Picture Quality Improvement Schemes for HDTV Applications

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I. Introduction

High-definition television (HDTV) is finding an increasing range of applications in areas such as broadcasting, digital cinema, and medical imaging. The conventional three-sensor camera system provides good image quality for these applications, however is expensive and not portable. A single-chip color camera system is one of the solutions to realizing inexpensive and portable cameras since: (1) With only one imager, there is a reduced part count for the imager, driver, and pre-processing circuits; (2) A color-separation optical system is not needed; and (3) A lens with a long back focal length for adapting to optical prisms is not needed, and a small, inexpensive lens can be used instead. However, to acquire a color signal with a single-chip image sensor, the number of pixels for each color channel is reduced if the sensor pixel count is to remain the same, which degrades the picture quality [1-3]. To attain an image quality comparable to or better than the conventional three-sensor camera system, the overall single sensor pixel count must be increased.

In [6], a single-chip CMOS image sensor with high pixel count (8 Mpixels) is presented. In [8], picture quality improvement methods for a single-chip color HDTV image acquisition system based on this 8Mpixel sensor are introduced. In this project, we further investigate the picture quality improvement schemes that are enabled by the availability of the high resolution imager. Specifically, we simulate and verify the picture quality improvement achieved using a 4x2 color filter array (CFA) discussed in [8]. We analyze its advantages over the standard Bayer CFA [5] and suggest directions for future work to overcome some of its limitations. Next, assuming that we are limited in spatial resolution by the CFA, we explore new demosaicing algorithms that seek to recover the resolution through intelligent colour interpolation. We present a preliminary approach to such demosaicing algorithms, examine its advantages, and suggest future work to overcome its limitations. Our project is therefore a continuation of the work in [6] and [8], with the ultimate goal being a commercially feasible single-sensor HDTV camera system that is not only inexpensive and portable, but also further enhances the picture quality that is achievable using expensive and bulky present-day systems.

II. Investigating Picture Quality Improvement through CFAs

A color filter array, or CFA, is a grid of Red, Green, and Blue filters that is overlaid on the image sensor pixel array to separate the three primaries during image capture, that is, spatially sample the R, G, and B intensities in an image. Since pixel outputs consequently only contain single-color information, the missing color values for each pixel must be filled in. This color interpolation technique of post-processing the sensor image to recover the full color image is known as demosaicing. In this section, we review the standard Bayer CFA that is used in most digital camera systems, present a new 4x2 CFA, and quantify the picture quality improvement using the 4x2 CFA over the Bayer CFA. We examine demosaicing in a later section. Our analyses of the CFAs is based on examining color aliasing effects in the final demosaiced images and comparing the overall MTFs and chromaticity charts. We show that the new 4x2 CFA significantly reduces color aliasing in the horizontal dimension due to its higher spatial resolution in all three color channels, but suffers from greater color aliasing in the vertical dimension due to non-uniform spatial sampling of the color channels. To suppress vertical color aliasing, we introduce vertical optical low-pass filters (O-LPFs) that blur the image in the vertical dimension. However, since this approach also reduces the resolution in the vertical dimension, we explore variations on the 4x2 CFAs that serve to improve the spatial resolution in both horizontal and vertical dimensions, thus minimizing color aliasing while preserving high resolution. The ultimate objective is therefore to investigate whether new CFAs are possible that improve picture quality, which would not only enhance the performance of the single-chip HDTV camera system, but would also serve as an alternative to the traditional Bayer CFA.

II.1 Bayer CFA Review

It is instructive to review the Bayer CFA and evaluate its picture quality performance since it will serve as the reference for the rest of the analyses in this section.

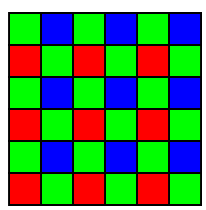

Figure 1. Standard Bayer CFA

Figure 1 shows the Bayer CFA. The Bayer CFA is known for good color reproduction. Note that we can mathematically express the above pattern in terms of the Green (G), and Blue (B) and / or red (R) spatial sampling functions as follows:

$$C_g(\mu,\nu) = \frac{1}{x_0 y_0} \sum_m \sum_n \delta\left(\mu - \frac{m}{x_0}, \nu - \frac{n}{y_0}\right)\left(1 + (-1)^{m+n}\right)$$

$$C_{br}(\mu,\nu) = \frac{1}{x_0 y_0} \sum_m \sum_n \delta\left(\mu - \frac{m}{x_0}, \nu - \frac{n}{y_0}\right)$$

where *m* and *n* are integers, and μ and ν are horizontal and vertical frequency variables, respectively. Based on these equations, we compute the spatial frequency transmission band of an 8M-pixel Bayer pattern which is plotted in Figure 2 below:

