

LIGHT-SENSITIVE VISUALIZATION OF MULTIMODAL DATA FOR NEUROSURGICAL APPLICATIONS

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ABSTRACT

We present a technique for enhancing multimodal visualizations for image-guided neurosurgery in the presence of adverse lighting conditions. In the surgical environment, images used for real time navigation are displayed in sub-optimal conditions due to the varying lighting conditions. Our approach actively monitors the incoming light on the display and appropriately enhances the visualization based on the change in light. Based on the results of a user study to evaluate our approach, we found that our enhanced visualization techniques were mostly preferred over regular visualizations.

Index Terms— Image-guided surgery, Illumination-based visualization, Medical visualization.

1. INTRODUCTION

Image-guided neurosurgery, especially in complex procedures, often involves the use of multimodal imaging data for real-time guidance. Images from a variety of medical image modalities such as Magnetic Resonance Imaging (MRI), functional MRI, diffusion-weighted MRI (DTI), Nuclear Imaging (SPECT, PET) are used to help with both surgical planning and guidance during the actual procedure itself. In modern image-guided neurosurgery, the navigation system (IGS) is equipped with infrared stereo cameras that track the position of the surgical tools in real-time and overlay this position on the pre-operatively acquired images. The images and tool positions are displayed on a computer screen generally located a few feet above the ground, and at least three feet away from the surgeons.

A problem with the current setup is that of varying illumination in the operating room which makes the image display on the IGS screen sub-optimal in many cases. This is complicated by the fact that the surgeons wear a head-mounted light, which introduces a focal light source directly pointing to the IGS screen when they are looking at it. The bright light shining on the screen affects the visual perception of the data

which now appears less saturated as compared to under normal illumination settings. In some cases under such bright illumination, smaller structures, for example thin blood vessels or focal functional activation regions can barely be seen. While the surgeon is looking downward during the surgery other observers such as neurologists, neurosurgery residents and others, are looking at the computer screen without any light shining on it and can therefore see the visualizations the way they were meant to be seen. While one could in principle simply focus on providing a *bright illumination* visualization setting that is appropriate for such adverse illumination conditions, the surgeons may turn-off the head mounted light to better observe the images and experts following the procedure need not be subjected to the enhanced (in some ways exaggerated) visualization. In that situation, a more “normal” visualization setting is needed. In other situations when a microscope is being used during surgery, the operating room lights may be turned off which too needs to be taken into account. Hence there is an advantage in being able to detect the ambient lighting conditions and manipulate the visualization settings to provide representations that are optimized (in real-time) to the actual conditions.

We have developed a technique that identifies changes in illumination conditions, using a commodity webcam, and accordingly modulates parameters to generate an enhanced visualization. The webcam placed on top of the computer screen continuously monitors the ambient illumination incident on the screen. We enhance the displayed visualization in real-time based on the incoming light detected by the camera. We conducted a user study to evaluate our visualization enhancements and report the results of our user study. All the source code will be made available as part of BioImage Suite (bioimagesuite.org), an open-source multi-platform advanced image analysis software.

2. METHODS

In our system, real-time response is as important as the ability to effectively visualize the multimodal data. We identify a change in the ambient illumination of the screen using a camera and enhance the visualization based on the incoming light. Our enhancements range from simple color-based

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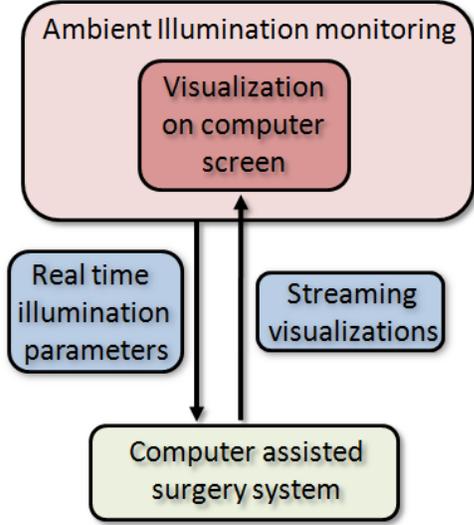


Fig. 1. This illustration depicts a schematic of our system with the novel illumination-based visualization and its interaction with the computed assisted surgical system. The illumination monitoring module consists of a webcam that monitors the ambient light and provides feedback to the computer assisted surgical system, which in turn modifies parameters and streams visualizations to the screen being looked at by the surgeons.

enhancements to more complex appearance-accentuating enhancements that lead to enhanced visualizations under bright illumination conditions.

