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MTF Measurements of Wide Field of View Cameras

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Abstract

In this paper we present an algorithm for estimating camera system modulation transfer functions (MTF) from highly distorted images. This algorithm estimates multiple oversampled line spread functions using different order polynomials and binning. The ensemble of oversampled line spread functions (LSF) are used to estimate the final system MTF. Moreover, the LSF derived from the highest order polynomial without overfitting is used to estimate the system MTF. We show the performance of this algorithm on synthetically generated images and on image captures from a commercially available camera. We compare this algorithm to the ISO 12233 standard.

Introduction

The ISO 12233 standard [1] is the most common method for measuring the modulation transfer function (MTF) of cameras or image sensors. Unfortunately, this standard fails to produce accurate results under several important imaging conditions. The specific situation that we focus on in this paper is measuring the MTF of highly distorted images. This type of image is often captured by wide field of view (WFOV) cameras. Moreover, in WFOV cameras, barrel distortion caused by the lens makes straight edges in the object plane become curved in the image plane. The ISO 12233 standard relies on straight edges in the image plane to estimate MTF.

There are two commonly used techniques to estimate the MTF of highly distorted images. The first technique estimates the image distortion, then corrects it and finally uses the ISO 12233 standard to estimate the camera MTF[2]. The second technique uses a pre–distorted target such that the image focused onto image sensor is undistorted and therefore the ISO 12233 standard can be directly used to estimate the camera MTF. In this paper we take a different approach. We solve this problem by modifying the ISO 12233 standard. Instead of fitting the edge with a least squares line, we use a set of polynomials each with a different order. Then we select the best fitting polynomial to estimate the camera MTF.

The remainder of this paper is organized as follows. In the Theory Section we describe the algorithm used to estimate the camera MTF. Then in the Results Section we present input images and output MTF plots. In the Discussion Section we present limitations of this method and finally in the Conclusion Section we present a summary.

Theory

In this section we describe our free form (FF) MTF algorithm. This algorithm builds on the ISO 12233 standard by using polynomial edge fitting and a method to determine the best polynomial to the measured edge. The algorithm is organized into three main parts. The first part performs edge detection on each row using a technique similar to Canny edge detection [3], but less complex. The next step calculates a set of MTFs, where each MTF is based on a different order polynomial fit to the edge points calculated previously.

During the second step, edge points estimated in the first step are used to fit a polynomial to improve the edge position accuracy. Then each row is shifted, by an amount determined by the polynomial, to create a super–sampled edge spread function just like the ISO 12233 standard. Then the edges are binned and averaged based on their position. Moreover, we bin the data such that the super–sampled line spread function has 4 times the resolution of the original row data in the image. Then the super–sampled line spread function is differentiated, windowed by a Hamming filter and finally Fourier transformed and normalized.

The final step of the algorithm selects the ”best” MTF curve from the set calculated in the second part of the algorithm. This is done by looking at the residual errors of the polynomial fit for the super–sampled line spread function. As the edge fit polynomial order is increased the residual errors drop. Moreover, when the residual error is plotted as a function of the polynomial order, it falls quickly and then flattens out. We try to select the highest order polynomial without overfitting. We estimate when overfitting has occured by measuring the difference in the residual errors of successive polynomial fits. When this value is less than a threshold, we determine that overfitting has occurred.

Pseudo code for our algorithm is shown in Algorithm 1. The run time of this algorithm is very close to commercial ISO 12233 implementations, on standard edge images, and generally does not suffer from the convergence problems. The computational complexity of our algorithm is O(num columns * (num rows)^2), where num columns is the number of columns in the image and num row is the number of rows in the image.

Results

In this section we present results from the algorithm described in the previous Section. First we show how close the algorithm compares to the theoretically expected value and the ISO 12233 standard. Then we show MTF measurements from a commercially available DSLR camera and compare these to the ISO 12233 standard.