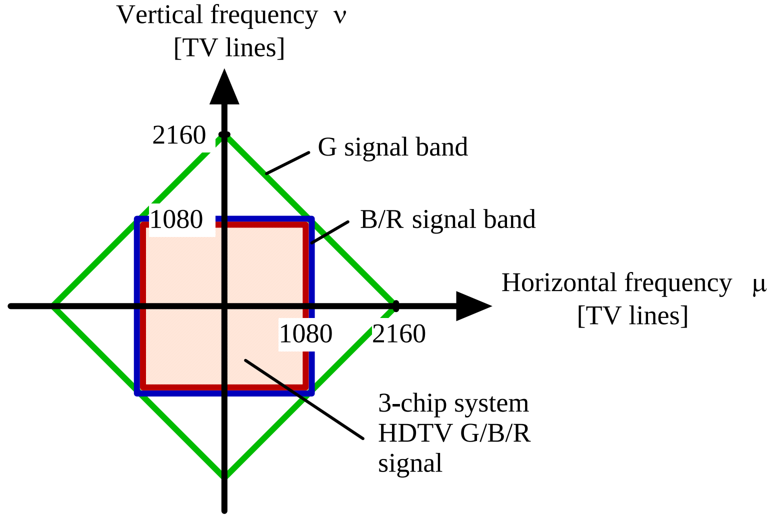

Figure 2. Bayer Pattern Frequency Pass Band

From the above, we observe that the Green channel has twice the sampling resolution that the Blue and Red channels have. Note that this is expected by examining the Bayer pattern in Figure 1. Also note that the horizontal and vertical sampling resolutions are symmetric. We verify our theoretical understanding by analyzing sensor image MTF characteristics using the Bayer CFA. The simulations are performed in ISET and representative results are discussed below.

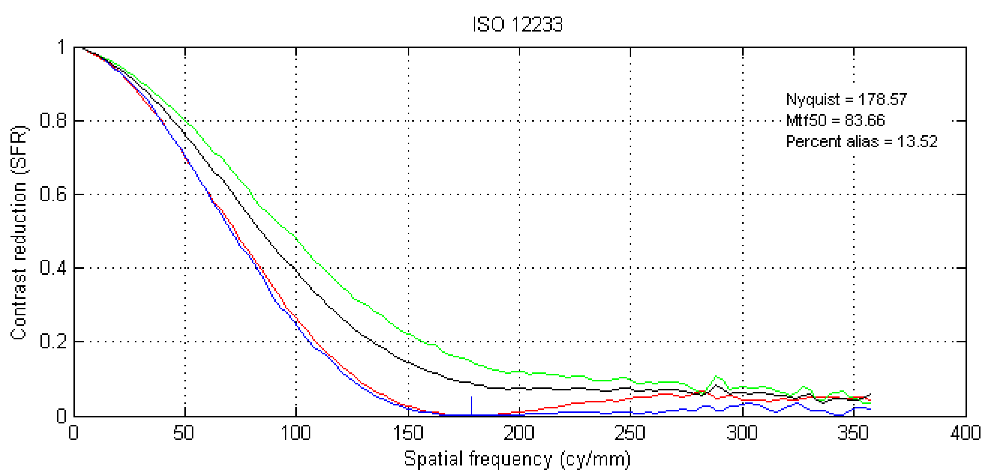

Figure 3. MTF Characteristics Computed from Sensor Image using Bayer CFA

Figure 3 shows an example of simulated MTF characteristics in the horizontal dimension (that is, only horizontal frequency variation in the scene). The MTF plot confirms that the Green signal has higher spatial resolution and hence a higher Nyquist frequency. On the other hand the Blue and Red signals have poorer MTF characteristics which is consistent with our predictions. Note that the Blue and Red MTFs coincide with each other which is also consistent from our formulation of the sampling functions for the color channels. We will present full simulation results when comparing the CFAs later in the report.

