RGB illuminant compensation using multispectral information

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Abstract

In the pursuit of more accurate color reproduction in digital imaging, this paper explores the integration of multispectral information to enhance RGB Automatic White Balance (AWB). Traditional AWB methods, which rely solely on RGB data, often struggle under varying lighting conditions. To address this, we investigate three approaches: i) extending RGB-based color constancy algorithms into the multispectral domain; ii) utilizing ambient sensors for real-time illuminant detection; iii) reconstructing spectral data from RGB images for subsequent spectral AWB. Our methods include advanced re-elaboration techniques to refine illuminant estimation before applying them to RGB data. Experimental results demonstrate that these multispectral approaches can significantly reduce color reproduction errors, achieving up to a 60% improvement over conventional methods. The findings suggest that integrating multispectral data into AWB algorithms offers substantial benefits for applications in photography, remote sensing, and medical imaging

Keywords: Spectral Imaging, Illuminant Estimation, Automatic White Balance

Introduction

RGB color compensation in digital imaging refers to the process of adjusting the levels of Red, Green, and Blue (RGB) in an image to correct or enhance its color balance (Gijsenij *et al.*, 2011). This process is essential because various factors, such as lighting conditions and camera sensor characteristics, can cause the colors in an image to appear inaccurate or unnatural. In professional digital photography color compensation is typically achieved through image editing software, such as Adobe Photoshop, GIMP, or Lightroom, which allows manual adjustment of RGB channels.
This can be done through levels, curves, or color balance tools. To further facilitate this task some cameras allow you to set a custom white balance by taking a reference photo of the gray card. The camera uses this information to adjust the RGB channels for the subsequent shots to ensure correct color balance. Color compensation using Automatic White Balance (AWB) is a technique used in most cameras and mobile phones to correct the color of images so that white objects appear white under different lighting conditions regardless of the color temperature of the light source in the acquired scene. This is done by automatically analyzing the image content. Once the most likely white point is determined, the image's color channels (Red, Green, and Blue) are adjusted accordingly by the algorithm. If the light source has a warm tone (e.g., incandescent light), the algorithm increases the Blue channel to counteract the yellow/red tint. If the light source is cool (e.g., fluorescent light), it increases the Red channel to counteract the blue tint. AWB compensation should ensure that the overall color balance of the image is natural, and the colors appear as they would under neutral lighting conditions, however AWB algorithms may badly fail when there are very few colors in the scene, for example a photo of a blue sky (they might misinterpret the overall color cast and adjust the colors incorrectly, leading to unnatural results), or when there are multiple light sources with different color temperatures in the same scene. For example, a room with both daylight from a window and incandescent lights can be challenging to balance.

Advancements in RGB-based Automatic White Balance (AWB) algorithms have focused on improving their accuracy, adaptability, and robustness in varying lighting conditions (Barron *et al.*,

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2017; Bianco *et al.*, 2015; Hu *et al.*, 2017). Despite these improvements, several intrinsic limitations remain due to the fundamental nature of RGB data (Buzzelli *et al.*, 2023a). To overcome these limitations, we may require integrating additional types of data, such as multispectral imaging, depth information, or more sophisticated scene understanding, to achieve more reliable and accurate white balance correction.

In this work we summarize our recent attempts to achieve RGB color constancy, focusing on three main approaches: **spectral-based** (Erba *et al.*, 2024a)**, spectral ambient sensor-based** (Erba *et al.*, 2024b)**, and based on spectral recovery from RGB data** (Agarla *et al.*, 2022; Buzzelli *et al.*, 2023b).
Spectral-based methods, as shown in Fig. 1, utilize multispectral imaging to estimate the scene illuminant more accurately across various wavelengths, which is then converted into the RGB domain for color correction.
Spectral ambient sensor-based methods, illustrated in Fig. 2, involve using external sensors to measure the scene's lighting conditions directly, which can then inform the color compensation process.
In the last approach, as shown in Fig. 3, the full spectral profile of the scene is reconstructed by a process of **spectral recovery from RGB data**. Once the spectral data is recovered, spectral-based methods are employed to estimate the scene illuminant with a greater accuracy across multiple wavelengths.

