4. Psychophysical experiments and apparatus

Image processing strategy was tested by psychophysical experiments. The test platform composed of a computer (Intel Core i7-3770 CPU @3.40 GHz, 4 GB DDR3 RAM, Lenovo, China), a helmet display for real-time image presentation, a micro camera for image acquisition. The Lenovo computer was used for system control, experiment recording and data processing. It was connected to the micro camera and display system. The micro camera was mounted on the helmet and acquired the visual information of the sights before subject's head. The 20 volunteers recruited (8 females and 12 males) with normal visual acuity of 20/20. The research adhered to the tenets of the Declaration of Helsinki.

In order to minimize the effect of experiment order, 50 experiment objects were shown to the subjects and helped subjects to be familiar with the objects that would be recognized. Subjects were trained to adjust to the helmet display and familiarize themselves with the procedure before the formal experiments. In a test, several objects chosen randomly from all the objects were placed together on the experiment table. During the recognition task, the subjects demanded to recognize as many ones as possible and tell the names within 15 seconds. The performance of subjects' responses was recorded by a camera. Subjects were permitted to move the helmets to watch the experiment tabled and objects from different vantage positions. But they were not allowed to touch the objects all through the experiment. In the searching trial, the subjects should find the given object within as little time as possible. The records were analyzed for recognition accuracy and searching time after the whole experiment. The recognition accuracy was the percentage of correct answers that comprised all the objects for a subject to recognize. The recognition results were represented as mean ± standard deviation%. Significance of the data was analyzed with t-test to compare the influence of image processing methods.

3. Results

The results of psychophysical experiments were recorded and analyzed. The performance of subjects in recognition task and searching task is presented in Figure 4. In the recognition task, the average recognition accuracy under ICE condition (75.7 ± 8.9%) increased significantly ($P < 0.001$)

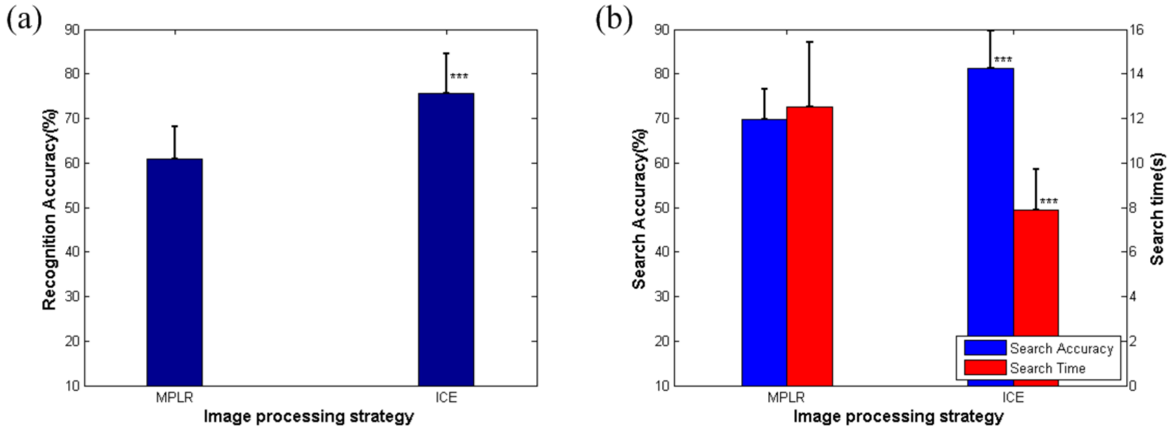

Fig. 4. The visual performance: (a) recognition accuracy in recognition task; (b) search accuracy and time in searching task.

compared with the under direct MPLR condition (60.8 ± 7.3%). In the searching task, the performance was described with the average search accuracy and time of successful search. The task performance was improved from MPLR condition (accuracy: 69.7 ± 6.9%, time: 12.5 ± 2.9 s) to ICE condition (accuracy: 81.3 ± 8.3%, time: 7.9 ± 1.8 s). The difference between performances under the two image processing conditions was also significant ($P < 0.001$).

4. Discussion

The epiretinal approach to vision restoration in this paper is based on a MEMS-based system consisting of a wearable microcamera, an information processor, a multichannel electrical stimulator and the thin-film flexible microelectrode array. The stimulation paradigm that is effective at stimulating retinal ganglion cell bodies and the safety profile of the prosthesis, an active implantable device, is encouraging. Behavioral studies with animals demonstrated the stability of the evoked visual perception and the viability of the implanted stimulating system over time. However, long-term safety and stability of our design is needed to be evaluated in human volunteers.

Implementation of image processing methods has been suggested as an effective way of improving task performances under simulated prosthetic vision. Some basic image processing algorithms like edge enhancement and contrast enhancement have already applied in current epiretinal device [14]. Based on a combined processing of image clustering and enhancement, the ICE strategy improved visual performance. Compared with the saliency-based methods [15], ICE strategy divided the images into clustered regions and enhanced the images without detecting the region of interest. The image features of the whole scene were preserved and highlighted, which was helpful to multi-object visual performance. The parameters of image processing model play an important role, so dynamic parameters optimization is worth studying in future.

5. Conclusion

In this paper, a MEMS-based system for epiretinal prosthesis was presented and an image processing strategy combining image clustering and enhancement techniques was proposed for improving the visual performance, which was evaluated in psychophysical experiments of recognition and searching tasks. The results indicated that ICE strategy was advantageous to multi-object recognition and searching performance. We hope our study on image processing will be helpful to the future design and development of visual prosthesis.

Acknowledgment

The research is supported by National Natural Science Foundation of China (51475288, 51305260 and 51275293), National Basic Research Program of China (2011CB707503), Project of State Key Laboratory of Mechanical System and Vibration (MSVZD201510), “ShuGuang” project (12SG14), Shanghai Committee of Science and Technology (11JC1406100, 13111102800).

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