2.1. System Overview

In order to obtain a seamless visual experience where the change in illumination conditions changes the displayed visualization, we needed a quick way to identify ambient incident light and detect changes in the ambient light around the screen. For this purpose, we interfaced with a commodity webcam and integrated the image capture functionality from OpenCV (Open Computer Vision library) into BioImage Suite. Figure 1 shows a schematic of our computer assisted surgical system with the novel illumination-based visualization module. The module communicates with the computer assisted surgery system based on changes in the ambient illumination. The surgical system then modulates parameters to enhance the visualization on the screen being looked at by the surgeons. Our GPU-accelerated volume rendering system allows real-time updates to the screen based on changes in the illumination.

The illumination monitoring module computes an illumination parameter (amb) based on red, green, blue values for the input scene. The illumination parameter can have values between 0.0 (completely dark environment) and 255.0 (very bright ambient illumination settings).

2.2. Visualization Enhancements

The enhancements applied to the displayed data ranged from simple color-modulation based enhancement to appearance accentuating enhancements. Figure 2 shows a sampling of the visualization techniques that were used to enhance the visual representation of the data. Inset (A) shows a **saturation enhanced representation** in the right image, where the saturation is increased after the composition phase in volume rendering before the resulting color is assigned to each pixel on the image plane. The saturation is manipulated using a shader program where the RGB to HSV conversion takes place, the saturation is enhanced and the reverse conversion then results in enhanced saturation for the volume rendered image.

Inset (B) shows the result of using an **advanced lighting model** (Cook-Torrance) as compared to the traditional lighting model. The Cook-Torrance light model [1] highlights features in the data better than a traditional lighting model. Under normal lighting conditions, there is some self shadowing but it is far more exaggerated under bright illumination conditions. The left image in Figure 2(B) shows examples of volume rendering with Cook-Torrance illumination under different ambient illumination settings (Left - Volume Rendering, Right - Volume rendered image for bright illumination with enhanced shadows).

Lighting can provide crucial perceptual shape cues to the viewer. We implement the Phong lighting model as given by the following equation:

$$I_{total} = k_a I_a + \sum_{i=1}^{\#lights} I_i \left(k_d (N \cdot L_i) + k_s (V \cdot R_i)^{shininess} \right)$$

The specular exponent (*shininess*) in the above equation is varied based on the incident illumination. For normal illumination conditions, a higher specular exponent creates specular highlights to provide shape cues but for bright illumination conditions the specular exponent is lowered to provide a more gradual dropoff of the specular highlight to convey shape better. Inset (C) shows the result of **varying the specular exponent** based on the incoming ambient light. The left image shows a volume rendered lit image of an aneurysm under normal illumination conditions. The right image shows a volume rendered image of an aneurysm under bright illumination conditions, where the specular exponent is lowered to increase the dropoff and therefore enhance the shape cues.

Inset (D) shows a **multidimensional transfer function** being used where the lighting conditions control the amount of feature enhancement being performed. Multidimensional transfer functions have been used to highlight regions of interest in a volumetric dataset [2]. We use a three-dimensional transfer function where the voxel intensity is mapped to the x-axis of the transfer function, the gradient value is mapped to the y-axis and the light intensity (obtained from the illumination module) is mapped to the z-axis of the transfer function.

