Benefit of Spatial Filtering for Visual Perception with a Subretinal Implant

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***Abstract*—Subretinal implants have proven to be capable of restoring vision to patients suffering from hereditary retinal degeneration diseases like retinitis pigmentosa and cone-rod dystrophy. Although they already provide basic visual perception, there is still much room for improvement in this field. Effects like electric field interference limit the visual acuity and may be the cause of the perceived vision to be blurred. This influence could be reduced by means of highpass spatial filtering. In this paper, based on the available reports about the visual perception parameters from the patients using the alpha-IMS subretinal implant, a model for the blurring effect of the patients retina is proposed. On this basis, highpass filters are suggested which will compensate the obscuring effect of the stimulator device plus retina system to some extent.**

I. INTRODUCTION

Vision is a complex form of information processing that depends partly on the retina. The profile of the human retina is illustrated in Fig. 1. In the sane eye photoreceptors in the outermost layer of the retina convert light into electrical currents that provide inputs to the second layer, i.e. the bipolar cells. These signals are processed by the amacrine and horizontal cells in this layer that perform lateral inhibition which is a type of highpass filtering resulting in contrast and edge enhancement. The signals are then forwarded to the ganglion cells whose axons build the optic nerve which leads ultimately to the visual cortex. Diseases such as retinitis pigmentosa or age-related macular degeneration are characterized by the loss of functional photoreceptors. Subretinal implants (also shown in Fig. 1) can replace their function to some extent, stimulating the subsequent retinal layers [1]. The natural optical pathway of the eye must be still operative, so when the eye is looking at a scene, the image is built on the retina as in the natural eye. The photodiode array on the stimulator device receives the light pixelwise and stimulates the corresponding electrodes to mimic the natural retinal behavior.

Results of clinical studies using the alpha-IMS subretinal stimulator [1] showed that retinal implants can restore various visual abilities in blind patients and help them to master everyday life. The alpha-IMS subretinal stimulator includes a 1500 pixel array. Every pixel has a size of 70 µm (electrode pitch) and comprises a photodiode, an amplification circuit and an electrode for charge injection into the neural tissue. The chip size is approximately 3 mm × 3 mm and provides a rectangular visual field of $10^\circ \times 10^\circ$. No color vision is available through electrical stimulation. However, different scales of gray can be distinguished depending on the retinal illuminance at the corresponding photodiode.

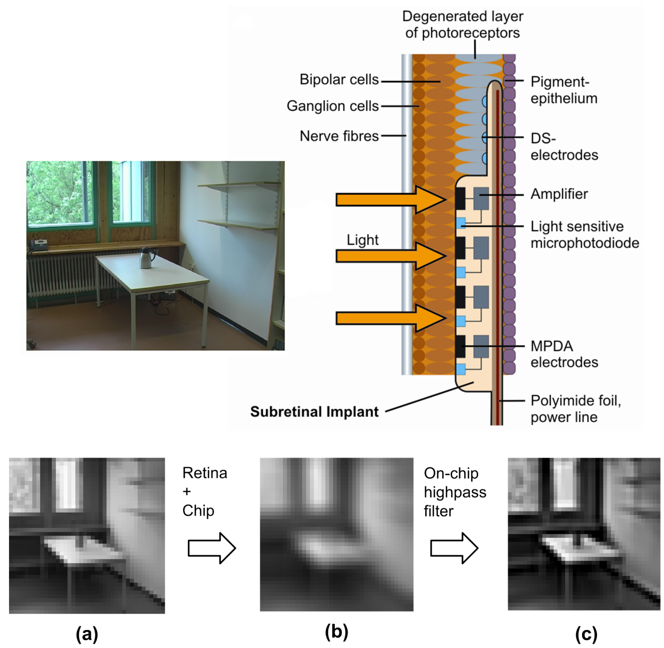

Fig. 1. Top: The human retina and the position of the subretinal stimulator; bottom: (a) Simulated original image scanned by the stimulator chip when an office with a table in the middle is observed; (b) effect of the spatial lowpass behavior of the chip plus retina combination; (c) perceived image with on-chip hardware implementing a proper spatial filter compensating the lowpass blurring effect. Picture inspired by [2]

