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Under Display Camera Image Recovery through Diffraction Compensation

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Abstract

Under Display Camera(UDC) technology is being developed to eliminate camera holes and place cameras behind display panels according to full display trend in mobile phone. However, these camera systems cause attenuation and diffraction as light passes through the panel, which is inevitable to deteriorate the camera image. In particular, the deterioration of image quality due to diffraction and flares is serious, in this regard, this paper discusses techniques for restoring it. The diffraction compensation algorithm in this paper is aimed at real-time processing through HW implementation in the sensor for preview and video mode, and we've been able to use effective techniques to reduce computation by about 40 percent.

Introduction

UDC is a technology for removing selfie camera holes located on the display side in line with full display trends [1]. The application of this technique increases the degree of freedom of the design side and reduces the limitations on the size and position of the camera. As a result, it is possible to make eye contact during video call on the UI side. And the improvement of this technology can be summarized by the evolution of the transmittance of the display panel, the reduction of diffraction, and compensation processing.

In commercial UDC panels, pixels in a specially designed form are placed in the UDC region, taking into account the quality of the image of the camera. In order to increase the transmittance of light and reduce the visibility of holes when using the display, it is necessary to devise such as increasing the size of pixels and placing them evenly. Commercial phones have been released since the second half of 2020, but they are inferior to existing cameras in terms of image quality. There are several studies that use DL algorithms to improve the image quality of the capture mode, but real-time algorithms that can be used in preview and video modes are difficult to apply.

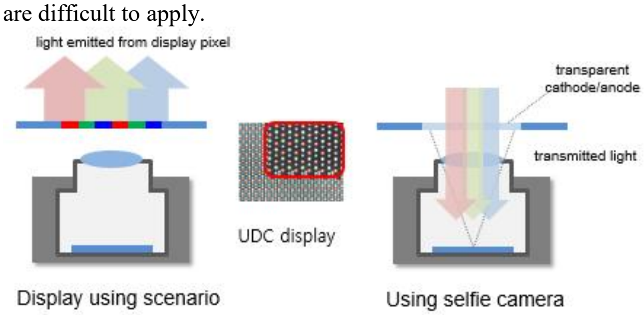

Figure 1. *UDC panel area according to usage*

As the light input to the camera passes through the display panel, attenuation and diffraction occur, resulting in several side effects. It can be divided into five major categories: 1) Ghost with a single subject divided into several parts, 2) Increased noise caused by low panel transmittance, 3) haze which appears by scattering optical light in a wide range, 4) yellowish phenomenon due to different transmittance by wavelength and 5) the flare around the strong light source is a representative deterioration.

This paper has been proposed with the aim of mitigating ghost removal and dehaze through a deconvolution algorithm. We try to removes the ghost on edge generated in the image through fast diffraction compensation algorithm for real-time image restoration. And discuss the factors that need to be corrected with respect to the location between the panel and the camera and the countermeasures and other attempts to restore image quality. Finally, it consists of reviewing the processing latency, performance, and processed result images of the algorithm implemented by HW.

Figure 2. *Image ghost on edge lines due to light diffraction*

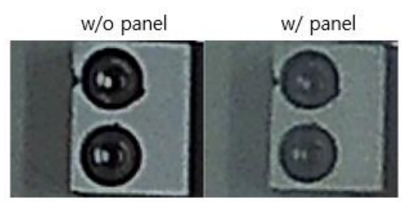

Figure 3. *Image haze due to light diffraction*

Light Diffraction due to Display Panel

In general, unlike normal OLED pixels, which are densely constructed, sparse pixels in UDC region are arranged evenly to allow the maximum inflow of light into the camera system. And to lower the visibility of the camera hole, larger pixels are placed.

Considering that the spacing between pixels is approximately tens to hundreds of um and the actual visible light wavelength is 400 to 700 nm, the impact received from the side lobe of the adjacent opening portion is limited.

The size of the diffraction is determined according to the ratio of opening size in display panel to slit width, and this value is more than about tens of times different in the UDC, so diffraction interference through adjacent aperture areas can be ignored.