II.2 New 4x2 CFA

We review the 4x2 CFA presented in [8] before comparing its performance to the standard Bayer CFA discussed above. The 4x2 CFA is shown below in Figure 4:

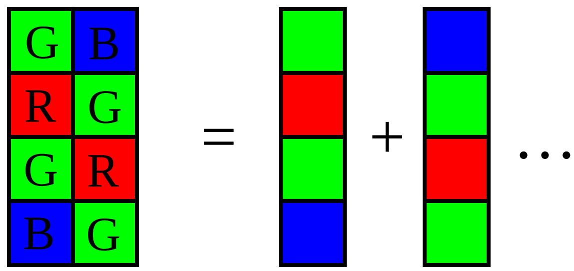

Figure 4. New 4x2 CFA

As can be observed from the above diagram, the 4x2 CFA increases horizontal spatial resolution of the Red and Blue channels. That is, all color channels now have the same horizontal spatial resolution which is equivalent to the Green spatial resolution of the Bayer pattern. Recall that the Bayer pattern had half the spatial resolution in the Red and Blue channels compared to the Green channel; the main contribution of the 4x2 CFA is that it increases the horizontal spatial resolution of the Red and Blue channels to equal that of the Green channel. Note that the limitation of the 4x2 CFA is non-uniform sampling in the vertical dimension for the Red and Blue channels resulting in poorer vertical resolution as compared to the Bayer CFA. This can often be tolerated since vertical resolution will be limited by the interlace scanning system. We also show how to compensate for it by using vertical optical low-pass filters (O-LPF).

We present a comparable mathematical formulation of the spatial sampling characteristics of the 4x2 CFA to be consistent with the analysis of the Bayer CFA.

$$C_g(\mu,\nu)=\frac{1}{x_0y_0}\sum_m\sum_n\delta\left(\mu-\frac{m}{x_0},\nu-\frac{n}{y_0}\right)\left(1+(-1)^{m+n}\right)$$

$$C'_{br}(\mu,\nu)=\frac{1}{2x_0y_0}\sum_m\sum_n\delta\left(\mu-\frac{m}{x_0},\nu-\frac{n}{2y_0}\right)\left(1+(-j)^{2m+n}\right)$$

The Green channel sampling function is the same as before but the new Blue / Red sampling functions show the factor of two improvement in horizontal resolution. The frequency transmission bands are plotted below and show the improvement in Red and Blue horizontal resolution but degradation in vertical resolution.

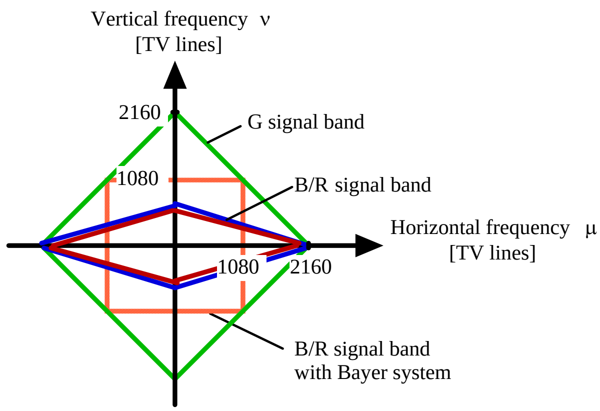

Figure 5. 4x2 CFA Pattern Frequency Pass Band

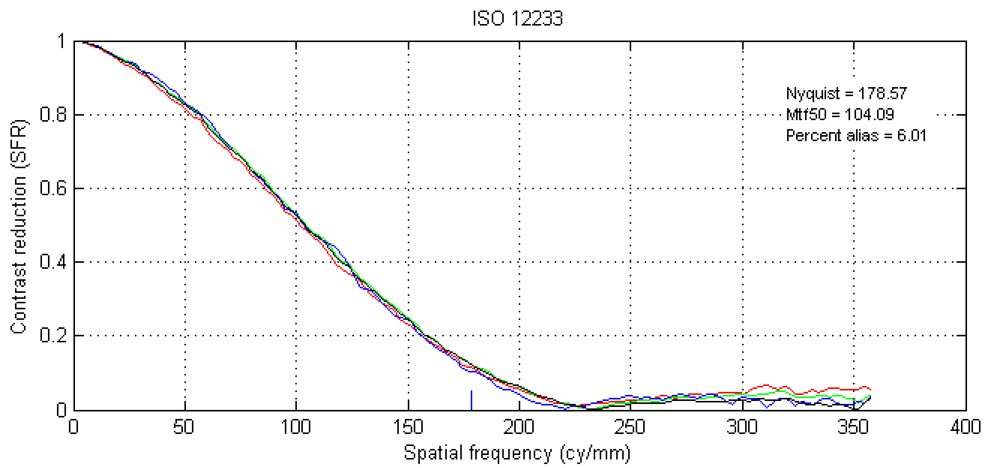

Figure 6. MTF Characteristics Computed from Sensor Image using 4x2 CFA

Figure 6 shows the typical MTF characteristics in the horizontal dimension using the new 4x2 CFA. As can be observed, the R, G, and B color channels all have the same horizontal spatial sampling frequency. We now present detailed results of our simulations and draw conclusions.