In order to evaluate the patients' visual perception quality, a specified protocol was applied using a projector screen setup. To measure the visual acuity, standardized Landolt C-shaped optotypes were used. The standardized basic grating acuity (BaGA) test [3] was used to test the maximum spatial resolution of a periodic stripe pattern that could be perceived by the patient. A maximum visual acuity of 0.04 and a maximum grating acuity of 3.3 cpd are reported. Various experiences of perceptions in daily-life are reported, including the recognition of facial expressions, distinguishing objects like cutlery or the stalk of a sunflower, just to mention a few.

Due to the spherical topology of the retina and the flat chip surface there always exists some distance between the electrodes and the bipolar cells. This results in electric interference between neighboring pixel electrode outputs and limits the maximum achievable resolution as every cell is stimulated by pixels neighboring the adjacent electrode [4].

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This is in agreement with the results of the clinical studies. The above mentioned clinical results confirm that patients perceive a blurred version of the image they look at, i.e. with less visual acuity than what is expected from the pixel density. Therefore, the chip-retina combination features a spatial lowpass behavior.

To visualize the results of the clinical study and the influence of the spatial lowpass system behavior on the visual perception, a model was extracted from the reported data in [1] and implemented in MATLAB®. Afterwards, it was investigated whether an on-chip spatial filter could improve the image quality by sharpening contours. Fig. 1 explains the concept.

This paper is organized as follows. In section II the implant system is briefly explained. In section III the model representing the lowpass behavior of the chip-retina couple is extracted considering the reported clinical results in [1]. Using this model, highpass filters are proposed in section IV. Their effect on the final perception is simulated on the captured videos with obscured scenes to visualize if an enhancement in the quality of visual perception is possible.

II. System Overview

A similar application-specific integrated circuit (ASIC) to the one used in [1] is designed and manufactured in a 0.35 µm CMOS technology. The chip has 40×40 pixels and 0.70 µm pixel size. The current generation chip is illustrated in Fig. 2. The chip is connected through a polyimide ribbon and lead wires flex to a receiver coil subdermally implanted behind the ear. The receiver coil is inductively powered by an external transmitter coil and an external power supply module which can be used to adjust different stimulation parameters. Data transmission is accomplished by amplitude shift keying (ASK) at 12 MHz frequency.

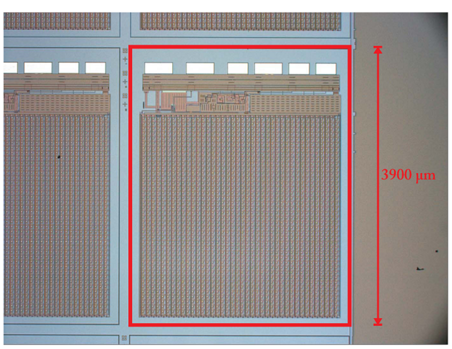


Fig. 2. The designed subretinal stimulator, the die area is marked by red

III. Model of Visual Perception

A. Modeling the Implant

To model the results of the clinical study the test patterns had to be recorded with an identical viewing angle and size compared to the patient's perspective during the standardized testing session. A video camera and a TV set were used to generate the test images of the Landolt C and the stripe pattern. The post-processing was performed using MATLAB®.

The camera lens was adjusted to 59 dpt, corresponding to the refraction of the healty eye [5]. A field of view of $10^\circ \times 10^\circ$ complies with an image plane of $17.4\,\mathrm{cm} \times 17.4\,\mathrm{cm}$ at 1 m distance to the camera lens. The camera viewfinder was adjusted to this window using an aperture diaphragm. The data inside this window corresponds to the image visible to the patient, which has to be cropped during post-processing.

