A Single-Camera High Dynamic Range Technique by Using Contrast Enhancement and Exposure Control

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Abstract—This paper presents a single-camera HDR imaging algorithm, which is able to solve all the extreme conditions by controlling the exposure time to get a well-exposed image and then enhancing it. The proposed system is divided into two parts, i.e. single-image HDR imaging technique and an exposure control method. The single-image HDR imaging technique integrates two methods, i.e. Dynamic Local Contrast Enhancement (DLCE) and fuzzy enhancement. The integrated result can handle both glaring region and dark region to exhibit good visibility for extreme conditions. In exposure control method, we utilize local average, camera response function and main object detection to achieve a well-exposed image. Finally, we implement our system on TI OMAP4430 embedded platform. The optimized program is able to achieve about 13 frames per second with VGA resolution.

I. INTRODUCTION

In general, there are two different methods to generate a HDR image/video. The first one is dual/multi-camera approach, and the second one is single-camera approach. The former one means it uses two or more low dynamic range (LDR) images, which are usually stored in 8-bit format, with different exposure values to generate one high dynamic range (HDR) image [1], then it utilizes tone mapping techniques [2] to convert the HDR image into LDR image, and then displays the LDR image on the conventional 8-bit display devices. The latter one means it only needs one image to generate a HDR image.

In existing technical literatures, there are many papers which are aimed at the single-camera HDR imaging. Among these techniques, the contrast limit adaptive histogram equalization (CLAHE) [3] has the best result of all. However, those methods will not work in many extreme conditions such as scenes with both high luminance part and low luminance part since they do not obtain an appropriate exposure image for enhancement. When there is an excessive front lit in the scene, all of the approaches are not capable of handling the over-exposed part and revealing the details of the bright part. Since that, this paper is going to present a single-camera HDR imaging algorithm which is able to solve all the extreme conditions by controlling the exposure time to get a well-exposed image and then enhancing it.

II. SINGLE-IMAGE-BASED HDR IMAGING TECHNIQUES

A. Dynamic Local Contrast Enhancement (DLCE) [4]

The DLCE method [4] is designed for improving the disadvantages of the CLAHE [3] method. The limited-height of CLAHE is fixed so that the contrast-enhancing intensity is not suitable enough for each case. In regarding to this, control the limited-height adaptively is necessary for each unique scene.

Firstly, the system divides the \( M \times N \) image into several blocks which is illustrated in Fig. 1. Secondly, calculate the histogram of each block which is illustrated in Fig. 2. In the third step, they use the histogram calculated in the previous step to find the limited-height and reallocate the clipped-histogram. Firstly, the average value of histogram \( H_{avg} \) is needed to be calculated, as shown in Eq. (1),

\[
H_{avg} = \frac{\sum_{i=0}^{255} S(i)}{256},
\]

where \( S(i) \) is the function of histogram. Besides, it introduces a dynamic weight \( \beta \) to control the limited-height clip. The formula is as below:

\[
\beta = \frac{\left(\frac{v_{max} + \alpha}{\sum_{m=0}^{m=n} D(x,y)}\right)}{255},
\]

\[
D(x, y) = |f(x, y) - A(x, y)|,
\]

where \( f(x, y) \) is the pixel value at the position \((x, y)\), and \( A(x, y) \) is the average value of the \( W \times W \) square which the central point is at \((x, y)\), the parameter \( \alpha \) is a global enhancement intensity parameter, and set the \( \alpha = 2.56 \) can achieve a decent result in most experiments.

Fig. 1. Illustration of dividing the image into several blocks.

Fig. 2. Illustration of calculating histograms of each block.

Those intensity of histogram exceeding the clip is clipped. The amount of exceeded part excess can be described as
equation (5), and is reallocated into each intensity $t$ of histogram to avoid resulting in an unnatural image, illustrated in Fig. 3.

$$excess_t = \begin{cases} H_t - clip, & \text{if } H_t > clip \\ 0, & \text{otherwise} \end{cases}, \quad t \in [0,255]. \quad (5)$$

Next, they calculate the mapping function of each block through the clipped-histograms obtained in the previous step. The formula of the mapping function is shown as below:

$$\text{Re}(x) = (H_{\text{max}}^\prime - H_{\text{min}}^\prime) \times CDF(x) + H_{\text{min}}^\prime \ldots (6)$$

$$H_{\text{max}}^\prime = H_{\text{max}} - \beta \times (H_{\text{max}} - H_{\text{min}}) \quad (7)$$

$$H_{\text{min}}^\prime = H_{\text{min}} + \beta \times (H_{\text{max}} - H_{\text{min}}) \quad (8)$$

$$CDF(x) = \sum_{i=0}^{\text{hist}} S'(i), \quad (10)$$

where $S'(i)$ is the function of clipped-histogram.

**Fig. 3. Illustration of reallocating the histogram.**

### B. Fuzzy Enhancement [5]

The proposed fuzzy enhancement method can be divided into three main steps: fuzzification, fuzzy enhancement, and de-fuzzification.