II.3 Results

Our purpose was to compare the performance of the 4x2 CFA with the standard Bayer CFA using a scene with varying frequency content in the horizontal and vertical dimensions. The approach was to compare the visual color aliasing effects in the demosaiced images and to quantify the color error by examining the chromaticity charts in various regions of the demosaiced images. All simulations were performed in ISET and the source code is attached in Appendix 1.

We first present simulation results using the standard Bayer pattern:

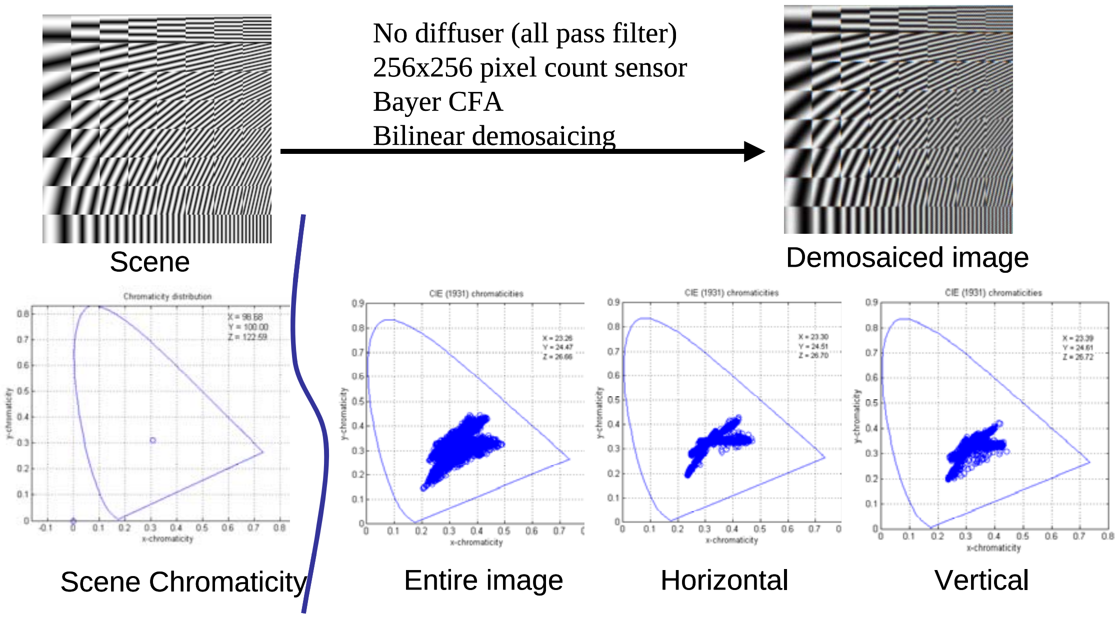

Figure 7. Examining Color Aliasing with Standard Bayer CFA

The ideal chromaticity chart for a monochrome image, shown in the bottom left part of Figure 7, is the reference point when quantifying color aliasing effects. The chromaticity chart labeled, "Entire image", corresponds to the entire image, while the charts labeled "Horizontal" and "Vertical" correspond to variations in only horizontal and only vertical frequency components, respectively. For example, the "Horizontal" chromaticity chart is obtained using only the lower part of the demosaiced image which does not have vertical frequency variations and only frequency variation in the horizontal dimension. Note that plotting the chromaticity charts from the demosaiced image has the disadvantage of including the color error introduced by the demosaicing algorithm. We account for this by using the same demosaicing algorithm in all simulations when comparing the Bayer CFA with the 4x2 CFA; thus differences in the chromaticity plots will only be due to the CFAs.

We next introduce a low-pass filter, implemented as a 2D Gaussian, with equal x and y standard deviations (where 1 pixel sd corresponds to 2.8 μm), in order to verify that limiting the maximum input signal frequency reduces color aliasing as is expected from Shannon sampling theory.