The ghost is generated by the side lobe of the single slot model, and the size of the signal is determined according to the size and incidence angle of the input signal.

The PSF range is proportional to the focal length, inversely proportional to the pattern period, and the side lobe strength is inversely proportional to the opening size.

Blur Model

The basic blur model can be described as followings. The observed image is the same as adding noise to the convolution result of the latent and PSF kernel,

$$z_i = h * x_i + v_i \qquad ($$

where z_i is observed image, x_i is latent image, h is PSF incurred by display panel and v_i is sensor noise.

And the problem of finding the latent image is the same to an optimization problem that minimizes the cost function created by adding the regularization term to calculate the x value, which is the latent image.

$$\hat{x}_i = \mathrm{argmin}_{x_i} \|z_i - h * x_i\|^2 + \lambda \|d * x_i\|_p \qquad (2)$$

where λ is regularization parameter, p is the value between $0 \leq p < 1$, d means gradient operator.

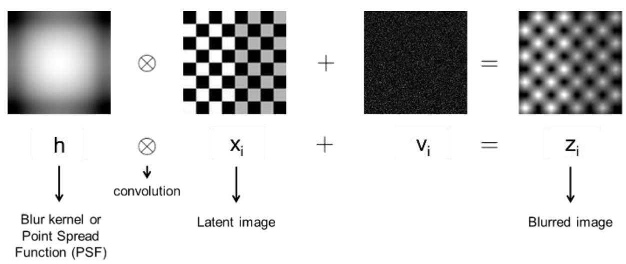

Figure 4. Blur model of Under Display Camera

Point Spread Function of blur model

One of the most serious causes of image quality degradation in UDC system is ghost on edge lines. Light incident into the spot light source appears in the form of diffraction spreading to the periphery, which can be expressed through the PSF.

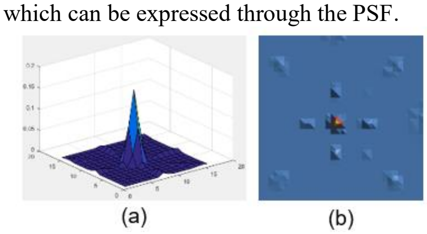

Figure 5. Point Spread Function under display camera. (a): 3D diagram for comparing the amount of side-lobe coefficient, (b): 2D drawing for position identification

The shape of this PSF is determined by the shape of the opening pierced between the pixels of the panel. By profiling this PSF by the panel, we can model the diffraction phenomenon and define the cost function and restore the image by finding the solution that minimizes it.

Diffraction Compensation

Several fast deblurring techniques using half quadratic methods and proximal operators have been studied [2-5]. Especially, in the paper of [5], a deblur solution is implemented in hardware manner for real time processing. The UDC compensation can be modeled as a problem compensates the same blur in the sensor due to the influence of the panel. Based on this, the UDC can be simplified as a spatial invariant deblur problem.

$$\hat{x}_i = \mathrm{argmin}_{x_{i,} d_{ref,i}} \|z_i - h * x_i\|^2 + \rho\lambda \left\|d * x_i - d_{ref,i}\right\|^2 + \lambda \left\|d_{ref,i}\right\|_p \qquad (3)$$

where ρ is regularization parameter, $d_{ref,i}$ is the auxiliary parameter where $d_i \; * \hat{x}_i$.

The solution of this equation can be solved by updating xi and d(ref,i,t+1) values in turn.

$$\hat{x}_{i,t+1} = a * \left(\bar{h} * z_i + \rho_t \lambda \cdot \bar{d} * \hat{d}_{ref,i,t}\right) \qquad (4)$$

$$a = \mathcal{F}^{-1}\left(\frac{1}{\|\mathcal{F}(h)\|^2 + \rho\lambda \|\mathcal{F}(d)\|^2}\right) \qquad (5)$$

$$d_{ref,i,t+1} = \mathrm{GST}_p(d * \hat{x}_{i,t+1}, \frac{1}{\rho_t}, \lambda) \qquad (6)$$

where $\mathrm{GST}_p\left(d, \frac{1}{\rho}, \lambda\right)$ is generalized soft-thesholding function. It doesn't output the input value below the threshold value based on the specific threshold value. It outputs L1 or L0 norm depending on the p value used only when the threshold value is exceeded.