$$V_{rgb} = MDTF(\sigma, \nabla, amb)$$

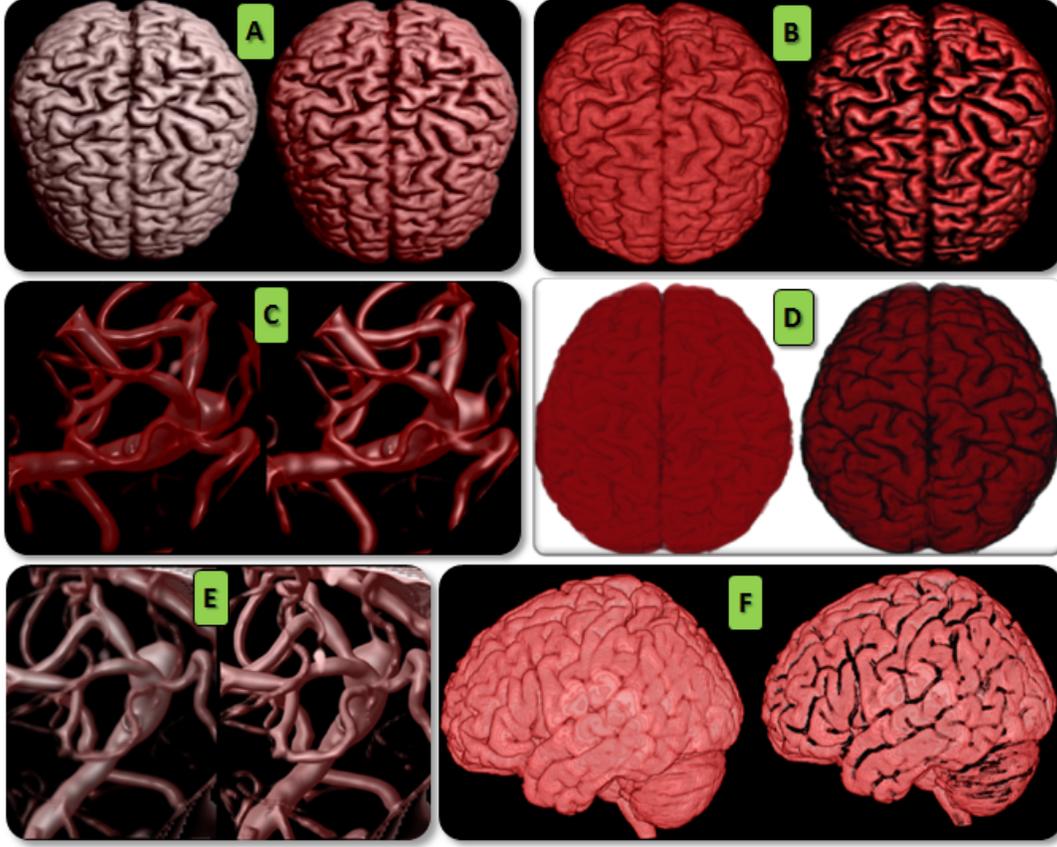


Fig. 2. Some of the Visualization Enhancements applied for Adverse Lighting Conditions: (A) - Saturation enhancement, (B) - Improved Lighting Model ([1]), (C) - Varying the Specular Exponent, (D) - Gradient-based boundary enhancement ([3]), (E) - Multidimensional transfer functions [2], (F) - Vicinity shading [4]. The brain images were generated from MRI data whereas the vascular images were generated from CTA data.

where V_{rgb} is the color lookup from the three-dimensional lookup table, σ is the voxel density, ∇ is the gradient magnitude and amb is the illumination parameter. For normal illumination settings, a volume rendered image of the brain is shown - Inset(D) left - whereas for bright illumination settings, the opacity of the silhouette lines is increased to accentuate structural features - Inset(D) right. The three dimensional transfer function accentuates boundaries by increasing the thickness of feature silhouettes for adverse lighting conditions.

Inset (E) shows a **gradient-based boundary enhancement** where vascular structures are accentuated to ensure their visibility. Voxels with high gradient magnitude are identified and accentuated to draw the viewer’s attention to these “features”. Under bright illumination settings, enhancing the features in a volume can ensure their visibility. We enhance the opacity of high gradient voxels by using a boundary enhancement technique [3]. The enhanced opacity ($O_{enhanced}$) is given by

$$O_{enhanced} = O_{original} * (k_{bc} + k_{bs}(|\nabla|^{k_{be}}))$$

where k_{bc} , k_{bs} and k_{be} control the enhancement of the voxel

opacity based on the voxel gradient. The right image highlights the structural features using gradient enhancement and emphasizes the relationships between the aneurysm and its surrounding vessels.

Inset (F) shows the **vicinity shading** enhancement where the valleys in the data are highly accentuated. Vicinity shading is a quick approximation of global illumination and is a way to estimate how much light each point on the surface is likely to receive given its location with respect to the surrounding anatomy [4]. Vicinity shading is given by

$$I = k_d(\tilde{E}N) \cdot L + k_s((\tilde{E}N) \cdot H)^n$$

where N is the surface normal (which in our case is the gradient of the voxel), L is the light vector, H is the half vector, k_d and k_s are the diffuse and specular lighting coefficients and where $\tilde{E}(p)$ represents the normalized irradiance arriving at point p . The left image in Inset (F) shows a standard volume rendering whereas the right image shows a vicinity shading-based enhancement where the sulci of the brain are accentuated.