Figure 1 shows a synthetically generated circular edge and Figure 2 shows the results of our FF algorithm and how it compares to the ISO 12233 standard and to the theoretically expected value of $sinc(xf_x) = \frac{\sin(\pi x f_x)}{\pi x f_x}$. Note that f_x is spatial frequency and x is pixel sampling distance. Figure 3 shows an image collected from a Canon EOS 5D Mark III DSLR. The selection box in this image shows a tilted straight edge used to calculate the MTFs shown in Figure 4. Figure 5 shows another image collected from the same Canon DSLR. The selection box in this

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```
idata = Read image data;
for i ← 1 to num rows do
    diff(idata(i,:));
    filter idata(i,:) with Gaussian kernel;
    Set all values of idata(i,:) less a threshold to zero;
    edgeEst(i)= centroid of idata(i,:);
end
for j ← 1 to num rows −1 do
    p = coefficients of polyfit order i to edgeEst;
    error(i) = calc fit errors of p given edgeEst;
    edgeEst2 = polyval(p,[1:num rows]);
    binData(1:4,1:num columns) = 0;
    binCount(1:4) = 0;
    for j ← 2 to num rows do
        binData(edgeEst2(j) mod 4,:) += barrel shift
          idata(j,:) by edgeEst2(j);
        binCount(edgeEst2(j) mod 4)++;
    end
    for j ← 1 to 4 do
        binData(j,:) = binData(j,:)/binCount(j);
    end
    for j ← 1 to 4 do