$$\text{i) } L_1 \text{ norm:} \quad \mathrm{GST}_1\left(x, \frac{1}{\rho}, \lambda\right) = \begin{cases} 0, & \text{if } |x| < \frac{1}{\rho} \\ \mathrm{sgn}(x)\left(|x| - \frac{1}{\rho}\right), & \text{otherwise} \end{cases} \qquad (7)$$

$$\text{ii) } L_0 \text{ norm:} \quad \mathrm{GST}_0\left(x, \frac{1}{\rho}, \lambda\right) = \begin{cases} 0, & \text{if } |x| < \sqrt{\frac{2}{\rho}} \\ x, & \text{otherwise} \end{cases} \qquad (8)$$

As shown in Figure 7, this function has the following tendency in terms of the characteristics in which the operation is performed based on the threshold value

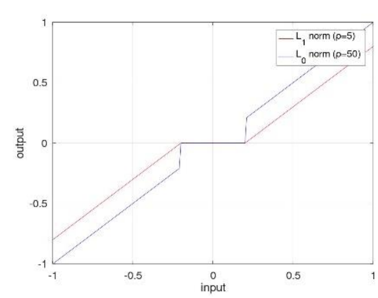

Figure 6. The input and output relationship of the soft-threshold function which L0-norm and L1-norm

Algorithm Optimization

Many operations are required to update x values, which is proportional to the PSF kernel size squared. Separable filter using singular value decomposition has been implemented to cope with PSF kernel processing which has increased compared to lens blur [3]. According to [3] and [5], deblurring can be processed with a dedicated deconvolution filter with given PSF.

$$a = USV^T \quad ($$

where U, V is unitary orthogonal matrices and S is diagonal matrix with non-negative elements.

$$\hat{a} = \sum_l s_l u_l v_l^T$$

where u_l and v_1 is l-th column vector of U and V, respectively s_l is l-th diagonal element.

In order to reduce the amount of two-dimensional filtering operation which is known to O(n^2) computational complexity, two-dimensional deconvolution can be approximated in the form of two cascading one-dimensional separable filters using singular value decomposition [3]. The 2D convolution operation amount of the PSF with the NxN size is N^2. The operation amount of the 1D separable filter with k singular values becomes (2*k*N).

By changing the cost function update method and simplifying the processing method, it succeeded in reducing the number of iterations and effectively reducing the amount of operation.

Resolution Improvement

In order to evaluate the diffraction correction performance, the resolution difference of the images before and after was quantitatively compared. When this is shown as a figure, it can be summarized as shown in the figure8. For reference, we added the resolution of the image when the panel was not installed. After the diffraction correction, the resolution of the image can be evaluated as a good performance.

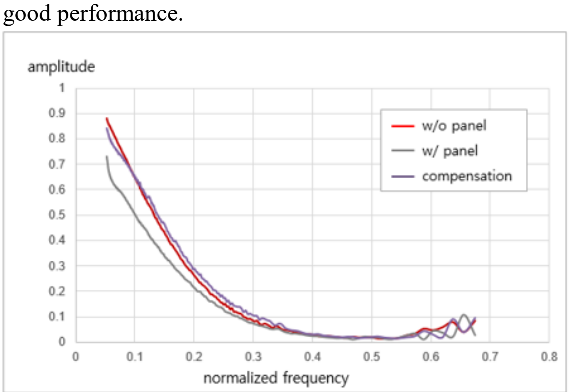

Figure 7. *Comparison of response curves by frequency before and after diffraction compensation*

For quantitative evaluation, values of MTF50/30/10 were respectively measured. As seen in the previous figure, it can be confirmed that each resolution value is corrected to the level of non-UDC image after diffraction compensation.