The Landolt ring consists of a ring that has a gap, thus looking similar to the letter C. The gap can be at various positions and the task during the study is to recognize the location of the gap. The minimum perceivable angle of the gap is taken as measure of the visual acuity. For the reported visual acuity of 0.04 the diameter of the Landolt C at 1 m distance of the eye is defined to 3.64 cm [6]. To obtain a digital image with an appropriate size, the test patterns of the standardized FrACT test were rephotographed from a TV screen and a white balance was performed to adjust the contrast.

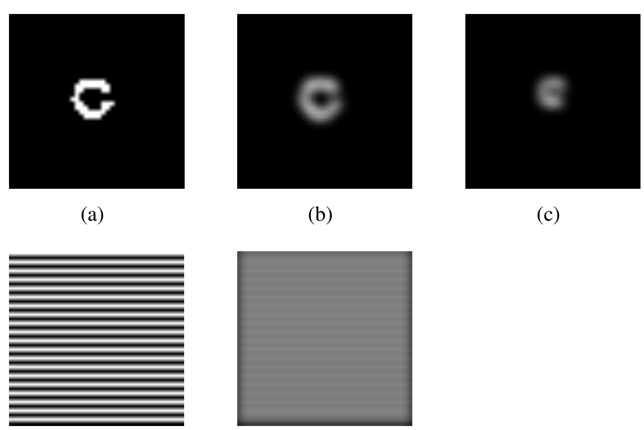
A good method to obtain the maximum perceivable spatial resolution is the use of a periodic stripe pattern. An implant with 40×40 pixels allows a maximum of 20 stripes. With the visual field of 10° the maximum achievable resolution is 2 cpd. This stripe pattern was generated using a MATLAB® script.

The test images were cropped to the size of the aperture diaphragm and converted to 8-bit grayscale. Afterwards, the image was resampled to 40×40 pixels.

In this study we assume that images processed using this workflow correspond to the output signals transmitted at the stimulation electrodes.

The resulting test patterns for a visual acuity 0.04 and a visual grating of 2 cpd are shown in Fig. 3(a) and Fig. 3(d).

Althougth the Landolt C ring is already beginning to loose its shape, which is indicative of proximity to the limitations of the chip, both patterns can easily be recognized with the healthy human eye. This leads us to the assumption, that the



(a) (b) (c)

(d) (e)

Fig. 3. Top: Landolt C test (a) Test pattern for a visual acuity of 0.04 ; (b) perceived test pattern for a visual acuity of 0.04 with lowpass filter ; (c) perceived test pattern for a visual acuity of 0.05 with lowpass filter; bottom: Grating acuity test (d) test pattern for 2 cpd; (e) perceived test pattern for 2 cpd with lowpass filter.

blurring effect resulting from the lowpass within the chip-retina combination has strong impact on the image quality.

B. Modeling the Clinical Results

Results of visual perception with the subretinal implant from nine patients participating in the trial were presented in [1]. We modeled the results of three typical subjects S5, S8 and S9. In this paper we concentrate on patient S8 with a visual acuity of 0.04 and a maxiumum achievable grating acuity of 2 cpd. According to German law a visual acuity less than 0.02 is defined as blindness, thus patient S8 can be considered as a patient with low vision rather than being blind.

To fit the model to the clinical results a gaussian lowpass filtering was performed on the pixelized image. The filter parameters depended on the individual patients.

The size of the filter kernels and the variance σ of the gaussian distribution were varied to subjectively match the clinical results. A 4^{th} order lowpass filter with $\sigma = 1.25$ turned out to match best to the clinical tests for patient S8. The transfer function of this lowpass filter with a cut-off frequency of $0.23 \cdot f_s$ is depicted in Fig. 4.

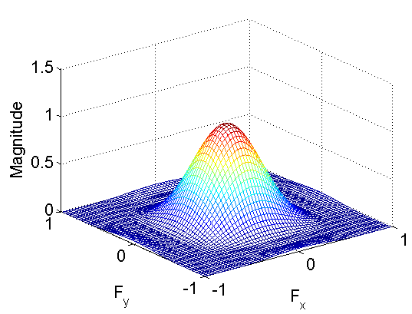


Fig. 4. Transfer characteristic of 4^{th} order gaussian lowpass filter with $\sigma = 1.25$ to match the clinical results. Image best seen in color.