3. USER EVALUATION

In order to test the effectiveness of our techniques, we conducted a user evaluation. The hypothesis was that under adverse illumination conditions, our “enhanced” visualizations are better at conveying structure as compared to standard visualization techniques without any enhancement. The independent variable in this case is the visualization technique. The user study was conducted with 16 subjects (11 males, 5 females, 21-34 age group). The subjects consisted of neurosurgeons, neurosurgery residents, neurosurgery fellows and experts in the field of neuroanatomy. We performed within-subjects analysis for our user-study. Subjects were shown two visualizations on the screen with a bright light directed at the screen. The visualizations were chosen in such a manner that they depicted the same data with and without any enhancement. The task was to pick one of the two visualizations shown that best conveyed structure and depth. The subjects were also requested to indicate the confidence in their answers for how much they preferred one enhancement over the other. We used a Likert scale to record the confidence (1-low confidence/preference, 5-high confidence/preference). We randomized the visualizations to balance ordering effects.

We analyzed the preference for every visualization technique enhanced under adverse illumination conditions when compared to a regular visualization. The results of the user evaluation can be seen in the graphs shown in Figure 3.

Subjects preferred the multidimensional transfer function (MDTF) technique the most with an average confidence of 4.0, which is the highest average confidence amongst all the techniques evaluated. Boundary enhancement (BE) was the second most preferred enhancement (94%) with an average confidence of 3.93. Image space saturation (IS) was preferred by 87.5% of the subjects with an average confidence of 2.875 as compared to no enhancement. Among the remaining enhancements, they were slightly preferred over regular visualizations but the confidence was not significantly higher. The only unexpected result was that subjects did not prefer the Vicinity shading (VS) enhancement - Figure 2F - as compared to the regular visualization which was preferred 56.25% of the time. Confidence comparison indicates that those subjects who preferred vicinity shading had higher confidence in their answer.

4. CONCLUSIONS AND FUTURE WORK

We have presented a novel technique that monitors the ambient illumination on the display in the operating room and modifies the displayed visualization in real-time based on changes in the illumination settings. The visualization parameters are varied based on the light settings to generate illumination-appropriate enhanced visualizations that convey depth and structure effectively. Results of a user evaluation found that subjects preferred multidimensional transfer

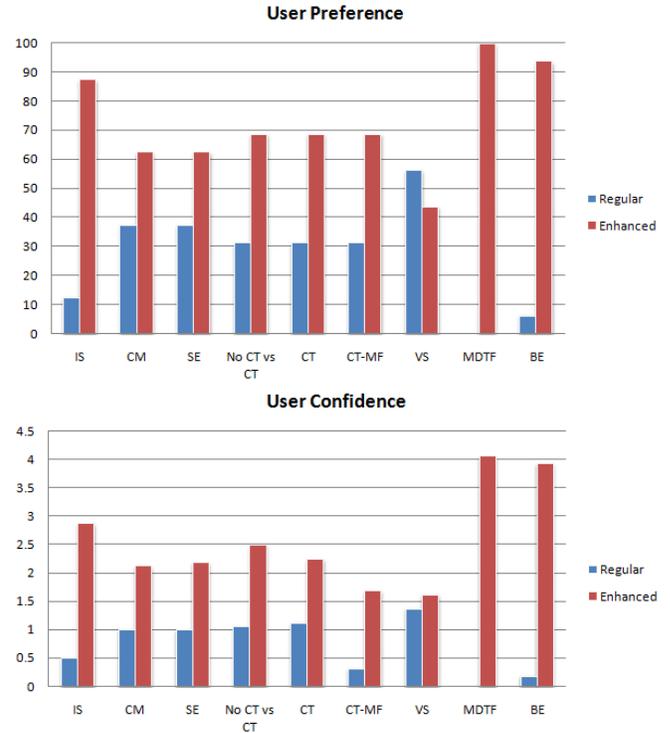


Fig. 3. In these graphs, we show the results of all the enhancement techniques that we evaluated. The top graph shows user preference and bottom graph shows user confidence for the visualization technique (enhanced vs regular). Here, IS = Image space saturation, CM = Colormap modulation, SE = specular exponent modulation, No CT vs CT = Std. lighting vs Cook-Torrance lighting model, CT = Modulating the result of Cook-Torrance lighting, CT-MF = Modulating only the microfacet term in the Cook-Torrance model, VS = Vicinity shading, MDTF = Multidimensional transfer functions and BE = Boundary enhancement. MDTF, BE and IS were the most preferred. (higher preference and higher user confidence).

function-based enhancement, boundary enhancement and saturation based enhancement the most under adverse lighting conditions.

5. REFERENCES

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