

## Variable-Rate Multispectral Illumination for Retinal Microsurgery: A Critical Review

Adaptive Multispectral Illumination for Retinal Microsurgery

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### Introduction and Significance

Vitreoretinal surgery is undertaken to treat several eye problems involving the retina, macula, and vitreous fluid, and this surgery is considered one of the most difficult to perform. Many eye problems are treated with vitreoretinal surgery including macular degeneration, diabetic retinopathy, and retinal detachment. During vitreoretinal surgery, small implements are inserted into the ocular vitreous cavity through small incisions and are manipulated within through microscopic visualization. There exist many complicating factors in the surgery, including difficult visualization of surgical targets, lack of tactile feedback, phototoxicity, and the requirement for high precision and accuracy. The surgeon experiences limited field and clarity of view, depth perception, and illumination, hindering identification and localization of surgical targets and leading to long operation times.

Long operation times during vitreoretinal surgery can cause many complications, not the least of which is phototoxicity. The current methods of illuminating the vitreous cavity are by using fiberoptic endoilluminators which use a continuously on white light source. However, the photosensitive light receptors in the retina are easily overactivated by the high-frequency components of the white light, causing phototoxicity and retinal damage. High frequency light such as blue and ultraviolet are especially harmful to the retina due to their very high energy. In a previous study, commercially available light sources for illumination exceeded ICNIRP guidelines for retinal damage within 3 minutes, while nine out of ten exceeded these guidelines for retinal damage within 1 minute. Since the typical vitreoretinal surgery takes around  $\langle \rangle$  hours, the risk for phototoxicity is very high. Reported frequencies of phototoxicity as a complication have ranged anywhere between 7% to 28%. While some measures have been taken to curb these issues by using xenon and mercury light sources with low blue spectral density, phototoxicity remains a large issue in vitreoretinal surgery.<sup>1</sup>

Previous papers by the Sznitman, et al. proposed a visualization system to reduce phototoxicity, working in tandem with a coloring system.<sup>2</sup> The visualization system was composed of two important features. Firstly, since most work is performed on the camera's video output, illumination was turned off in between frames. This significantly reduced illumination time without any loss of video clarity. Secondly, the light source used for illuminating the retina

cycled between using low-energy red or IR light and normal white light. Red or IR light, being of a lower frequency, damages the retina much less than conventional white lights.<sup>3</sup>

The automated coloring system was proposed by Sznitman, et al. to ameliorate the surgeon's difficulty in identification and localization of surgical targets. The surgeon cannot be expected to operate using only red light illumination, so the coloring system proposed to use the few white-light frames to extrapolate blue and green channels to their succeeding red monochrome images, resulting in artificial color. The coloring system, called active scene rendering (ASR), proceeds through the following steps. First, SIFT features of the retina were calculated and a simple translation transformation of the retina from the previous color frame to the current frame is calculated. The tool is segmented out using pose estimation of a calibrated 3D model of the tool. The green and blue channels from the most recent previous color image are then translated using the calculated translation and added to the red channel from the current monochrome image. Finally, the tool image is added using a color tool model and the estimated 3D pose from the previous pose calculation.<sup>2</sup>

### **Problem and Hypothesis**

This visualization system and automated coloring system proposed by these previous papers have been proven to work and significantly reduce phototoxicity, but many improvements are possible. The previously proposed method currently only uses white light illumination at a constant rate in relation with the red-light only illumination. The problems with this can be best explained by looking at two extremes. In cases where the surgeon is looking at a single section of retina without much movement, there is no need to always illuminate with white light. There is no change that requires a new white light image to base the green and blue channel images from to minimize error. Alternatively, in cases where the eye is manipulated at a very fast rate or the retina is undergoing transformations that are not simple transformations, there is a much greater need to illuminate with white light to catch the changes in the image than the current constant-rate algorithm can allow. Ideally, a program should be developed which allows greater white-light illumination rates during times of high movement and lesser white-light illumination rates during times of low or no movement.<sup>1</sup>

This new paper by Sznitman, et al. proposes and implements such an algorithm, using cost function analysis to minimize both the phototoxicity cost of using more white light and the surgical error cost of having errors in the recolored images.<sup>1</sup>

## Technical Approach

### *Surgeon Impairment Cost*

The surgeon impairment cost ( $S(\epsilon)$ ) is modeled as a pair of functions that describe how errors in using green and blue channel images from the most recent white-light illuminated image could affect the image. To calculate this cost, it is assumed that the error in both green and blue channels are the same as the red channel. The error in the red channel,  $\epsilon_t^R$  is easily calculated by taking the mean squared error between the red channel in the most recent previous white-color image and the red channel at in the current monochromatic frame. Below a certain threshold, the surgeon impairment cost is linearly related to this error; above this threshold  $\epsilon^*$ , error does not increase because the image is already too distorted to discern anything useful.<sup>1</sup>

$$S(\epsilon) = \begin{cases} 1 & \text{if } \epsilon > \epsilon^* \\ \frac{\epsilon}{\epsilon^*} & \text{otherwise} \end{cases}$$

$$\epsilon_t^R = \|M_t^R - M_{t_w}^R\|_2$$

### *Phototoxicity Cost*

The phototoxicity cost ( $T(L_t)$ ) as a function of the total amount of illuminated white light on the retina ( $L_t$ ) assumes an exponential loss of phototoxicity as the time elapsed since the white light illumination increases. This is modeled this way since previous studies have discerned a relationship much like an exponential loss for phototoxicity effect.<sup>3</sup> In addition, the phototoxicity cost also models an upper limit; once enough damage has been done to the retina through phototoxicity, no further damage can be done.

$$T(L_t) = \begin{cases} 1 & \text{if } \varphi(L_t) > L^* \\ e^{-\frac{(\varphi(L_t) - L^*)^2}{2}} & \text{otherwise} \end{cases}$$

