Computers & Graphics 54 (2016) 57–64

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Special Issue on CAD/Graphics 2015

An energy-saving color scheme for direct volume rendering

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ARTICLE INFO

Article history:
Received 12 April 2015
Received in revised form
12 July 2015
Accepted 13 July 2015
Available online 21 July 2015

Keywords:
Direct volume rendering
Energy saving
Color scheme

ABSTRACT

Energy-adaptive color selection or design has recently received much attention with the spreading of the organic light emitting diode (OLED) display. Current solutions optimize color sets by analyzing the energy consumption of the 2D rendered images with the screen-space energy model. The comprehensive influence with respect to the volume visualization like the illumination model, the light, as well as the semi-transparency is not considered. This paper presents an energy-saving color scheme selection and optimization approach for direct volume rendering on OLED displays. We propose an illumination-aware energy estimating model that formulates a simplified equation between the display energy consumption and a specific color scheme in object space, making it practical to achieve global color scheme optimization. By performing the color scheme optimization, we obtain an optimal color transfer function, with which we can generate energy-aware direct volume rendering images for OLED display. Experimental results demonstrate the efficiency of our approach on OLED display systems.

1. Introduction

The display is a major source of energy consumption in modern computer and mobile device systems, and consumes up to 38% and 50% energy of the total energy consumption, respectively [1,2]. Dimming is a traditional and widely used scheme for reducing the energy consumption for the convectional liquid crystal display (LCD) equipped with a high-intensity backlight. Recently developed organic light-emitting diode (OLED) display [3] emits light per pixel individually, which means its energy consumption is directly dependent on the content displayed [4]. This brings a new opportunity for energy-adaptive color design targeted to future display systems [5,6]. A pioneering work [4] models the energy consumption of an OLED display system based on pixel, image and code level. This model-based color design scheme enables effective color design for various targets like the user interface [4] and web browser [7].

Direct volume rendering is an effective method used to display meaningful information from 3D scalar fields [8]. Color plays an essential role in labeling internal structures of a scalar field. However, few attention has been paid on the energy-adaptive color design in volume visualization community. It is quite challenging because the comprehensive influence with respect to the volume visualization like the illumination model, the light, as well as the semi-transparency.

Model-based color design approaches compute a color set $\mathbf{C}=\{\mathbf{c}_0,\mathbf{c}_1,\mathbf{c}_2,\ldots\}$ that simultaneously minimizes the energy consumption $E(\mathbf{C})$ and the loss of perceptual quality $E_{penalty}(\mathbf{C})$

$$\min_{\mathbf{C}} E_{cost}(\mathbf{C}) = \min_{\mathbf{C}}(E(\mathbf{C})+\lambda E_{penalty}(\mathbf{C})). \tag{1}$$

The above equation advocates attention on three aspects, namely, the consumed energy E with respect to the color set $\mathbf{C}$, the evaluation of the loss of perceptual quality $E_{penalty}$, and the optimization function. The dynamically weighting parameter λ is used to balance the influences of the energy and the quality items.

Existing solutions employ the screen-space energy model [4,9] that solely relates to the color values in 2D images. This works well for 2D data visualization in which the color set is directly mapped to the resultant image. Direct volume rendering, however, involves a complicated coloring process, where a color set denotes the optical properties of structures. The color in each pixel of the resulting image relates to not only the employed color sets (optical properties), but also the illumination model, the light source, as well as the semi-transparency effect. It is desirable to design a comprehensive energy estimating model that takes the 3D visualization process into account and meanwhile is computation-

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http://dx.doi.org/10.1016/j.cag.2015.07.015
0097-8493/

efficient. This paper proposes an efficient energy consumption model $E(\boldsymbol{C})$ by constructing an equation between a color scheme and the total energy consumption subject to 3D visualization configurations. It allows for real-time energy estimating with a given color set, and enables fast color optimization in the context of 3D visualization.

The second item $E_{penalty}(\boldsymbol{C})$ in Eq. (1) is designed to evaluate the perceptual quality loss with respect to a color set. It is usually expressed as the distinguishability of the color set, e.g., the sum of the Euclidean distances in the color space of all color pairs in the color set [9]. Note that color is typically used for labeling in visualization, and the hue value plays the essential role. To make a color set suitable for labeling nominal data, the hue values of all colors should be as diverse as possible, which induces an additional constraint.

The optimization goal is to determine a color set that minimizes Eq. (1). Known solutions can be classified into two categories: discrete and continuous. The former determines the optimal color set by evaluating the cost function of a discrete set of candidates. The latter requires a non-linear iterative optimization process. Performing the continuous optimization in the entire color space remains a challenging task.