In the fuzzification part, they firstly define membership function $\mu_{xy}$ expressed as:

$$\mu_{xy} = \begin{cases} (f_{xy} - f_{\text{min}})/(\tilde{f} + \sigma - f_{\text{min}}), & f_{xy} \leq \tilde{f} + \sigma \\ (f_{\text{max}} - f_{xy})/(f_{\text{max}} - \tilde{f} - \sigma), & f_{xy} > \tilde{f} + \sigma \end{cases}, \quad (11)$$

where $f_{\text{min}}, f_{\text{max}}, \tilde{f}$ and $\sigma$ denotes the minimal gray, the maximal gray, the average gray and the standard deviation of the original image, respectively. If $f_{xy} = \tilde{f} + \sigma$, $\mu_{xy} = 1$. If $f_{xy} = f_{\text{min}}$ or $f_{xy} = f_{\text{max}}$, $\mu_{xy} = 0$. Otherwise, $\mu_{xy} \in (0,1)$. When $f_{xy} \leq \tilde{f} + \sigma$, $\mu_{xy}$ will increase along with the increasing of $f_{xy}$. When $f_{xy} > \tilde{f} + \sigma$, $\mu_{xy}$ will also increase along with the decreasing of $f_{xy}$. Then, if they enhance $\mu_{xy}$, the high brightness will be decreased and the low brightness will be increased. So, the new membership function of fuzzy set is expressed as

$$\mu'_{xy} = \sqrt{\mu_{xy}}, \quad (12)$$

Because of $\mu_{xy} \in [0,1]$, then $\mu'_{xy} \in [0,1]$, and $\mu'_{xy} \geq \mu_{xy}$. But the contrast of image will be degraded because the high brightness is decreasing and the low brightness is increasing. So, $\mu_{xy}$ is transformed only once in order to control the degrading of contrast. The $\mu'_{xy}$’s derivative is shown in Fig. 4.

In the defuzzification part, the enhanced image can be obtained by the inverse transformation of Eq. (11), which is also expressed as:

$$f_{xy}' = \begin{cases} \mu'_{xy}(\tilde{f} + \sigma - f_{\text{min}}) + f_{\text{min}}, & f_{xy} \leq \tilde{f} + \sigma \\ f_{\text{max}} - \mu'_{xy}(f_{\text{max}} - \tilde{f} - \sigma), & f_{xy} > \tilde{f} + \sigma \end{cases} \quad (13)$$

### III. PROPOSED METHOD

![System flow chart.](image)

#### A. Integration of DLCE and Fuzzy Enhancement

Fig. 5 is the whole flow of proposed system. In the harsh environment detection process, it computes some parameters to check the image if it is a harsh environment image and check it if it is over-exposed. If the image is not over exposed and in a harsh environment, the system will do the integration method to this image.

This proposed algorithm is based on the methods dynamic local contrast enhancement (DLCE) and fuzzy enhancement,
which are just introduced in Section II. Those two methods have its pros and cons: DLCE is good at dealing with the dark region, but the glaring region is enhanced meanwhile, that is not the result we want to obtain. Fuzzy enhancement is good at restraining the glaring region, but the contrast of whole image is restrained.

Consequently, in this paper we present a method which is able to achieve an appropriate result having the advantages and getting rid of the drawbacks of the both two methods.

Firstly, we define a cost function $E(t;x,y)$. As the name implies, the value of $E(t;x,y)$ is the cost which we want to get down. The cost function $E(t;x,y)$ is defined as:

$$ E(t;x,y) = \alpha [t - F(x,y)]^2 + \beta [t - D(x,y)]^2, \quad (14) $$

where $F(x,y)$ is the enhanced image by fuzzy enhancement, $D(x,y)$ is the enhanced image by DLCE, $\alpha$ and $\beta$ are the weighting parameters and $t$ is a variable, which determines the value of cost function $E(t;x,y)$.

And we define $t$ as below:

$$ T(x,y) = \arg\min E(t;x,y), \quad (15) $$

If we can find a specific $t$ which minimizes the cost function, then that is the pixel value we want. The final value $t$ makes the two quadratics $\alpha [t - F(x,y)]^2$ and $\beta [t - D(x,y)]^2$ have the smallest sum, which means the value $t$ is at the middle point of two values, $F(x,y)$ and $D(x,y)$.

Besides, $\alpha$ and $\beta$ are also important factors. They control the degree of how the final result like the two enhanced images. If $\alpha$ is larger than $\beta$, the final result is more like the fuzzy-enhanced image than the DLCE image. If $\beta$ is larger than $\alpha$, the final result is more like the DLCE image than the fuzzy-enhanced image. Here we let the weighting parameter $\alpha = 1 - \beta$, and the weighting parameter $\beta$ is defined as:

$$ \beta(f_{xy}) = \frac{\log_{2}(256-f_{xy})}{\log_{2}(256)}, \quad (16) $$

where $f_{xy}$ is the pixel value at the position $(x,y)$ of the original image. It is observed that when $f_{xy}$ is approaching to the glaring region, the value of $\beta$ drastically decreases. Glaring part of the original image is enhanced more by the fuzzy enhancement, the dark region is enhanced more by the DLCE.