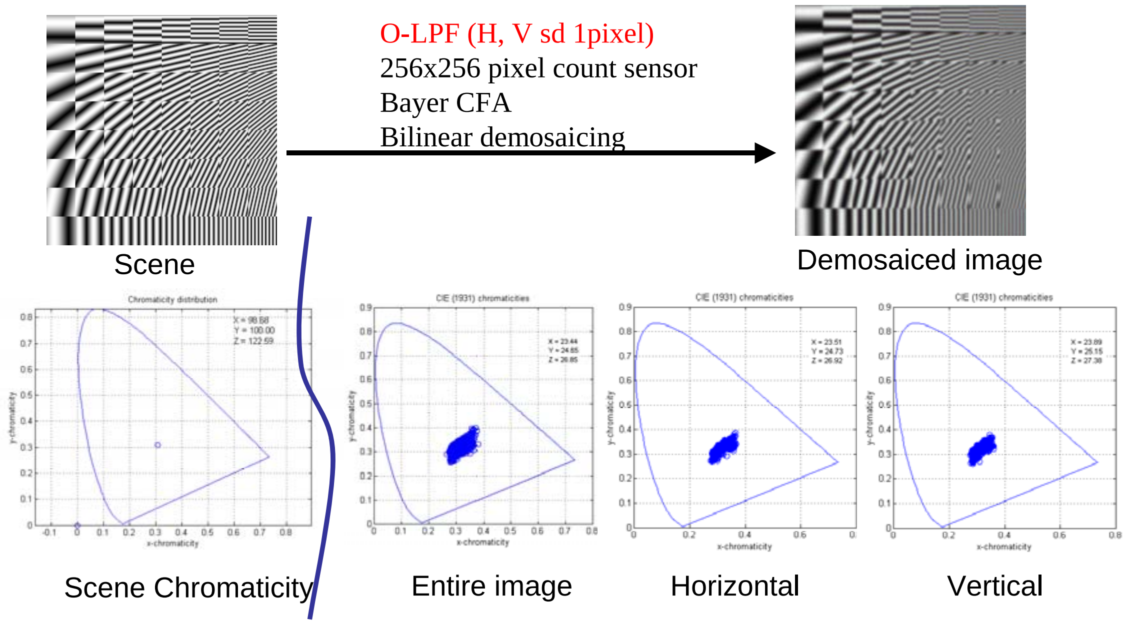

Figure 8. Examining Color Aliasing using O-LPF with Standard Bayer CFA

Note that the three chromaticity charts on the right each show a smaller spread. Comparing Figures 7 and 8 shows that the O-LPF reduces the color error in both horizontal and vertical dimensions and hence across the entire image.

We next present comparable simulations with the new 4x2 CFA. ISET was modified to accept the new 4x2 CFA and to allow simulation of the entire imaging pipeline using the 4x2 CFA instead of the Bayer CFA.

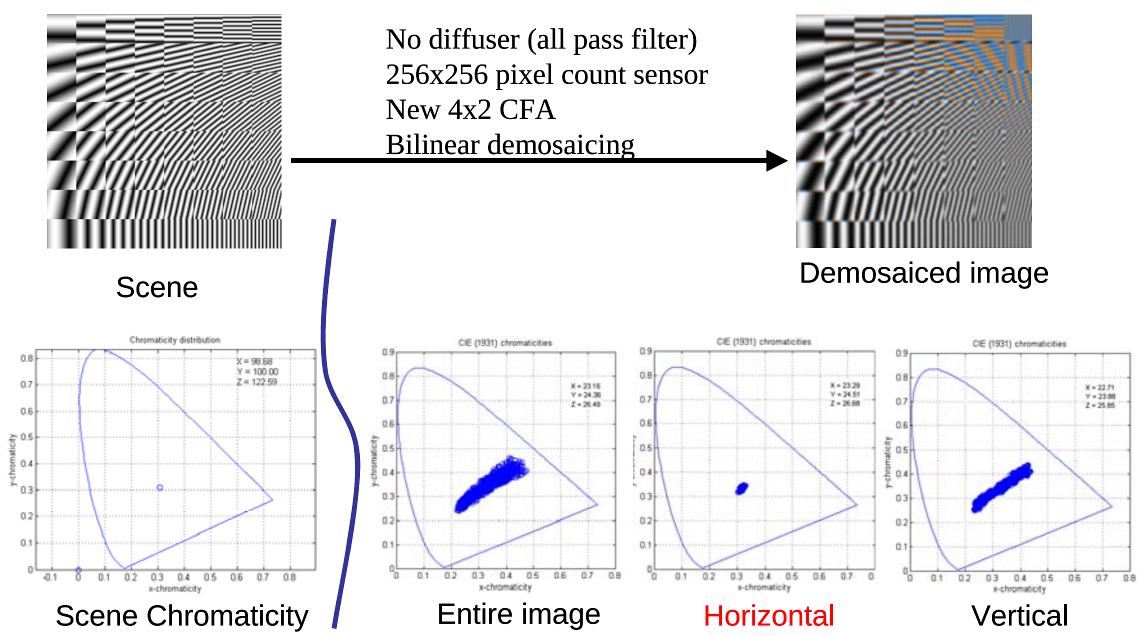

Figure 9. Examining Color Aliasing with New 4x2 CFA

The first observation, when comparing Figure 9 with Figure 7, is that the color error in the horizontal dimension is significantly reduced. By closely examining the lower part of the demosaiced image, we observe that color aliasing is almost negligible. The chromaticity chart in the horizontal dimension of the demosaiced image also has a much smaller spread than the corresponding chart that was obtained using the Bayer CFA in Figure 7. We therefore conclude that the improvement in horizontal sampling resolution of the Red and Blue color channels achieved using the 4x2 CFA indeed significantly reduces color aliasing in the horizontal dimension.