In summary, this paper presents a comprehensive color scheme optimization for energy-saving volume rendering. Our approach can be formulated as a *model-based color design* process, which combines a fast display energy estimating model in object space and an effective color scheme optimization under several perception-based quantified constraints. Two main contributions of this paper are itemized in the following:

- A compact and efficient illumination-aware energy estimating model that characterizes the relationship between the color set and the total consumed energy while the visualization results are display on an OLED display;
- A perception-driven color optimization technique that is global, computationally efficient, and balances the degree of energy saving and preservation of perceptual quality. Two variants, discrete color selection and continuous color optimization, are described to conform to users' specified demands.

The rest of this paper is organized as follows: Section 2 introduces the related work. Section 3 describes our energy-saving direct volume rendering framework briefly. Section 4 presents our approach in detail. The implementation details and results are given in Section 5. We conclude the paper in Section 6.

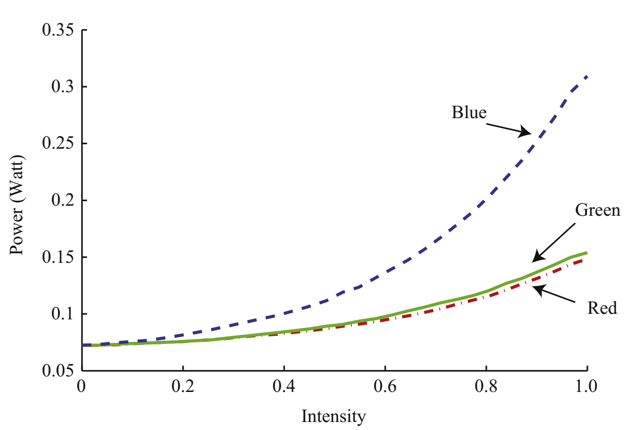

Fig. 1. The energy consumption in Watt with respect to each color channel. The statistics is measured on a μOLED-32028-P1 AMOLED display module, and is used in our experiments. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2. Background and related work

2.1. OLED display

TFT-LCD is the most popular flat-panel display in the past decade. Most LCD displays take a CCFL (Cold Cathode Fluorescent Lamp, or white LED in most recent displays) as a backlight, which normally consumes a constant energy. In contrast, OLED is an emerging display technology that emits light by the display elements and does not need an external light source. For more details refer to [3].

An OLED display contains three independent light emitting components for three color channels of each pixel. Dong and Zhong [4] gave a generic form of the energy consumption of a colorful OLED display with a resolution of N_r pixels

$$E = E_0 + \sum_{l=1}^{N_r} \Big(f_r(R_l) + f_g(G_l) + f_b(B_l) \Big). \tag{2}$$

where $f_r(\cdot), f_g(\cdot)$ and $f_b(\cdot)$ denote the energy consumption with respect to the red, green and blue color channels, respectively. The constant, E_0, accounts for a static energy consumption that is dominated by a driven current of the control chips on the OLED display. E_0 can be estimated by measuring a completely black screen. The three functions, $f_r(\cdot), f_g(\cdot)$ and $f_b(\cdot)$, can be obtained by measuring the energy consumption of the corresponding channel individually with different intensity levels. Fig. 1 charts the eigen intensity-power curve measured on a μOLED-32028-P1 AMOLED display module from 4D system [10]. Note that the blue channel consumes more energy than the red and green channels on the same intensity level.

2.2. Color design in volume visualization

Color design has been an open problem among artists and scientists, and many strategies and guidelines for colormap creation has been developed for various tasks [11–15].

Expressiveness and aesthetics are of great importance for color design. For instance, a knowledge-based system is proposed to capture established color design rules into illustrative visualization [16]. Harmonic color set expresses aesthetically pleasing in terms of human visual perception [17]. Well-studied image-space enhancement scheme can be used to improve the harmony among the colors of a given photograph or of a general image [18]. Generally, these color scheme design methods are mostly focus on the faithfulness of a visualization, as well as the expressiveness and aesthetics of the result images. In our paper, we concentrate on energy-saving visualization by design a new color scheme for 3D visualization.

2.3. Energy-aware color scheme

Existing energy-adaptive color scheme includes two stages: (1) estimating the energy consumption with respect to a color set, and (2) computing an optimal color set subject to certain constraints. The energy consumption in terms of pixel and image can be estimated with a computational model, like the one shown in Eq. (2). To speedup the computation, some simplified methods are studied. Chuang et al. propose to sum up the maximum color components from each display tile followed by a normalization process [9,19]. This model is suitable for displays that have several independent backlight panels (e.g., HDR displays). Dong and Zhong introduce a learning-based sampling strategy to accelerate the energy estimation in the image level [4]. It achieves 90% accuracy with 1600 times reduction of the sampling number.