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Spatial Frequency Response of Bayer Color Image Formation

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Most color imaging systems today are based on a monochrome detector with a color filter array (CFA). Typically the Bayer CFA is used. An imaging system's spatial frequency response (SFR) is one of its most meaningful characteristics. It is directly related to the system's capability to resolve objects. This work presents a model for calculating the SFR of a Bayer color capture system. Our two dimensional model deals with a color input signal, and accounts for both sampling and interpolation processes. It can be applied on any linear interpolation.

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1. Introduction

The most common color camera technology is based on spatial-multiplexing using a color filter array (CFA): spectral channels are captured in alternating pixels of a single monochrome sensor. A generalized CFA approach has been proposed for hyperspectral imaging [1]. Couillaud et al. applied a frequency domain based method for evaluating the image quality obtained by different CFAs [2]. A Bayer pattern CFA is very common [3]. Following image acquisition, interpolation known as demosaicking is applied, to estimate the color (RGB) values per pixel. Interpolation can be a linear process [4, 5]. Then, each output color pixel can be expressed as a linear function of its surrounding pixels in the raw Bayer sensor image. Thus, it can be expressed as a convolution of the raw Bayer sensor image with some filter kernel. More advanced, non-linear demosaicking methods were introduced more recently [6–8]. While non-linear demosaicking approaches typically result in a sharper image, linear interpolation is still being used. Faster and easier implementation are two main reasons. The notion of spatial frequency response (SFR) is enabled by linear-systems theory. Thus, our Bayer SFR model assumes linear interpolation.

An imaging system's SFR is an important property. It is often used during the system design phase, for comparison between several systems, and in performance prediction models. Such models are required during system design. In some cases, they can be used when the possibility to perform actual experiments is limited due to high risk or cost [9]. For a linear, space-invariant system, the SFR is given by the system's modulation transfer function (MTF). A thermal imaging system's minimum resolvable temperature difference (MRTD) [10] is an important performance measure. It is spatial frequency dependant, and is inversely proportional to the MTF. The same is true for minimum resolvable contrast (MRC) [11], an analog of the MRTD in visible light systems.

Dubois [12] analyzed the SFR of a raw Bayer signal, excluding interpolation. On the other hand, Elor et al. [13] analyzed the SFR of linear interpolation of Bayer-based data, excluding the raw acquisition SFR. The scene in [13] is assumed to be monochrome. Ref. [13] also assumed signal integration along the vertical axis. This assumption simplified the mathematical derivations, resulting in a one-dimensional SFR. However, vertical integration does not take place in practice. We show that there actually is a frequency response in both directions. Interestingly, this is the case even if the input signal varies only in the horizontal direction. Hubel et al. [14] presented empirical measurments of the SFR of a Bayer sensor, and compared them to a FOVEON X3 sensor, for which limitations peculiar to a CFA do not exist.

In this work, we present a unified model. We analyze the *two-dimensional* SFR of a Bayer imaging system, caused by *both* CFA sampling and linear interpolation processes. Moreover, we do not limit the analysis to a monochrome scene. In contrast to Refs. [12, 13], we present a simulation which is consistent with our theoretical model for Bayer SFR.

2. Background

2.A. Bayer image formation

The Bayer image formation process is illustrated in Fig. 1. A Bayer CFA [3] is illustrated in the middle. Let x and y denote discrete horizontal and vertical axes, respectively. We define their origin to be at the bottom left point of the Bayer grid which is illustrated in Fig. 1. An RGB signal is denoted by $s_R(x, y)$, $s_G(x, y)$ and $s_B(x, y)$. These are the original signals that the Bayer system aims to estimate, while using a single

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