The vertical dimension suffers from more color aliasing than was noticed with the Bayer CFA. This is again consistent with our predictions. We propose minimizing the color aliasing in the vertical direction by introducing an optical low-pass filter that only blurs in the vertical direction. The O-LPF is implemented by only adjusting the vertical dimension of the 2D Gaussian filter. The results are presented below:

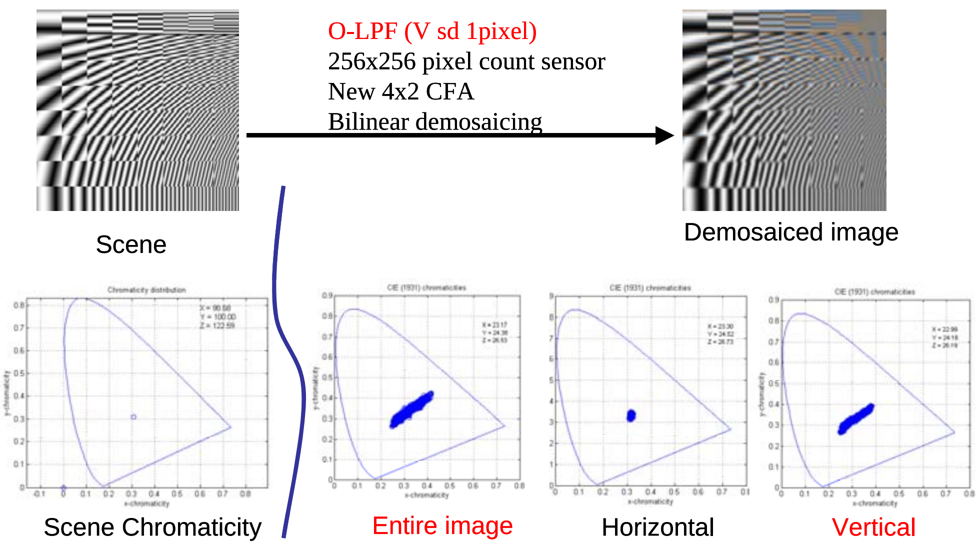

Figure 10. Examining Color Aliasing using vertical O-LPF with 4x2 CFA

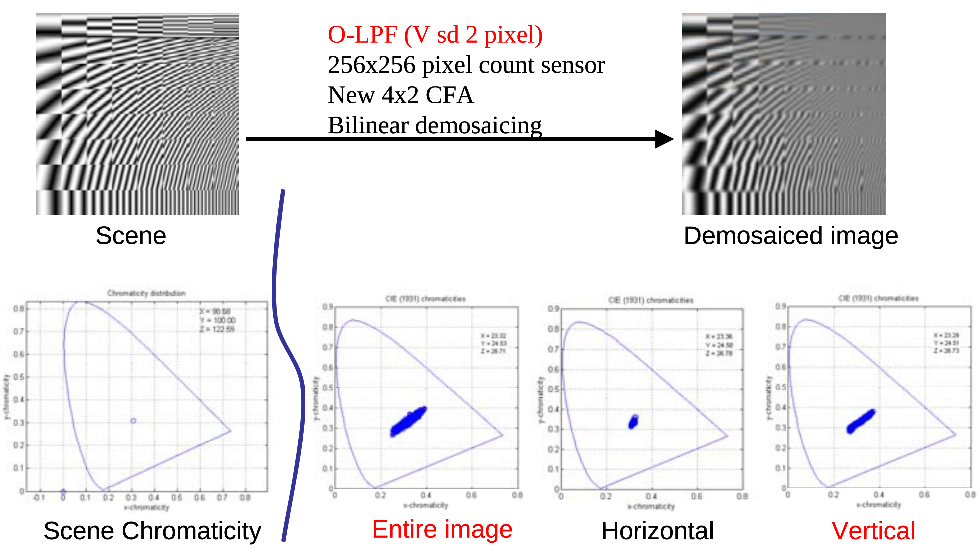

Figure 11. Examining Color Aliasing using vertical O-LPF with 4x2 CFA

Figures 10 and 11 show the result of introducing vertical O-LPFs. The color aliasing in the vertical dimension is reduced, as compared to Figure 9. However, as can be observed from Figure 11, significantly blurring the image in the vertical dimension to reduce color aliasing has the detrimental effect of resolution loss.

