Moire reduction using inflection point in frequency domain

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ABSTRACT

Digital still cameras generally use an optical low-pass filter (OLPF) to enhance the image quality by removing high spatial frequencies causing aliasing. While eliminating the OLPF can save manufacturing costs, images captured without using an OLPF include moiré in the high spatial frequency region of the image. Therefore, to reduce the presence of moiré in a captured image, this paper presents a moiré reduction method without the use of an OLPF. First, the spatial frequency response (SFR) of the camera is analyzed and moiré regions detected using patterns related to the SFR of the camera. Using these detected regions, the moiré components represented by the inflection point between the high frequency and DC components in the frequency domain are selected and then removed. Experimental results confirm that the proposed method can achieve moiré reduction while preserving detail information.

Keywords: moire reduction, optical low pass filter

1. INTRODUCTION

Charge coupled device (CCD) image sensors are widely used in imaging systems, where the image sensors are two-dimensionally arranged to convert the input image into electrical signals. The spectrum of the original image is repeated in the x and y directions when the image is captured by a camera. According to sampling theory, fine features are acquired when the spatial frequency of an image exists under the Nyquist frequency, causing aliasing with image distortion. This image distortion usually generates a moiré pattern. Thus, to prevent this distortion, the spatial frequency of an image is limited to below the Nyquist frequency. Generally, an optical low-pass filter (OLPF) is used to remove spatial frequency components above the Nyquist frequency, where the OLPF splits the incoming light into two beams: an ordinary and extraordinary beam [1-3]. As a result, the aliasing and moiré patterns are removed, thereby improving the image quality.

However, to reduce the manufacturing costs of digital cameras, a moiré reduction method without the use of an OLPF was recently introduced [4]. This method converts the interpolated RGB image signals into luminance and chrominance signals and then applies a low-pass filter. However, the use of a low-pass filter results in detail loss.

Accordingly, this paper presents a moiré reduction method that can preserve detail information without the use of an OLPF. First, the proposed method analyzes the SFR (spatial frequency response) of the camera and identifies lines corresponding to the SFR using the ISO 12233 resolution chart. The line patterns are then modeled in the spatial domain using the intensity difference in the luminance channel. The patterns are determined using the intensity difference between the current pixel and the neighborhood pixels in the horizontal and vertical directions, and then used to detect moiré regions. Next, each moiré region is analyzed in the frequency domain. In each moiré region, the maximum values per frequency are calculated to detect the moiré component in the frequency domain. The moiré component is then determined as the inflection point among the maximum values per frequency located in the frequency domain between the high frequency and DC components. As a result, the moiré pattern is reduced by removing its frequency component. Experimental results show that the proposed method can reduce moiré patterns and color smearing, while preserving detail information.
2. DETECTION OF MOIRE REGION

The resolution of a camera is analyzed by measuring the SFR, which represents the relationship between the spatial frequency of the input image and the response of the camera. The SFR is obtained by changing the MTF (modulation transfer function) according to the spatial frequency. The MTF is given by

\[
\text{MTF} = \frac{C_o}{C_i}
\]

(1)

where \(C_i\) and \(C_o\) represent the contrasts of the input and output spatial frequencies, respectively. Here, as shown in Fig. 1, the MTF of the digital camera is calculated using a pattern with a robust edge in the ISO 12233 resolution chart, while the SFR of the digital camera is determined as corresponding to 5% of the MTF and set to a spatial frequency of 0.7 [5, 6].

![Figure 1. SFR of camera using ISO 12233 resolution chart.](image)

Also, the spatial frequencies of the lines in the ISO 12233 resolution chart are calculated using the ratio of the picture height to the line width as follows.

\[
f_{sp} = \frac{P_h}{L_w}
\]

(2)

where \(L_w\) and \(P_h\) represent the line width and picture height, respectively. The SFR of the digital camera is compared with the spatial frequency of the lines in the ISO 12233 resolution chart and matched to line 7. This represents that the spatial frequency of line 7 corresponds to the SFR of the digital camera. To analyze the moiré feature, the ISO 12233 resolution chart is captured by the camera and all the lines are observed. As shown in Fig. 2, moiré exists for all the lines with a higher spatial frequency than the SFR, where these lines show a gap of two pixels or one pixel.
Therefore, the patterns of these lines are modeled in the spatial domain using the intensity difference in the luminance channel. The intensity differences in the Y image between the current pixel and three neighborhood pixels in the horizontal direction are calculated as follows.

\[
\begin{align*}
    d_1 &= |Y(x, y) - Y(x+1, y)| \\
    d_2 &= |Y(x, y) - Y(x+2, y)| \\
    d_3 &= |Y(x, y) - Y(x+3, y)|
\end{align*}
\] (3)

where \( Y(x, y) \) is the current pixel in the Y image and \( Y(x+1, y) \), \( Y(x+2, y) \), and \( Y(x+3, y) \) are the neighborhood pixels in the horizontal direction. The same process is applied in the vertical direction.

