A critical review of the slanted-edge method for color *SFR* measurement

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Abstract: Critical examination of the slanted-edge method for color *SFR* measurement reveals inaccuracies in the estimated *SFR*, due to the use of demosaicing. The proposed method resolves these inaccuracies by eliminating the need for demosaicing during *SFR* measurement.

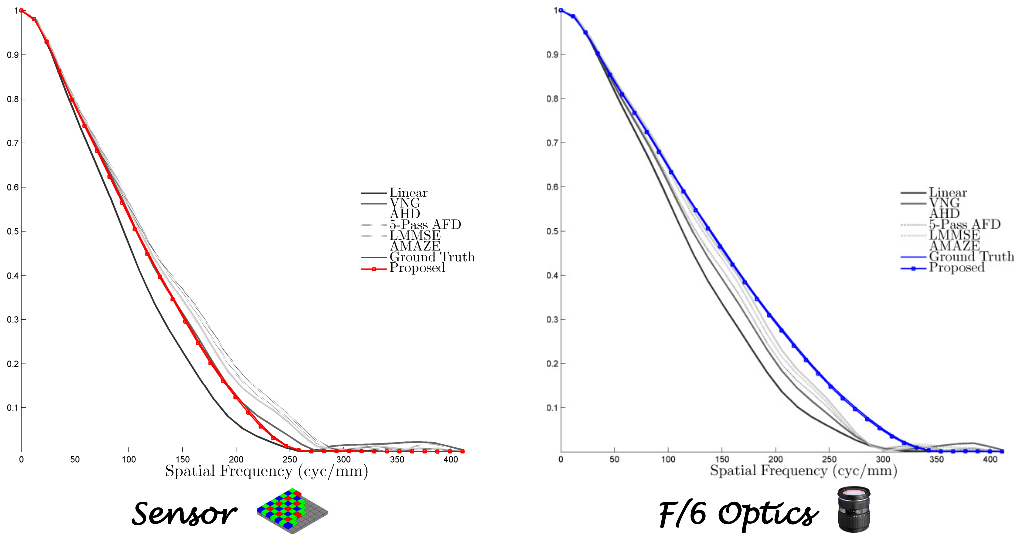
OCIS codes: (110.4100) Modulation transfer function; (110.4850) Optical transfer functions

1. Introduction

The spatial frequency response (*SFR*) of a digital image acquisition system is an objective measure of image quality that describes an imaging system's ability to capture or maintain the relative radiometric contrast of increasingly fine sinusoidal patterns [1]. The *SFR* neatly encapsulates the influence of the optical elements, the pixel MTF and the camera electronics, on image quality.

The slanted-edge algorithm outlined in the *ISO12233* standard is the most celebrated method for identifying the *SFR*, and finds widespread use in diverse disciplines such as remote sensing and radiology. The benefit of the slanted-edge method over its counterparts lies in the relative ease with which the *SFR* can be determined for aliased imaging systems. The method relies on the analysis of the sampled image of a slanted edge. It exploits the variation in the sampling phase of the slanted edge to create a "super-resolved" edge response, whose resolution exceeds the sensor's native resolution.

Our investigations into the slanted-edge algorithm and tools based on the algorithm have revealed an interesting fact: *demosaicing[1] influences the SFR estimates of color cameras*. The SFR plots of *Fig.*1 illustrate this behavior.



- *Bayer CFA with pixel pitch* $= 1.2\ \mu m$
- *Red*/*Blue channel Nyquist* $= 208.33\ cyc/mm$
- *Green channel Nyquist* $= 294.63\ cyc/mm$

- *Red channel cutoff* $= 260.41\ cyc/mm$
- *Green channel cutoff* $= 303.03\ cyc/mm$
- *Blue channel cutoff* $= 347.22\ cyc/mm$

Fig.1 Impact of demosaicing on *SFR* estimation using *SFRmat3*
The synthetically generated *CFA* image was demosaiced using LibRAW

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[1] Demosaicing refers to the process of inferring the missing colors at each pixel while minimizing the occurrence of color moiré, and visual artifacts. It is an integral component of the digital imaging pipeline.

The gray plots in *Fig.*1 represent the *SFR* of the red & blue channels estimated from the various demosaiced images. The input to each demosaicing algorithm is a synthetically generated color filter array (*CFA*) image of a blurry slanted edge (slant angle= 5.7 degrees).

While it may be argued that the *SFR* should encapsulate the effect of demosaicing, we believe that the ability to estimate the *SFR* independent of demosaicing provides the following benefits:

1. ability to compare the image quality of cameras with vastly differing CFA architectures
2. ability to characterize the effect of demosaicing on the spatial frequency response of an imaging system

The proposed method eliminates the need for demosaicing by accommodating the sparse structure of *CFA* color sampling within the slanted–edge method. A quick look at the dotted plots in *Fig.*1 reveals the benefit of the proposed method.