It can be observed, that this implementation of the lowpass filter, representing the blurring effect due to cross-talk between the distinct electrodes, has a slight ripple at frequencies higher than $0.5 \cdot f_s$. However we decided for this modeling because the results of the visual acuity test were best in coincidence with the clinical results.

Fig. 3(b) and Fig. 3(c) visualize perceived test images resulting from the modeled lowpass filter. While the gap of a Landolt C corresponding to a visual acuity of 0.04 can be clearly recognized, this is not possible for the next smaller Landolt C for a visual acuity of 0.05.

The stripe pattern for 2 cpd processed with the lowpass filtering is illustrated in Fig. 3(e). It is still possible to distinguish between dark and light stripes, but the contrast between the stripes is limited. The image appears as a gray plane with slightly darker stripes. This is in close accordance with the reports about daily-life experiences of the patients during the trial [1].

IV. Spatial Filtering

Because a small gap between the electrode array and the stimulated retinal cells is to be expected, the lowpass will be inevitable [7]. However, its quality and thereby influence on the image quality and especially vision contrast may vary.

This leads to the idea to enhance the perception of image contrast by the implementation of an on-chip highpass filter to shift the stimulation spectrum to higher spatial frequencies so, that the effect of the inherent lowpass filtering will be moderated or even eliminated.

The subretinal implant comes without any external signal processing device, therefore this compensation is intended to be implemented directly within the pixel array using an analog current-mode approach. In this way, an instantaneous filtering of the image can be achieved. A Compensation filter qualified for an on-chip implementation has to be of low hardware cost and consume little energy. Thus, only low order filter kernels with few coefficients are qualified for a linear convolution on the pixel array. Additionally, the mean illuminance of the image has to be the same. This is possible if the coefficients of the filter kernel sum up to 1.

To model the benefit in visual perception of spatial filtering, videos representing daily-life experiences were recorded. Different types of highpass filters in combination with the retinal lowpass filter were applied on the captured scenes. We show here the effects of a 3^{rd} order laplacian filter as in Eq. 1 and the 5^{th} order linear filter of Eq. 2. While for the implementation of the laplacian filter only 4 adjacent pixel cells are affected, the 5^{th} order linear filter requires connections to 12 neighboring and next-neighboring pixels.

$$G_{Laplacian} = \begin{pmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{pmatrix} \tag{1}$$

$$G_{Linear,5} = \begin{pmatrix} 0 & 0 & -0.5 & 0 & 0 \\ 0 & -0.5 & -1 & -0.5 & 0 \\ -0.5 & -1 & 9 & -1 & -0.5 \\ 0 & -0.5 & -1 & -0.5 & 0 \\ 0 & 0 & -0.5 & 0 & 0 \end{pmatrix} \tag{2}$$

Fig. 5(a) shows an exemplary scene representing a building at a small viewing distance. The effect of the modeled lowpass characteristic for a visual acuity of 0.04 can be observed in Fig. 5(b). The windows are barely distinguishable from the wall and the housetop merges with the periphery.

Fig. 5(c) visualizes the image after the application of the third order laplacian filter as in Eq. 1. The contrast has been increased and the position of the windows can be located more precisely. Even the tree on the left side of the building can be recognized. The roof is distinguishable from the surrounding.