Next, the patterns for the horizontal direction are determined using two conditions of \( H_1 \) and \( H_2 \), representing a higher spatial frequency than the SFR and a gap of two pixels or one pixel, respectively, using the threshold \( T_1 \).

\[
H_1 = \begin{cases} 
    d_1 > T_1 \text{ and } \\
    d_2 > T_1 \text{ and } \\
    d_3 < T_1
\end{cases}, \quad H_2 = \begin{cases} 
    d_1 > T_1 \text{ and } \\
    d_2 < T_1
\end{cases}
\] (4)

\[
T_1 = Y(x, y) \times 0.05
\] (5)

The same process is applied in the vertical direction.

To verify these patterns, the patterns for line 9 are checked using a higher spatial frequency than the SFR. As shown in Fig. 3, the patterns are seen when using the intensity difference in the horizontal and vertical directions, respectively. Therefore, the proposed method detects moiré using patterns related to the SFR of the camera. Fig. 4 shows the moiré detection results using the ISO 12233 resolution chart. In luminance channel, moiré is detected in the lines with a higher special frequency than the SFR.
3. MOIRE REDUCTION IN FREQUENCY DOMAIN USING INFLECTION POINT

A Fourier transform is applied to analyze the moiré regions in the luminance channel. A Fourier image using a logarithmic transformation contains all the frequency components, while normalization using the DC value provides the dominant components in the frequency domain. As shown in Fig. 5(b), there are 5 dominant values: the DC value, two points corresponding to the frequency of the stripes in the original image, and two points corresponding to the frequency of the stripes with moiré. Therefore, to detect the frequency of the moiré component between the frequencies of the stripes in the original and the DC value, the maximum values per frequency in the Fourier image are first selected and denoted as $M_i$.

$$M_i = \max_{F(u,v), i|f(u,v)} \sqrt{R^2(u,v) + I^2(u,v)}$$  \hspace{1cm} (6)

where $u$ and $v$ represent the frequency variables, $f(u,v)$ represents the frequency components with the same distance $i$ from the dc component, and $R(u,v)$ and $I(u,v)$ are the real and imaginary parts of $F(u,v)$, respectively. In Fig. 5(b), the circles in the Fourier image represent equal frequencies. The graph in Fig. 5(c) indicates the maximum values per frequency in the Fourier image and shows the inflection point with large variations from the dominant values. Therefore, to detect the frequency of the inflection point, a second-order deviation is first calculated among the maximum values per frequency as follows.
The frequency of the inflection point $I$ is then detected by selecting the frequency of the maximum value when it simultaneously satisfies the conditions of threshold $T_2$ and sign changes. The threshold $T_2$ is set to 10, empirically.

$$I = \begin{cases} \text{true,} & \left| \frac{\partial^2 M_i}{\partial t^2} \right| > T_2, \frac{\partial M_i}{\partial t} < 0, \frac{\partial M_{i-1}}{\partial t} > 0, \text{and } \frac{\partial M_{i+1}}{\partial t} > 0 \\ \text{false,} & \text{otherwise.} \end{cases}$$

where $M_{i+1}$ and $M_{i-1}$ are the maximum values for the neighborhood frequencies of $M_i$ and subscript $i$ indicates the frequencies when the image is transformed to the frequency domain.

Next, the location of the inflection point $I(u, v)$ in the frequency domain is determined by selecting the magnitude and frequency of the inflection point $I$. The moiré is the reduced by removing the moiré component in the frequency domain. However, detail is lost when all the moiré components are removed, as they contain detail information from the original image. Therefore, to reduce the detail loss when removing the moiré component, the original location of the inflection point is replaced using the average value of the 8-neighborhood region in the frequency domain. The average value of the 8 neighborhood, $I_{avg}(u, v)$, is calculated as follows.

$$I_{avg}(u, v) = \frac{1}{9} \left[ I(u, v) + I(u, v+1) + I(u, v-1) + I(u+1, v) + I(u+1, v+1) ight. \\
+ I(u+1, v-1) + I(u-1, v+1) + I(u-1, v) + I(u-1, v-1) \left. \right]$$

Finally, the corrected image in the frequency domain is converted to the spatial domain using an inverse Fourier transform and combined with the chrominance components. Fig. 6 shows a moiré image and the results after moiré removal. The two points corresponding to the frequency of the stripes with moiré are removed and moiré is eliminated in the high spatial frequency region.

![Diagram showing moiré analysis](image_url)
4. EXPERIMENTAL RESULTS

An experimental evaluation of the proposed moiré reduction method was carried out for both the luminance and color channels using an NX-100 camera without an OLPF and the ISO 12233 resolution chart. The captured image of the ISO 12233 resolution chart and the results of the moiré reduction are shown in Fig. 7. Fig.7(a) shows the moiré images and the result image of moire reduction in vertical line 7 and 8. Fig.7(b) shows the moiré images and the result image of moire reduction in horizontal line 7 and 8, respectively. The moiré patterns are reduced for the lines with a high spatial frequency.
5. CONCLUSION
This paper proposed a moiré reduction method that diminishes the detail loss from an image in the case of no OLPF. First, the presence of moiré is detected using the pattern of the SFR. Next, the feature of the detected moire region is analyzed in the frequency domain. The moiré component representing the inflection point between the high frequency and DC components in the frequency domain is then selected. Finally, the moiré is reduced by substituting the moiré component with the average of the neighborhood values in the frequency domain. Experimental results confirmed that the proposed method can reduce moiré while preserving detail information.

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