        lsf(j:4:4*num columns) = binData(j,:);
    end
    MTF = fft(hamming filtered lsf);
    if i > 1 and abs(error(i) - error(i − 1)) < threshold
     then
        return MTF;
    else
        continue loop;
    end
end
```

Algorithm 1: FF Algorithm

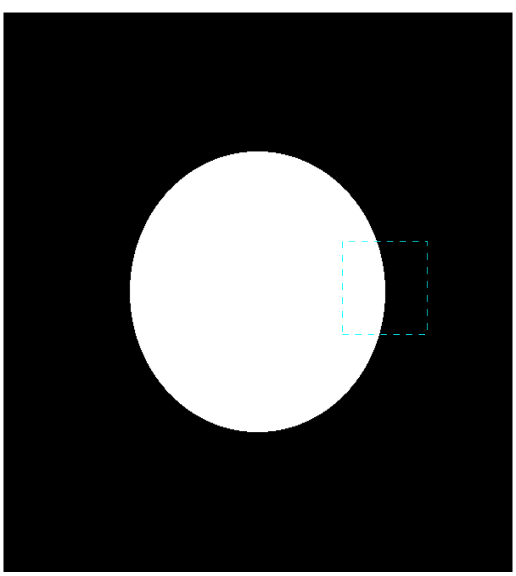

Figure 1. *Synthetically generated circular edge*

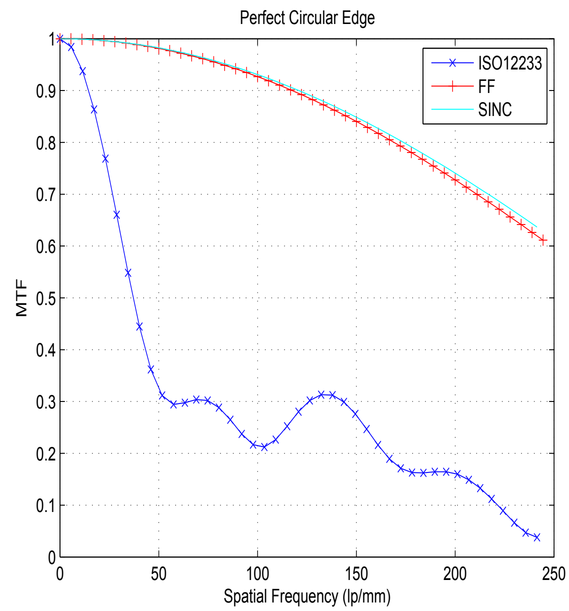

Figure 2. *MTF of synthetically generated circular edge*

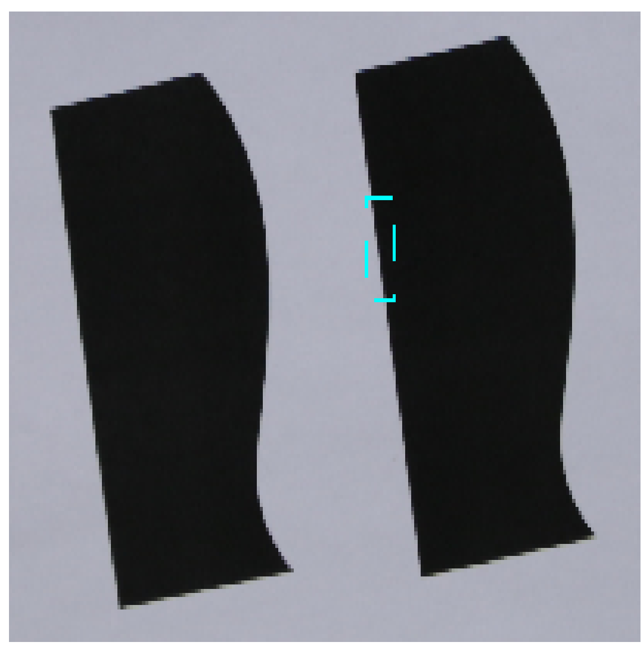

Figure 3. *straight Edge*

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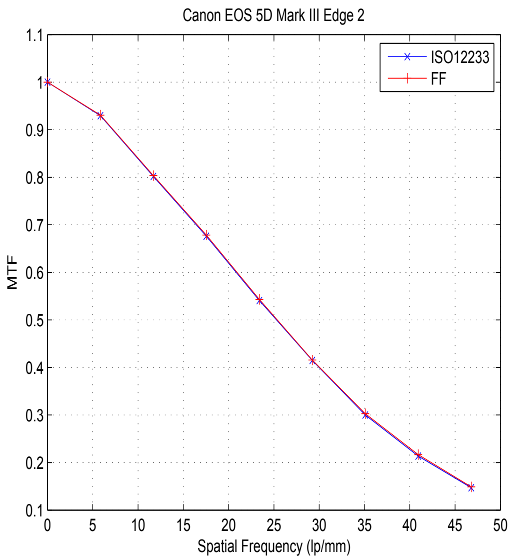

Figure 4. *MTF of straight edge*

image shows a convex edge that represents a distorted straight edge. The MTFs calculated from this edge are shown in Figure 6. Figure 7 shows another image collected from the same Canon DSLR. The selection box in this image shows a concave edge that represents a distorted straight edge. The MTFs calculated from this edge are shown in Figure 8. Figure 9 shows another image collected from the same Canon DSLR. The selection box in this image shows a polynomial edge that represents a distorted straight edge. The MTF of this edge calculated by the FF algorithm is shown in Figure 10. Note that the ISO 12233 standard did not produce a result for this edge.