In Fig. 5(d) the 5^{th} order highpass filter was used in combination with the discussed lowpass filter. Bordering effects become visible around the edges, as at the transition

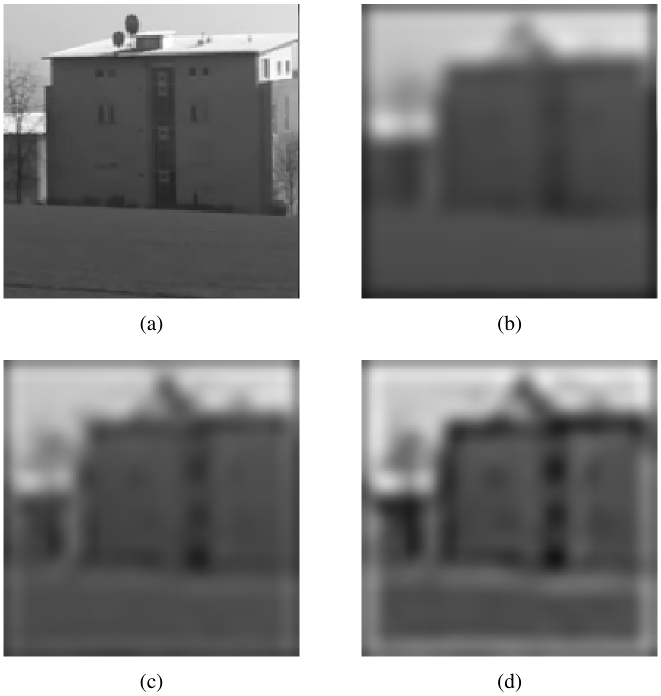


Fig. 5. Exemplary scene at small viewing distance showing the effect of spatial filtering:(a) Original scene; (b) scene processed by properties of the chip lowpass filter for a visual acuity of 0.04; (c) laplacian highpass filter applied on the results of (b); (d) 5^{th} order linear highpass filter applied on the results of (b)

between the housetop and the walls. Although this filtering is too much for a patient achieving a visual acuity of 0.02 and better, it might be advantageous for patients with lower visual perception.

Both filters discussed in this work raise the gain at medium to high spatial frequencies. This is illustrated in Fig. 6. While the black curve shows the transfer characteristic of the modeled lowpass for a visual acuity of 0.04, the blue curve show the lowpass filter in combination with the laplacian filter. The red curve shows the lowpass filter in combination with the 5^{th} order linear filter. The superelevation for medium frequencies is obvious.

Although the maximum resolvable spatial frequency is not influenced by applying a highpass filter, the amplitude for

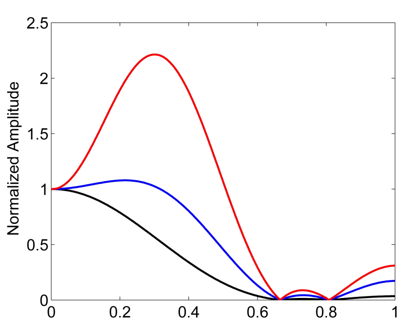


Fig. 6. Transfer characteristics of the modeled lowpass filter for an orignial visual acuity of 0.04 (black), lowpass plus laplacian filter of Eq. 1 (blue) and lowpass plus 5^{th} order filter of Eq. 2 (red).

medium and higher frequencies up to $0.5 \cdot f_s$ can be raised. This results in more image contrast. The laplacian filter lifts the overall transfer function at a frequency of $0.3 \cdot f_s$ from a value of 0.54 up to an amplitude of 1. Using the 5^{th} order filter the amplitude at $0.3 \cdot f_s$ reaches around 2.21.

An accentuation of contrast in between the laplacian and the 5^{th} order linear filter would be best for the image quality with this model cross-talk effect model. However, the laplacian filter comes with the lowest possible hardware cost. Additionally, it consumes two times less energy compared with the 5^{th} order linear filter. Thus the laplacian filter is a good compromise between contrast enhancement and the on-chip implementation cost.

V. Conclusion

We visualized the results of the clinical study reported in [1] through simulation, by reproducing the used test patterns and the implementation of a MATLAB® model. The model represented the properties of chip-retina interface lowpass characteristic of a patient with a visual acuity of 0.04 and 2 cpd. The results were in close accordance to the previously reported values.

Further on we showed how an on-chip spatial filtering could improve image contrast and thus affirmatively affects visual perception with subretinal implants.

Although this study suggests that patients would benefit from spatial filtering, before choosing a distinct filter kernel, different types of filter matrices should better be validated by patients carrying a subretinal implant.

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