### *Total Cost Minimization*

In order to choose illumination for the next frame, the weighted sum of phototoxicity costs and surgeon impairment costs are minimized. The weight of the sums is determined by  $\lambda$ , which can be adjusted by the surgeon to emphasize minimizing the phototoxicity cost (lower quality images) or minimizing the surgeon impairment cost (greater risk of phototoxicity). This is in actuality very computationally simple, since the next frame only has two illumination settings.

$$L_{t+1} = \arg \min_L E(\mathbf{L}_{t+1}, \hat{\epsilon}_{t+1}) = \arg \min_L \{(1 - \lambda)S(\hat{\epsilon}_{t+1}) + \lambda T(\mathbf{L}_{t+1})\}.$$

$$(1 - \lambda)S(\hat{\epsilon}_{t+1}) + \lambda(T([L_t; 1]) - T([L_t; 0])) \geq 0$$

### *AASR (Adaptive Active Scene Rendering) Coloring Algorithm*

The new coloring algorithm is an adaptation of the previous ASR (Active Scene Rendering) coloring algorithm described by Sznitman et al., while incorporating error estimation for the determination of illumination type from white-light illumination to red-light illumination for the following frame. The AASR algorithm proceeds through the following steps. First, the tool is detected and segmented from the image using a 3D tool model and pose estimation. The green and blue channels from the previous color image are added to the red images from the current monochrome image to generate the synthesized color image. Finally, both the surgeon impairment cost and phototoxicity cost are calculated for the present frame and used to determine the illumination type for the following frame. There is no simple transformation determination in this algorithm, because it is assumed that any significant changes in the retina will cause an increase in the surgeon impairment cost, which will cause much more white-light illumination pictures to be taken. Because of that, it can be assumed that the retina has not changed significantly from the previous white-light illuminated image.<sup>1</sup>

### **Validation and Analysis**

To validate the new AASR coloring algorithm and compare its effectiveness to the previous ASR coloring algorithm, five image sequences of membrane peelings on phantom eyes were recorded using white light, so that a ground truth is known. On these five images, AASR was run with three settings and ASR was run with four settings. The surgeon impairment error was calculated by using the mean squared error, while the phototoxicity error was calculated as a ratio of the proportion of white light used. The results are shown in Figure 1, and reveal that AASR performed with less phototoxicity risk for the same coloring accuracy when compared to ASR for all settings used.<sup>1</sup>

## Visual Tracking of Surgical Tools in Retinal Surgery using Particle Filtering

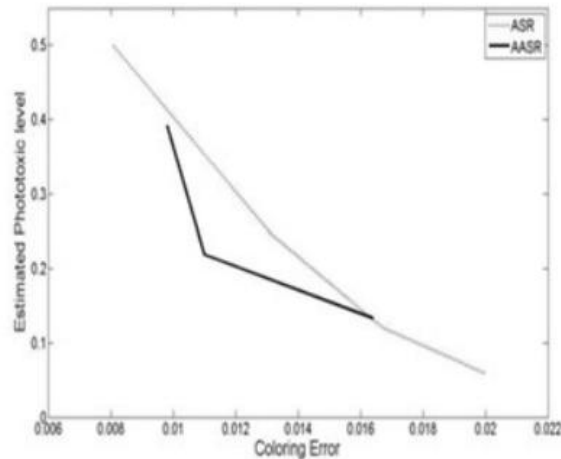


Figure 1: Error analysis comparing ASR and AASR coloring methods.

### Conclusion

In conclusion, the new AASR coloring algorithm and visualization system effectively minimizes both the phototoxicity cost of using too much white-light illumination and the surgeon impairment cost of using too little white-light illumination. During many changes of the retina, the rate of white-light illumination is automatically increased, while during periods of stationary movement, the rate of white-light illumination is automatically decreased. In addition, a weighted preference towards either greater photo accuracy or lesser risk of phototoxicity can be adjusted by the surgeon himself, providing effective operation control.

### Personal Thoughts

In terms of these research papers, I felt that the methods used were very innovative and focused on a very important issue in vitreoretinal surgery. The papers were clear to understand mathematically, though at times the terminology was a bit difficult to understand. In terms of improvement, I felt like the experimental validation could be improved and the graphical presentation could have been more descriptive. In addition, I believe that 3D pose estimation for the tool, to segment the tool from the image for every frame, might be too inefficient for online, in-vivo applications. However, this ties in very well to the project that William and I are working on; a particle filter that implements mutual information to track the tool would be able to segment very efficiently for in vivo applications. Regardless, it is very clear from these research papers that tool tracking for vitreoretinal surgery is a key method and definitely deserves our effort.

## Reading List

1. Sznitman, R., Rother, D., Handa, J., Gehlbach, P., Hager, G.D., Taylor, R.: Adaptive multispectral illumination for retinal microsurgery. In: Jiang, T., Navab, N., Pluim, J.P.W., Viergever, M.A. (eds.) MICCAI 2010. LNCS, vol. 6363, pp. 465–472. Springer, Heidelberg (2010)
2. Sznitman, R., Billings, S., Rother, D., Mirota, D., Yang, Y., Handa, J., Gehlbach, P., Kang, J., Hager, G., Taylor, R.: Active multispectral illumination and image fusion for retinal microsurgery. In: Navab, N., Jannin, P. (eds.) IPCAI 2010. LNCS, vol. 6135, pp. 12–22. Springer, Heidelberg (2010)
3. Ham, W.J., Mueller, H., Ruffolo, J.J., Guerry, D., Guerry, R.: Action spectrum for retinal injury from near-ultraviolet radiation in the aphakic monkey. *Am. J. Ophthalmol.* 93, 299–306 (1982)