The following section provides a detailed description of the inner workings of the proposed method. *Section.*(3) describes an experimental validates the proposed method.

2. Proposed Method for *SFR* estimation from *CFA* image

The fundamental difference between the slanted-edge *SFR* algorithm outlined in the *ISO12233* standard and the method outlined in *Fig.*1**,** is the ability to accommodate the sparse arrangement of colors in the *CFA* pattern within each step of the slanted-edge algorithm.

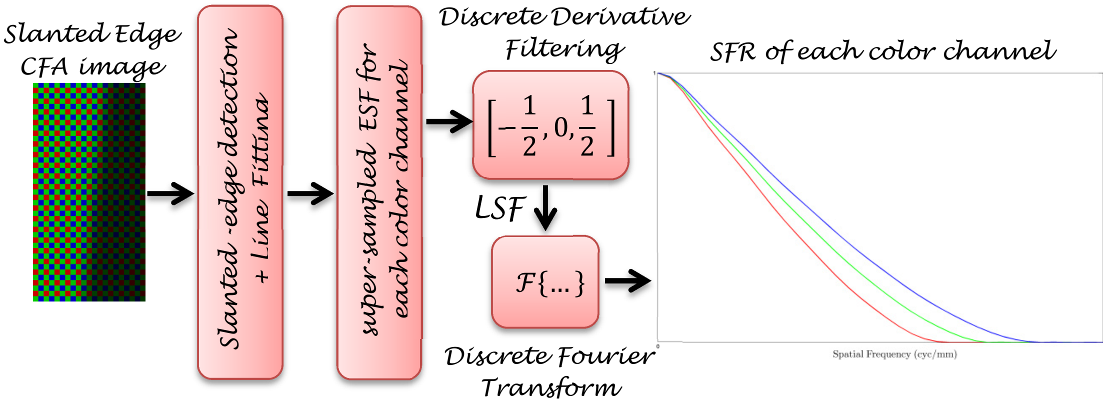

Fig. 2 Proposed Workflow for estimating the *SFR* from the *CFA* image of slanted edge

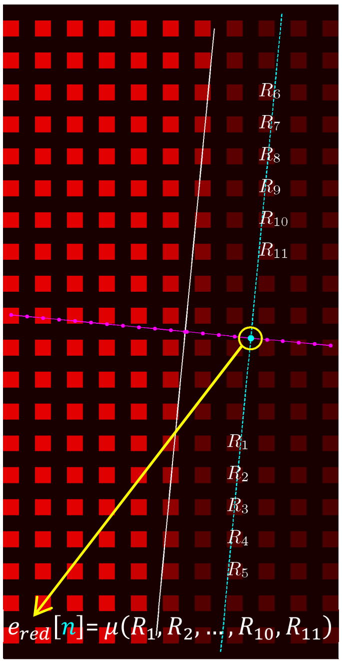

Fig. 3 Proposed strategy for identifying the super-sampled *ESF* of the Red channel

The process of *SFR* estimation begins with the identification of the slope and intercept of the slanted edge within the region-of-interest. This step involves identifying the pixels that make up the slanted edge, followed by a robust line fit to the edge pixels. The *CFA* edge-detection method outlined in [2] is used to identify the edge pixels. The next step in the process involves identifying the super-sampled *ESF* for each color channel, using the strategy outlined in *Fig.*1. The solid white line represents the location of the ideal step edge, while the magenta dots represent points on the super-sampled *ESF* grid. The n^{th} sample of the *ESF* (represented by the cyan dot) can be strictly inferred from the pixels $(R_1, R_2, \dots, R_{10}, R_{11})$ that intersect the cyan line in *Fig.*1. Notice that the slope of this line is designed to match the slope of the slanted edge. The process is repeated for each *ESF* sample, in each color channel.

Close examination of *Fig.*1 reveals that the tails of the super-sampled *ESF* are estimated from the fewest *CFA* samples, and consequently most influenced by noise. The influence of noise on the estimate of the *ESF* & *LSF* can be minimized by adopting the following strategy

1. fit sigmoid functions to the *ESF* tails prior to derivative filtering
2. fit a mixture of Gauss-Hermite polynomials [3] to the super-sampled *LSF* prior to computing the Fourier transform of the *LSF*

The final step in the estimation process involves compensation of the magnitude response of the discrete derivative filter, as recommended by [4].