The above results are consistent with our theoretical predictions and analyses. The 4x2 CFA reduces color aliasing in the horizontal dimension but suffers from worse aliasing in the vertical dimension. We expected the aliasing in the vertical dimension to be worse than with the standard Bayer CFA, and it would be interesting to understand how the non-uniform sampling of the Red and Blue channels affects the type of color aliasing (that is, which colors are aliased more than others). We showed that introducing a vertical O-LPF reduces color aliasing as expected. The 2-pixel diffuser suppressed most of the color aliasing, but the cost was loss in resolution.

We investigated other variations in CFAs that would provide high spatial sampling resolution in both the horizontal and vertical dimensions. One variation is presented below:

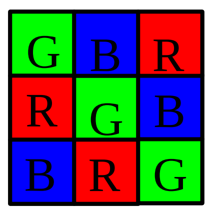

Figure 12. 3x3 CFA Concept

The motivation behind the 3x3 CFA is to achieve symmetric horizontal and vertical resolution in all color channels. The Green channel is expected to have the same resolution as before in both horizontal and vertical dimensions. The Red and Blue channels are also expected to have the same resolution as Green in both horizontal and vertical dimensions. Hence, we considered the above CFA pattern to be an improvement over the 4x2 CFA pattern.

We did not obtain results that would be consistent with the above expectations. The MTF characteristics in both the horizontal and vertical directions were worse than the Bayer characteristics. The chromaticity charts over various regions of the demosaiced image also showed more color error than when using the Bayer CFA. We did not have sufficient time to develop a mathematical formulation for the spatial sampling resolution using the 3x3 CFA as we did for the Bayer and 4x2 CFAs. We intend to theoretically understand the spatial sampling resolution achievable in all color channels and more thoroughly investigate the 3x3 CFA in a future work.

III. Investigating Picture Quality Improvements through Demosaicing

As was alluded to previously, demosaicing or color interpolation is required to fill in the missing color information for each pixel and hence recover a full color image. The second part of this project therefore investigated picture quality improvement by using new demosaicing algorithms. The assumption was that the spatial sampling resolution was now fixed by the CFA, for example Bayer, and color resolution could only be recovered or enhanced using demosaicing. We do not review demosaicing algorithms here since the subject is vast and we cannot do justice to it in this brief exposition. However, we encourage the reader to consult the references we list for background.

III.1 New Demosaicing Algorithm

The purpose of our new demosaicing algorithm is to improve picture quality by minimizing color aliasing especially in high spatial frequency. This demosaicing algorithm was first proposed in [8] and we briefly review it here. It is known that human vision has greater sensitivity to the luminance values than the chromatic signal in a scene. We consider a high frequency signal as a mainly luminance signal and substitute a monochrome signal for the color signal. This interpolation will be applied only for high frequency, and the Green signal, which is the main component of the luminance, can be used for interpolation processing of the Red and Blue signal. Interpolation processing for the Red and Blue signals is achieved as follows. We assume the system has a Bayer pattern CFA. In the vertical direction, we place an optical low-pass filter (O-LPF) characterized by 2-pixel summation. In the horizontal direction, we create every color signal, then limit the frequency band above that of HDTV. For each of these signals, we consider positions for which there is no sampling signal and prepare an interpolated signal as a function of the other color signal components after assigning them respective weights. Specifically, interpolation processing for the B and R signals can be given by the following equations.

$$B' = (2G+R) / 3$$
$$R' = (2G+B) / 3$$

where G, B, R are signals output from each horizontal pixel, and B’, R’ are interpolated signals. In these equations, the G signal component is given a weight twice that of the R and B signal components.

III. 2 Results

We show some results below:

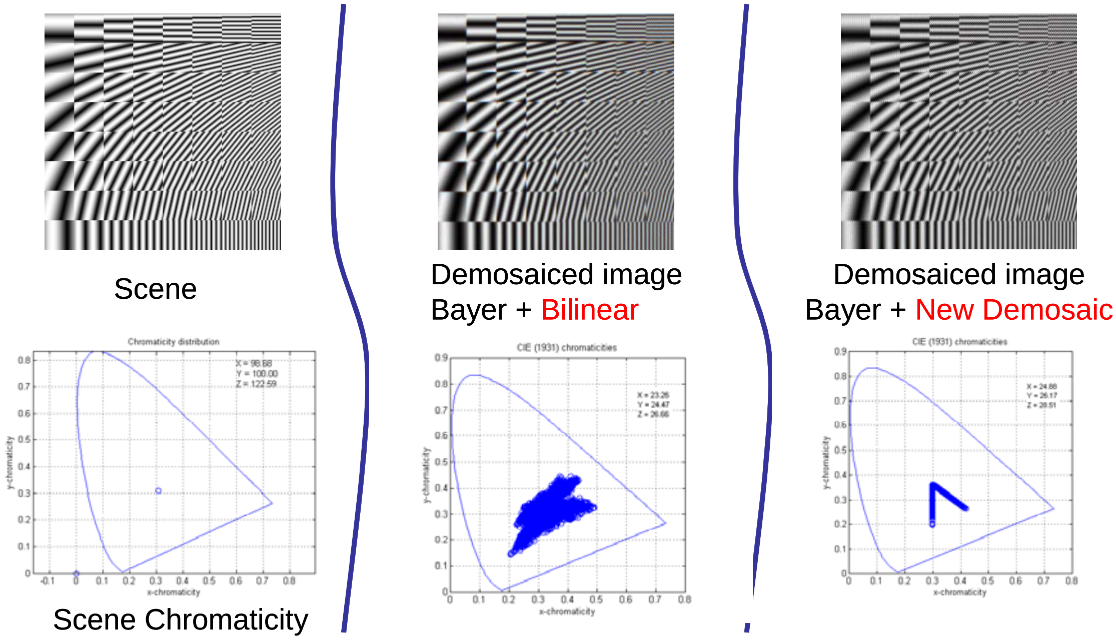

Figure 13. Examining the New Demosaicing Algorithm

Note that there is no optical low-pass filter in order to show the characteristic of the new demosaicing algorithm. Compared with the standard bilinear demosaicing algorithm, our method significantly reduced color aliasing. However, the bi-directional shape of the chromaticity plot is of interest. We thought that this demosaicing algorithm is ideal for monochrome signal, however we can observe that if there is only a non-color signal, color aliasing (specifically, false colors) will occur towards the Blue or Red direction from the center of the color chromaticity chart.

IV. Conclusions

We investigated picture quality improvement schemes, motivated by single-chip HDTV applications, that focused on minimizing color aliasing. We approached the problem from two different directions: 1) We sought to improve upon the Bayer CFA in order to increase the spatial sampling resolution of all color channels; and 2) We sought to establish new demosaicing algorithms that would reduce color aliasing effects using different interpolation techniques.

For the first approach, we presented a 4x2 CFA that was theoretically predicted to improve horizontal resolution for the Red and Blue channels. We showed using simulations that there was indeed reduced color aliasing in the horizontal dimension. We expected worse performance in the vertical dimension which was also confirmed in the simulations. We mitigated the vertical color aliasing by introducing optical low-pass filters in the vertical dimension. However, since this also results in loss in resolution, we investigated variations in the CFA such that both horizontal and vertical spatial resolution could be increased. We hypothesized a 3x3 CFA which we intend to further investigate theoretically and practically in future work.

For the second approach, we presented a new demosaicing algorithm for especially high spatial frequency image regions. We showed simulation results that demonstrated reduction in color aliasing for monochrome images over a standard bilinear demosaicing algorithm. We observed a bi-directional chromaticity plot, as opposed to an ideal dot, which could be due to the fact that we interpolate Blue using Green and Red, and interpolate Red using Green and Blue, that is, we do not use any weights for the target interpolated color itself. Mitigating this will be the subject of future work. Another future work with the demosaicing algorithm is color change. Using a Macbeth D65 color chart, we observed that most of the color turns monochrome. While color aliasing is minimized, there is also some de-saturation especially in Blue and Red. We attribute this again due to the fact that we do not assign any weights to the target interpolated color itself. We therefore intend to continue future work to improve the proposed demosaicing algorithm. We will try adding some color detection or frequency detection methods to make the demosaicing algorithm more adaptive to general scenes. For example, if the image, or a sub-block of the image, is predicted to be a chromatic and / or low frequency image, we do not apply this demosaicing algorithm and instead use a standard demosaicing algorithm.

We leveraged ISET extensively throughout this project. We also hope that in the course of using ISET for our project, we have also contributed towards the development of the tool, especially in customization. For example, ISET now has the capability to use user-specified CFAs in the imaging system pipeline. Whereas ISET previously has a 1D diffuser (optical low-pass filter), ISET now has a 2D O-LPF that enables selective blurring in the horizontal and vertical dimensions. Finally, ISET is now adaptable to using customized demosaicing algorithms in the image processor stage.

We also take this opportunity to acknowledge the invaluable assistance of Dr. Joyce Farrell and Prof. Brian Wandell, especially in modifying ISET as per our requirements.

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