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Color-appearance-model based fusion of gray and pseudo-color images for medical applications

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ABSTRACT

Fusion of gray and pseudo-color images presents more information of biological tissues in a single image and facilitates the interpretation of multimodalities in medical practice. However, fused results are hampered by the problems of blurred details, faded color and artifact contours. This paper reports a method to solve the problems by precisely predicting the attributes of color perception using the color appearance model of International Commission on Illumination published in 2002 (CIECAM02). First, a rainbow palette is generated from the color attributes. It is uniform in lightness, and thus the valuable information of pseudo-color image can be totally sealed in its chromatic properties. Then the fusion process is carried out with the adjustment of gray image in lightness. Here, the predicted hue and saturation of pseudo-color image is merged with the predicted lightness of gray one. Therefore, information of two original images exists separately in achromatic and chromatic properties of the resulting image. Based on different color spaces (CSs) and color appearance models (CAMs), the color aggregations available for displaying fused images are presented and compared. The aggregation based on the CIECAM02 exhibited more uniform variation in lightness and hue. Fused results of simulated lesion and breast phantom manifested the compromise between the scope of gray and the perception of color. Furthermore, in the quantitative experiment on 49 sets of simulated ultrasound and strain images, the visual information fidelity (VIF) was applied to assess the similarity between the result and its sources. It revealed the superiority of the proposed method over the traditional ones including CSs-based methods, transparency technique, alternating display technique, frequency encoding methods, and maximum-selection-rule based rules. The results of two clinical cases demonstrated its practicality in medical applications. Besides, its feasibility in fusing two high-resolution structural images was preliminarily approved based on the simulated MRI data.

1. Introduction

It is a difficult task for clinicians to mentally translate and integrate the medical images obtained from multimodalities. Pixel-level fusion, also called "integrated visualization" [1], merges complementary information of biological tissues into a single image. The result benefits the interpretation of multimodalities, so facilitates the diagnosis or therapy in medical practice. An example of typical applications displays the color-scaled glucose analogue distribution on a conventional gray-scaled computed tomography (CT) modality, which may prospectively discriminate the cancer in early stages [2]. Most medical modalities can be included in image fusion, such as CT, magnetic resonance imaging (MRI), multimode ultrasound (US), positron emission tomography (PET), and single photon emission computed tomography (SPECT) [3–6]. In other applications, fusion technique merges two complementary gray-scaled modalities to facilitate the lesion localization in a conventional surgery or an interventional therapeutic process [7,8].

Before fusion, original images should be registered, which may be performed using the design of instruments [3], or implemented by software algorithms [9–11]. This step transforms original images into the same coordinate system and determines the validity of fusion to a large extent. Methods for image registration are not within the scope of the present paper. The original images in the experiments are instinctively well-registered, so we report the research on integrated visualization of gray and pseudo-color images in this paper.

One of the most widely used fusion methods is the transparency technique [12] which uses a matte component to manifest the extent of a coverage attenuating the background [13]. This easy-implemented method can be well transplanted to various real-life

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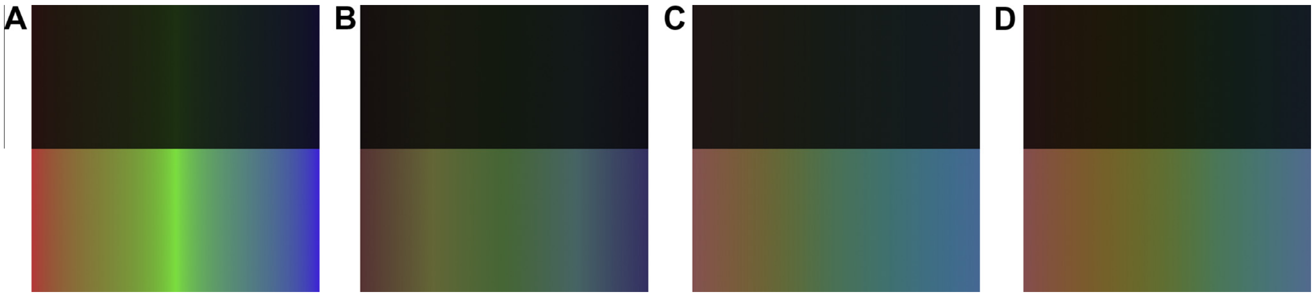

Fig. 1. Palettes based on different color spaces and color appearance models with low (the upper images) and moderate lightness (the lower images): the HSI (A), HSV (B), CIE 1976 L*a*b* (C) and CIECAM02 (D) were applied.