For the image shown In Figure 1, the calculated MTF50 sensitivity to edge selection placement, i.e., if we move the selection box up or down by a few 10s of rows, is approximately 5% for both our algorithm FF and the ISO 12233 standard, but the ISO 12233 standard underestimates the MTF50 by approximately 6 times. Here we define the MTF50 as the spatial frequency where the MTF is equal to 0.5, and sensitivity is defined as the standard deviation divided by the mean of the statistic we are measuring. This gross underestimation with the ISO 12233 standard can be observed in Figure 2.

In Figures 3, 5, 7 and 9, i.e., the Canon DSLR captures of objects containing edges simulating complex edge distortion, the sensitivity to edge selection for FF is less than 5% while the variation for the ISO 12233 standard is more than 51%. In addition the ISO 12233 standard underestimates MTF50 by around 1.6 times. For many edges ISO 12233 did not produce a result.

Discussion

In the Results Section we show that our algorithm can be used estimate system MTF even for complexly distorted images. This allows the MTF of imaging systems to be characterized across the field of view, including WFOV cameras. The idea of using higher order polynomials to improve the ISO 12233 standard has been explored by commercially available tools, but they have never demonstrated higher than second order in their imple-

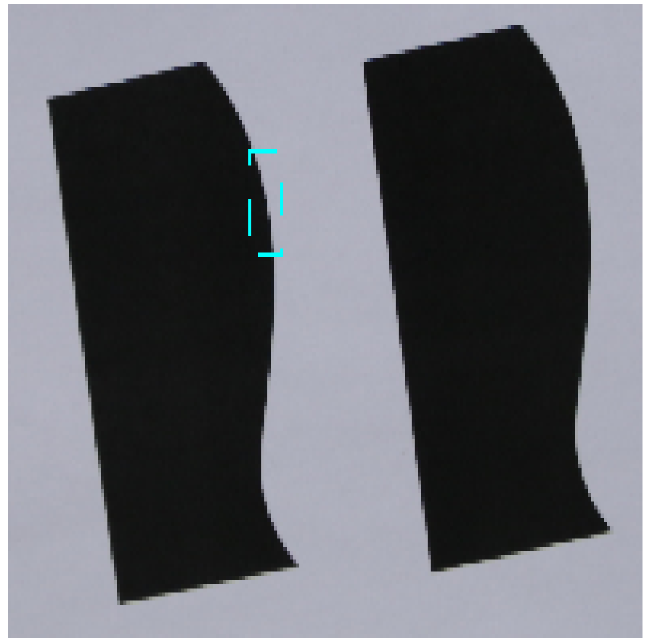

Figure 5. *Circular edge*

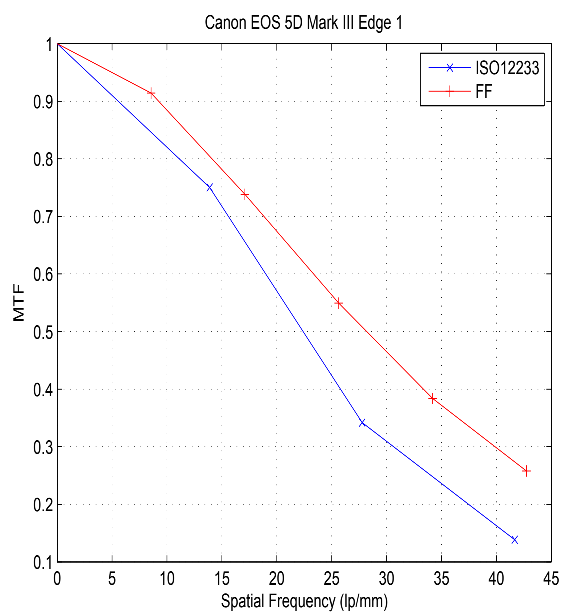

Figure 6. *MTF circular edge*

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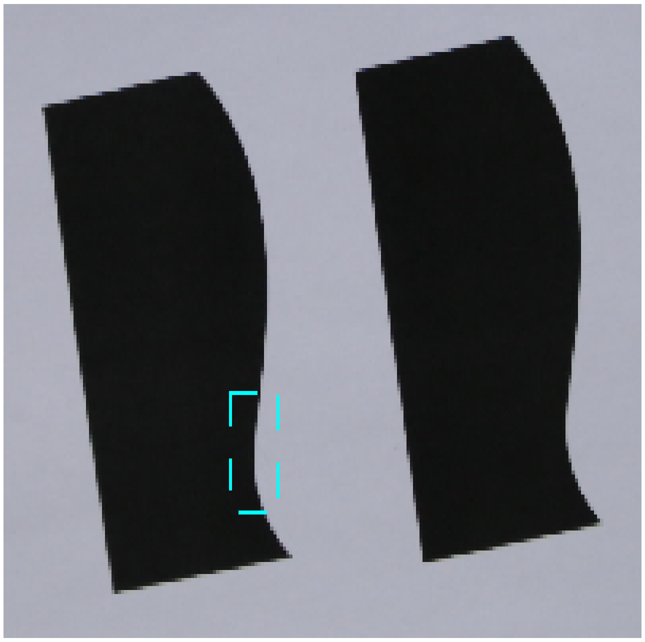

Figure 7. *Polynomial edge 1*

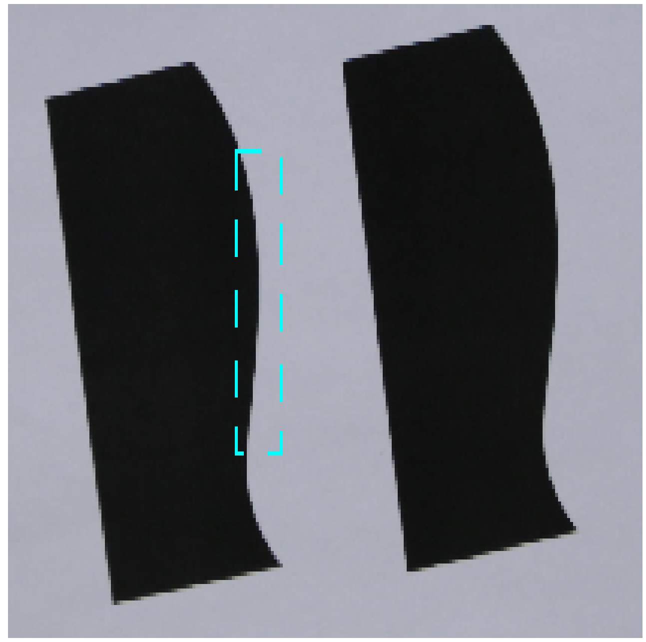

Figure 9. *Polynomial edge 2*

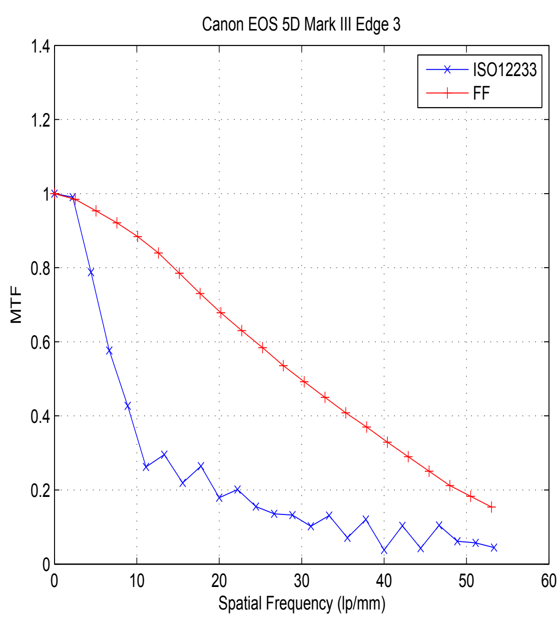

Figure 8. *MTF of polynomial edge 1*

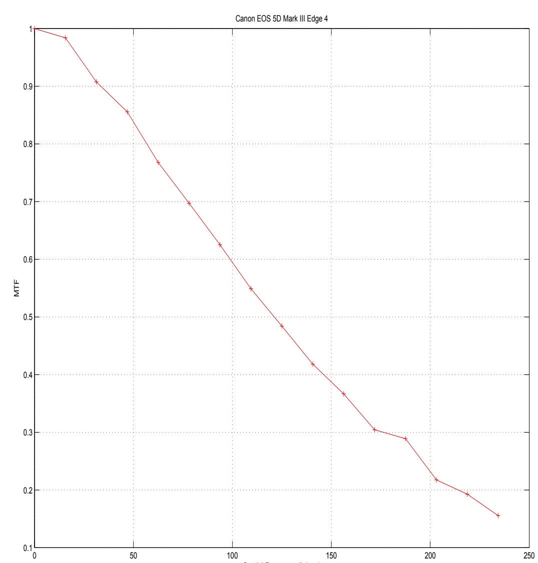

Figure 10. *MTF of polynomial edge 2*

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mentation.

Although this algorithm is more robust to low light, i.e., images with low signal to noise ratio (SNR), than the ISO 12233 standard, its performance is nevertheless degraded under these conditions. Our algorithms is more robust to noise than the ISO 12233 due to the initial ”Canny”–like edge estimation algorithm.

Conclusions

In this paper we have described a new algorithm for estimating the MTF of highly distorted images. We have shown that this algorithm can accurately estimate the MTF of complexly distorted images as would be common with WFOV cameras. Finally, we have also shown this algorithm achieves the same results as the ISO 12233 standard on straight edges.

Acknowledgments

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