Cycle/Pixel	MTF50	MTF30	MTF10
w/o panel	0.13	0.19	0.28
w/ panel	0.10 (-24.6%)	0.16 (-11.9%)	0.27 (-3.7%)
compensation	0.14 (+3.6%)	0.19 (+4.0%)	0.30 (+6.5%)

Table 1. *Representative MTF values before and after diffraction compensation*

Considerations in implementation

When using the diffraction correction feature, the sensitivity degradation of the image sensor due to panel transmittance should be considered. This can be made up to some extent by the adoption of sensitive sensors, such as increasing the size of pixels or employing high-sensitivity whie pixels. And we need to consider image quality degradation by adjusting deblur strength due to worse noise level. Because sensitivity is about 20% compared to normal sensor, tuning for noise is required in ISP.

In addition, UDC determines diffraction and several image quality factors depending on the relationship between the display panel and the camera module. Completion of the camera system in the set may result in a physical configuration between the camera and the panel intended by the assembly tolerances, as well as physical shocks, etc. We consider these variations to define the calibration factor and discuss countermeasures accordingly.

The PSF changes depending on the tilt, shift, and interval change of the camera module for the panel. This variable is added to the modeling so that the PSF can be adjusted through modeling parameter adjustments.

Image Recovery Results

By implementing a diffraction compensation algorithm, it shows good performance and image quality results. A deconvolution filter was implemented based on the methods of [3] and [5], and it was approximated in the form of two one-dimensional cascading separable filters to reduce the amount of radiation, and then processed twice. The results are shown in the figures below.

Figure 8. *Image comparison before(left) and after(right) diffraction compensation*

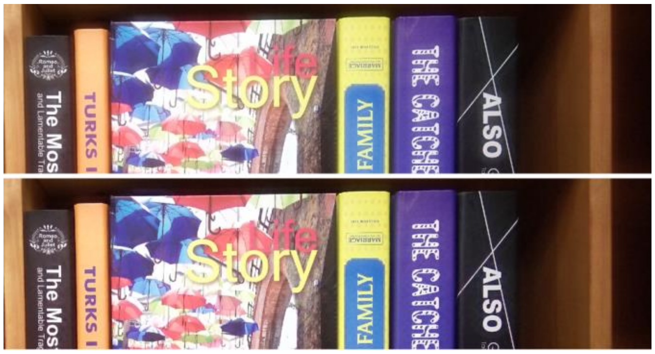

Figure 9. *Image comparison before(top) and after(bottom) diffraction compensation*

The processing images show that most of the ghosts are removed and the overall contrast of image is enhanced through dehazing performed.

Future Works

Restoration techniques are being developed to improve flare phenomena such as Figure below, one of the features of UDC images. If the shape of the window is close to the circular shape of the light entering between the panel pixels, these flares rarely occur. However, to increase the transmittance of the panel, windows on panel having a wider area is created, resulting in a flare determined by the shape of the opening in the area where the light is saturated.

Figure 10. *Image flare phenomenon due to display panel diffraction*

This diffuses light across an area proportional to the intensity of light, which will be improved by post-processing in the AP when considering a lot of resource required such as memory to cover the huge image region.

And consideration of change in blur kernel is needed according to lens field caused by lens aberration. And change of blur kernel size should be covered according to focal distance in the future.

Conclusion

We have introduced a diffraction compensation algorithm for image quality restoration of UDC, which is in the spotlight. Considering the mass production of UDC system, we reviewed main calibration factors and examined the possibility of factors that need consideration for image quality restoration. We reviewed how to implement the practical algorithm for HW IP, image performance, and result images. With the proposed diffraction compensation algorithm, we can cover new technologies required to popularize UDC.

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Author Biography

Jeongguk Lee was born in Gwangju, Korea, on 1976. He received the M.S. degree in electronic and electrical engineering from Pohang University of Science and Technology (POSTECH), Korea, in 2003. After graduating from graduate school, he learned about image sensor work at Hynix. He is currently developing imaging signal processing algorithms such as sensor HDR and deblur in Sensor development team, System LSI, Samsung Electronic