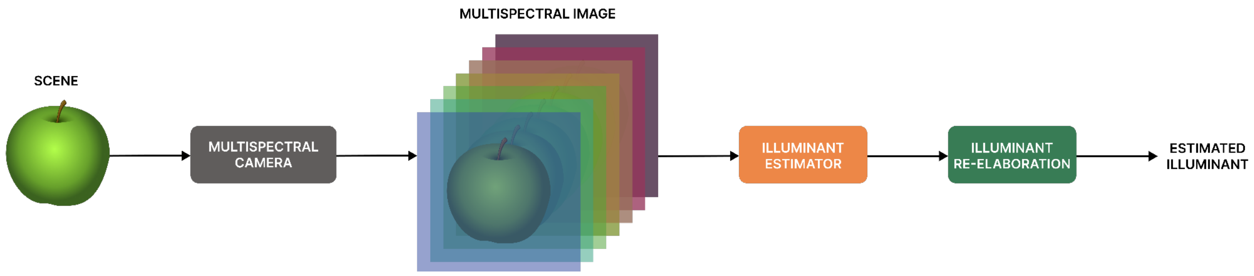

Fig. 1 - Spectral-based illuminant estimation

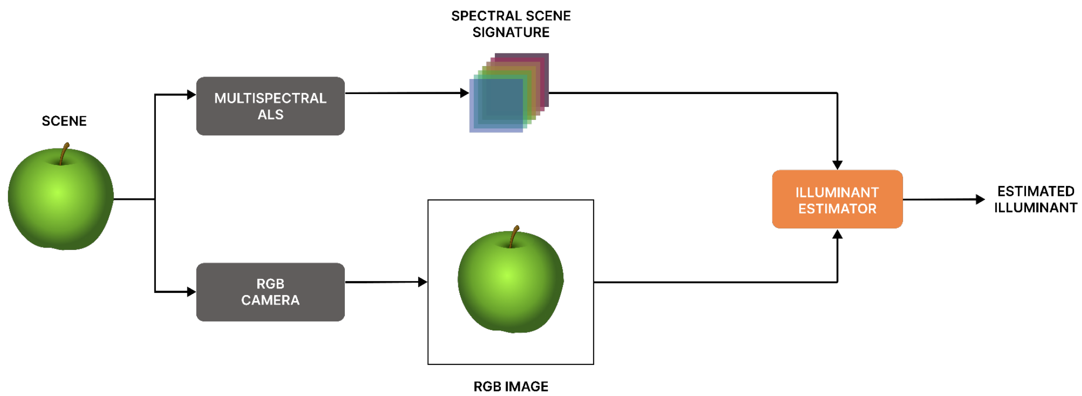

Fig. 2 - Spectral ambient sensor-based illuminant estimation

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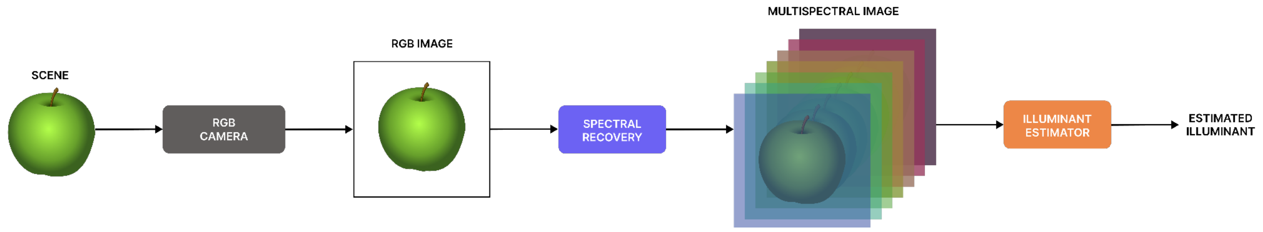

Fig. 3 - Spectral recovery-based illuminant estimation

Spectral-based Automatic White Balance

It is likely that future mobile phones will include high-resolution multispectral sensors. Traditionally used in fields like agriculture and medical imaging, multispectral technology is becoming more feasible for mainstream devices due to advancements in miniaturization, which reduces the size and cost of these sensors, making them suitable for integration into mobile phones. Considering this observation, in our paper titled "RGB Color Constancy Using Multispectral Pixel Information" (Erba *et al.*, 2024a) we propose a novel method to enhance computational color constancy by leveraging multispectral imaging for illuminant estimation and subsequent correction in the raw RGB domain. To this end, we extend a set of existing camera-independent RGB illuminant estimation algorithms to operate on multispectral data and investigate whether this richer data source can improve the accuracy of color constancy.

Our methodology involves two primary steps:

1. **Multispectral Extension of RGB Algorithms:** We first extend a selected number of sensor-independent AWB algorithms belonging to the edge-based color constancy framework (Van De Weijer *et al.*, 2007) from the RGB domain to a multispectral domain. However, we found that merely extending these algorithms to multispectral data is insufficient for achieving optimal color constancy.

2. **Re-elaboration of Multispectral Estimations:** To overcome the limitations of the initial step, we introduce a process to re-elaborate the multispectral estimations before converting them into raw RGB data. This step involves using the camera sensitivity function and various re-elaboration methods, such as average multiplicative weight, average additive bias, optimization-driven multiplicative weight, and feed-forward neural networks. These methods aim to refine the accuracy of the final RGB illuminant estimation.

Our results, validated on the NUS dataset (Nguyen *et al.*, 2014), demonstrate a significant improvement in color constancy performance, with a 60% reduction in mean reproduction angular error compared to traditional raw RGB methods.