3. Experimental Validation

The objective of the experiment described in *Fig.*1 is to compare the *SFR* estimated from the *CFA* image of a slanted edge (proposed method) with the *SFR* estimated from a full-color RGB image of the slanted edge (*SFRmat-v3*). The digital back in the Sinar P3/86H medium-format facilitates the comparison by permitting us to capture RGB information at each photosite (in 4-shot mode), and eliminating the need for demosaicing. A 360-ppi image of a straight edge (contrast ratio 4:1) printed on 4" × 6" Premium Glossy Photo Paper @ 1440 × 1440 dpi, serves as the target. The target is mounted on a rotation stage positioned 280 inches from the camera, and uniformly illuminated using 4700K Solux lamps. Care is taken to ensure that the camera optical axis intersects the axis-of-rotation of the edge target. An artificial *CFA* image obtained by sub-sampling the color channels of the full color RGB image serves as the input to the proposed method. Close examination of the *SFR* plots in *Fig.*1 reveal significant agreement between the *SFR* estimated from the *CFA* image and the full-color RGB image.

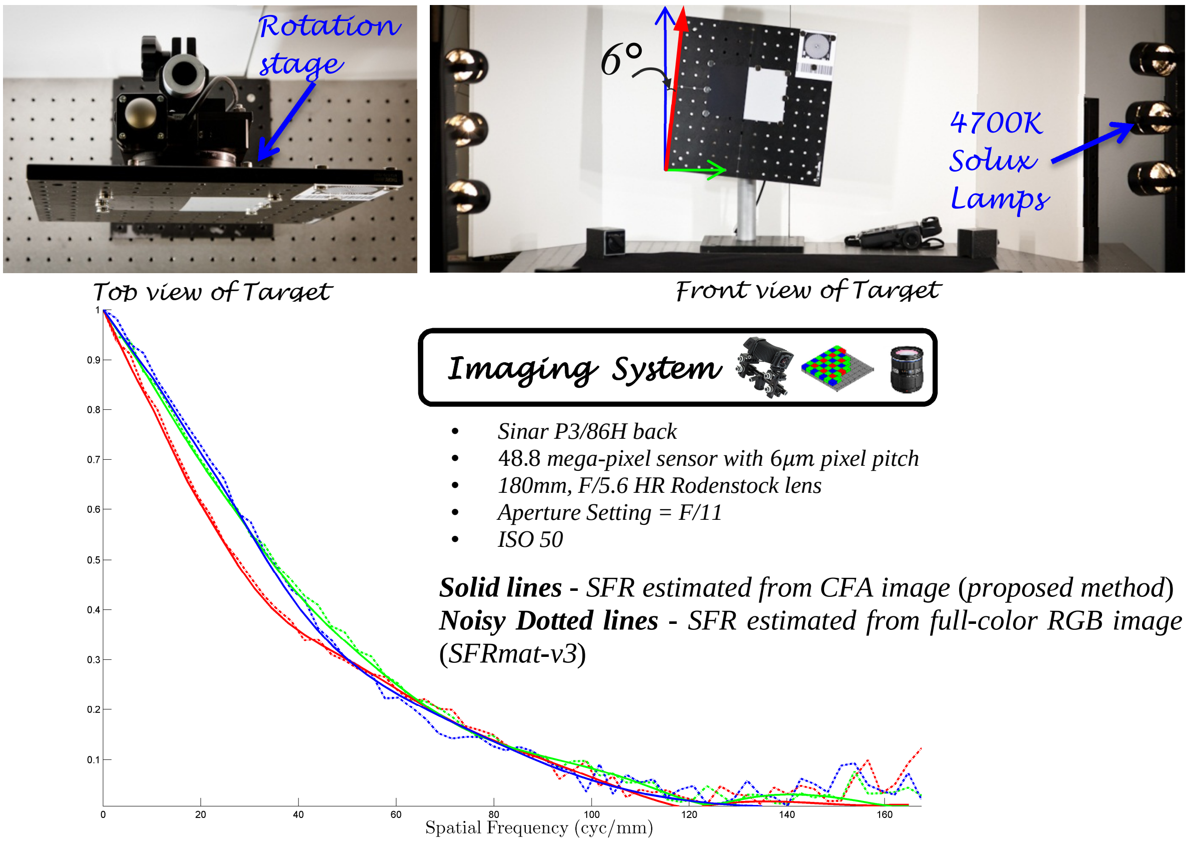

Figure 4 Experimental Validation of proposed method for *SFR* estimation in color camera

4. Summary

The findings reported in this work suggest caution when using tools that rely on the slanted-edge algorithm to identify the *SFR* of color cameras. Experiments reveal systematic errors in the *SFR* estimates due to the use of demosaicing when estimating the *SFR*. The proposed modification to the slanted-edge algorithm eliminates the need for demosaicing by accommodating the sparse structure of *CFA* color sampling within the slanted–edge method. The method will facilitate the comparison of image quality of cameras with vastly differing *CFA* architectures, and help characterize the impact of a specific demosaicing algorithm on image quality.

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5. References

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