applications [7,8,14]. Fusion can be also accomplished by alternating display methods in which the merged pixel is entirely derived from one or the other volumes [15]. A deformed way temporally alternates the original image on the screen to present the information of sources [16]. Another kind of fusion methods are based on the color space (CS), including the RGB (red, green, blue) model, HSI (hue, saturation, intensity) model, and HSV (hue, saturation and value) model [12,17], in which modalities are inserted into some of the three channels. In a recent study, the retina-inspired model is combined with the HSI model to integrate MRI details to the PET images [18]. Frequency encoding methods are developed to facilitate the interpretation of one modality by merging with details from the other [19]. Much effort has been made to retain the original information as much as possible, assorting to the multi-resolution analysis [20–22]. In our earlier research, we compared the performance of the multi-resolution analysis and proposed fused rules for biomedical applications [23,24].

The key difficulty in fusion may be the compromise of original images and schemes to tell the two sources apart. When a gray and a pseudo-color image are fused, color perception fades away in the fused results of transparency technique and the alternating display methods. Meanwhile, blurred or missed gray details are also apparent in these cases. In fused results of the frequency encoding method, information from the gray image may not be sufficient for localization, whether the multi-resolution analysis is applied or not.

Color spaces (CSs) may provide an inspiring idea of the fusion: modalities inserted in different channels are independent to some extent, so both can be interpreted by the observer. However, methods based on the RGB model spoil the interpretation style of original palettes; those based on the HSI or HSV model fail to separate the two sources in the fused image without the consideration of human visual system and the prediction of color attributes, so decrease the resolution of color on a low gray level and ruin the uniformity of intensity variation of different colors.

To overcome these limitations, we introduce the process for predicting the color attributes in medical applications by using color appearance model (CAM) of International Commission on Illumination published in 2002 (CIECAM02). It is not only crucial for sealing valuable information in pseudo-color image, but also important for separating the chromatic and achromatic attributes of original images. After generation of the palette with a uniform lightness for pseudo-color display, color attributes of two original images are separated. Subsequently, the gray image is adjusted and presented by lightness, while the color image is expressed by hue and saturation.

The advantage of applying the CIECAM02 is essentially attributed to its color distribution. As an example, Fig. 1 illustrates the variation of color from red[1] to blue based on the CSs and the CAMs. As shown in the upper images, colors looked faded with the low lightness, no matter what CS or CAM was applied. However, they were relatively easier to tell apart by using the CIECAM02. In the lower images, palettes were shown with proper lightness. However, although the same lightness was assumed based on the HSI and HSV, the real perception of lightness was not the same to different colors: green was extremely bright in the HSI CS, while yellow and cyan were extremely bright in the HSV CS.

Referring to the relatively authoritative definition in color terminology, attributes of color perception have been categorized [25], which implies a fact that human can tell three kinds of color perception apart. Those attributes are the lightness and brightness which refer to the level of perceived light; the hue which has the common name like red, yellow, green, and blue; the colorfulness, chroma, and saturation which reflect the purity of the color. Compared with the absolute attributes of brightness and colorfulness, relative attributes of lightness, chroma, and saturation are approximately constant across variations in luminance level. They will provide stable results in computerized image fusion under various viewing conditions. Accordingly, color separation is relied on the attributes of hue, lightness, saturation in our research.

The remaining sections are organized as follows. Section 2 elaborates the forward and the reverse transformation of a digital image and its color attributes. The generation of uniform lightness palettes, and the process of fusing are detailed subsequently. Section 3 describes the comparative experiments on the pseudo-color palette, compromise of the resolution of hue and lightness, similarity between the result and the sources, the fusion effect in real-life cases and the feasibility in fusing two high-resolution structural images. Section 4 concludes the applicable scope of the proposed method and summarizes the research.

2. Methods and materials

2.1. Transformation between standard RGB and CIEXYZ

For color measurement, the basis of modern colorimetry, the CIE recommended the CIEXYZ CS, which allows the specification of color matches through CIE XYZ tristimulus values. When it becomes popular to develop the models for predicting color appearance phenomena, the CIEXYZ CS has been applied to all CAMs [25]. Meanwhile, it is also the start point of the standard RGB (sRGB) CS, which is used to display the Graphical User Interface (GUI) in most Windows Operation Systems. In essence, the transformation from CIEXYZ to sRGB is to change the primaries, since those used in CIEXYZ CS are invisible for a screen monitor. In this process, an additional gamma correction is involved to ensure that the gray level of sRGB CS is linear to the human sense of lightness [26,27].

Calculating the sRGB tristimulus values from the XYZ tristimulus values begins with a linear transformation. The intermediate

[1] For interpretation of color in Figs. 1 and 3–10, the reader is referred to the web version of this article.