Spectral ambient sensor-based Automatic White Balance

The motivation for this work stems from recent technological advancements in spectral imaging and color correction, as highlighted by a recent patent from Apple (Jia *et al.*, 2020). This patent describes an electronic device equipped with control circuitry that gathers Ambient Light measurements using a color ambient light sensor. These responses of the sensor are processed to generate a color rendering index for the ambient light, which is then used to correct the color of captured images via a color correction matrix, leading to more faithful color rendering. In our paper titled "Improving RGB Illuminant Estimation Exploiting Spectral Average Radiance" (Erba *et al.*, 2024b) we present a novel AWB method where the image acquired by a conventional high-resolution RGB color camera is combined with a low-resolution spectral image acquired by an Ambient Light Sensor, producing a high-resolution spectral image.

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Our approach focuses on three key points:

1. **Spatial Resolution for Input Sampling:** We investigate the optimal spatial resolution for sampling input images in terms of both RGB color and spectral information to maximize performance. By dividing the input image into patches and using these patches for training, we determine the most effective patch size for illuminant estimation.

2. **Illuminant Prediction Domain:** We explore whether it is more advantageous to predict the illuminant in the spectral domain or the RGB color domain. This investigation allows us to refine our model's approach to predicting illuminants, ensuring that the estimation is as accurate as possible in the RGB color space.

3. **Loss Function Domain:** Assuming that the illuminant is predicted in the spectral domain, we examine whether it is better to define the loss function in the RGB color domain or the spectral domain. This analysis helps to fine-tune our model's training process, leading to improved accuracy in the final illuminant estimation.

Our experiments, conducted on the NUS multispectral radiance dataset, demonstrate that the best results are achieved when the model is trained to predict the illuminant in the spectral domain using an RGB color loss function. This approach leads to a significant improvement in the mean recovery angular error, reducing it by 66% compared to the best-tested spectral method and by 41% compared to the best-tested RGB method.

AWB using spectral recovery from RGB data
A third approach is to use RGB data to recover spectral information, which can then be utilized to apply spectral methods for AWB.

This process begins with reconstructing the full spectral profile of the scene from the RGB image using techniques like spectral reconstruction algorithms.
Our paper "Fast-n-Squeeze: Towards Real-Time Spectral Reconstruction from RGB Images" (Agarla *et al.*, 2022) introduces one such efficient algorithm for real-time spectral reconstruction from RGB images. The method combines a global RGB-to-spectral linear transformation matrix, estimated through Moore-Penrose pseudo-inverse (Penrose, 1955), with a lightweight convolutional neural network (CNN) for scaling the output (Iandola, 2016). The first part, "Fast," estimates the transformation matrix based on low-level image features, while the second part, "Squeeze," uses a CNN to refine the reconstruction through global scaling. The method, designed for the NTIRE 2022 Spectral Reconstruction Challenge (Arad *et al.*, 2022), achieves a balance between computational efficiency and reconstruction accuracy, offering superior performance with fewer artifacts compared to other state-of-the-art methods. Fast-n-Squeeze operates at 198 FPS on a GPU, making it highly suitable for real-time applications.

Alternatively, in our paper "RGB Illuminant Compensation Using Spectral Super-resolution and Weighted Spectral Color Correction" (Buzzelli *et al.*, 2023b) we estimate spectral information from RGB data and use it for illuminant estimation. The paper introduces a novel method for spectral illuminant correction in smartphone imaging, improving color accuracy by leveraging Spectral Super-resolution and Weighted Spectral Color Correction (W-SCC), which applies per-wavelength weight optimization to correct color discrepancies. Additionally, by combining the spectral illuminant estimation with RGB illuminant estimation, a joint estimation approach is also developed. To test the effectiveness of the approach, Moore-Penrose pseudo-inverse (Penrose, 1955) and a sensor sensor-independent AWB method (Bianco & Cusano, 2015) are employed respectively for spectral reconstruction and illuminant estimation. However, any algorithm could theoretically be adopted.

Through experiments on synthetic images, simulated with Huawei P50 camera sensor and Ambient Multispectral Sensors (AMS), the method shows significant reductions in colorimetric errors compared to traditional pipelines, achieving improved accuracy in color correction. The proposed W-SCC approach has applications in areas such as color analysis, computer vision, and industrial inspection, with potential for future enhancements through advanced optimization techniques and machine learning.

In general, once the spectral data is recovered, spectral-based methods are employed to estimate the scene illuminant with greater accuracy across multiple wavelengths. The refined illuminant estimation is then converted back to the RGB domain for color correction. This hybrid approach leverages the richer spectral information derived from RGB data to improve the accuracy of color compensation, combining the strengths of both RGB-based and spectral-based techniques.

Conclusions

This paper demonstrates the effectiveness of integrating multispectral information into RGB color constancy algorithms, significantly enhancing color accuracy under diverse lighting conditions. By extending traditional RGB-based methods to the multispectral domain and employing re-elaboration techniques, we achieved a substantial reduction in reproduction angular error. The use of ambient sensors and spectral recovery from RGB data further improved the precision of illuminant estimation. These advancements underline the potential of multispectral imaging to overcome the limitations of conventional RGB-based color correction, paving the way for more accurate and reliable color constancy in digital imaging. Future work will focus on refining these methods and exploring their application in various fields, including consumer electronics, remote sensing, and healthcare imaging.

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