B. Exposure Control Method Based on Camera Response Function

In the proposed system, input image will be scanned if it is over-exposed. If it is, the exposure control process will adjust the exposure value of the camera by referring to some information. Next, we will introduce them in the following.

Firstly, we introduce the parameter, white_count, which is defined as below:

$$ \text{white\_count} = \text{white\_count} + 1, \text{if } A(x,y) > 0.9L. \quad (17) $$

The white_count is the major factor to determine whether the image is over-exposed or not. If it is, the exposure control process will adjust the exposure time of the camera.

When the aperture size is fixed, we define the irradiance $E$ and exposure time $t$, and define $Z$ as the pixel value in the condition, exposure degree is $X$, and $g$ is the non-linear camera response function. Their relationship [6] can be expressed as:

$$ g(Z_{ij}) = \ln(E_i) + \ln(t_j), \quad (18) $$

As the camera response function is derived, we can utilize the Eq. (18) to compute the irradiation $E$.

$$ \ln E_i = g(Z_{ij}) - \ln t_j, \quad (19) $$

According to Eq. (19), if we assume that the position of pixel and the irradiance are fixed, the equations of the current frame and next frame are:

$$ \ln E = g(Z_i) - \ln t_j, \quad (20) $$

$$ \ln E = g(Z_{j+1}) - \ln t_{j+1}, \quad (21) $$

If the target luminance $Z_{j+1}$ is $0.9L$, the exposure time of the next frame can expressed as:

$$ t_{j+1} = e^{g(Z_{j+1})-g(Z_j)} \times t_j, \quad (22) $$

When the white_count $> 0.01N$ ($N$ is the total number of pixel), we define $Z_j$ as the average value of all the $A(x,y)$ that are higher than $0.9L$, and we call the set of the pixels white region. When the white_count = 0, we define $Z_j$ as the highest value of all$A(x,y)$.

$$ Z_j = \frac{\sum_{i} I_{\text{white\_region},A(i,j)}}{\text{white\_count} \times \text{max}(i,j)A(i,j)}, \quad \text{if white\_count} > 0.01N \quad (23) $$

When the target luminance $Z_{j+1}$ is $0.9L$, we can achieve the best performance and quality of the result image in our experiments, as shown in Table I.

<table>
<thead>
<tr>
<th>Target luminance $Z_{j+1}$</th>
<th>Average Convergent number of frames</th>
<th>Average luminance of the whole image (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75L</td>
<td>6.4</td>
<td>86</td>
</tr>
<tr>
<td>0.8L</td>
<td>6.2</td>
<td>92</td>
</tr>
<tr>
<td>0.85L</td>
<td>5.8</td>
<td>102</td>
</tr>
<tr>
<td>0.9L</td>
<td>4.3</td>
<td>120</td>
</tr>
<tr>
<td>0.95L</td>
<td>4.2</td>
<td>145</td>
</tr>
</tbody>
</table>

IV. EXPERIMENTAL RESULTS
The proposed system is implemented on Pandaboard (TI OMAP4430) as shown in Fig. 6, and its result is shown in Fig. 8. We optimize the integration of DLCE and fuzzy enhancement by changing the equation (15) into equation (24), and we use Taylor Expansion to simplify the square root operation in fuzzy enhancement. Then, we build a Look Up Table (LUT) of exponential value to reduce the computation cost of equation (22). Finally, system achieves 13fps at VGA solution after optimization, which reduces 38% of original computation time.

In the following parts, we demonstrate the results of single-image HDR imaging techniques, including fuzzy enhancement, DLCE, and the proposed method. Further, we compared the proposed exposure control system to the webcam’s auto-exposure system.

In Fig. 7, we can notice that when there is excessive front lit, the proposed system can still reveal the details of glaring region and dark region. However, in the meantime the image from webcam’s auto-exposure system cannot reveal the details of the glaring region.

\[ t = \frac{\alpha F(x,y)+\beta D(x,y)}{\alpha+\beta} \]  

(24)

V. CONCLUSIONS

This paper presents a method which merges the two images obtained from fuzzy enhancement and DLCE into an image having the advantages from both of the two methods. Nevertheless, we found that the limit of single-image based HDR imaging techniques is that they all need to have well-exposed input for enhancement. The well-exposed input represents the input has information in both glaring regions and dark regions. Thus, we came out an idea that we just have to control the exposure time of camera, and then we can obtain a well-exposed input for the proposed method for enhancement. From the experimental results, we can observe that the proposed system is really good at dealing with the glaring regions and also the dark regions.

REFERENCES