An Approach to Improve Cell-Phone Cameras' Dynamic Range Using A Non-linear Lens Correction

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ABSTRACT

Most cell-phone cameras today use CMOS sensors with higher and higher pixel counts, which in turn, results in smaller pixel sizes. To achieve good performance in current technologies, pixel structures are fairy complicated. Increasing complexity in pixel structure, coupled with optical constraints specific to cell-phone cameras, results in non-uniform light response over the pixel array. A cell-phone camera sensor module typically has a light-falloff of -40% from center relative to an edge. This high fall-off usually has non-radial spatial distribution making lens fall-off corrections complicated. The standard method of reducing light fall-off is linear (i.e. multiplicative gain), resulting in close to a ~2x peripheral gain and a corrected image with lower dynamic range.

To address this issue, a novel idea is explored where the fall-off is used to increase the dynamic range of the captured image. As a typical lens fall-off needs a gain of up to 2x centre vs edge, the fall-off can be thought of as a 2D neutral density filter which allows up to 2x more light to be sensed towards the periphery of the sensor.

The proposed solution uses a 2D scaled down gain map to correct the fall-off. For each pixel, using the gain map, an inflection point is calculated which is used to estimate the associated pixel transfer characteristic which is linear up to the inflection point and then becomes logarithmic.

Keywords: cell-phone camera, lens fall-off, lens correction, high-dynamic range;

1. INTRODUCTION

As cell-phone cameras today use CMOS sensors with smaller and smaller pixels (5Mpix CMOS module with 1.75um pixel size was used in this paper as the 'real case') and as module manufacturers decrease the height of the module, significant lens fall-off (>40%) results. In addition, the fall-off is usually not uniform, generating hue-shading which is also not radial. The direct implication is that the SNR of the captured image is not isotropic and more, if linear lens correction[1,2] is used, the dynamic range of a captured image would follow the lens fall-off profile when clipping occurs. If the fall-off is not significant (<5%), this is unnoticeable. However, when it is significant, and when the scene exhibits high dynamic range, some details are lost when linear lens correction (multiplicative gain of up to 2x and more) is used.

In this case, one may use this disadvantage of the cell-phone camera module to extract the extra information that can be captured because of the lens fall-off in a high-dynamic range scene. This idea is explored in the present paper and a method is proposed to recover the details otherwise lost in highlights. This is achieved by applying a transfer characteristic for a lens correction function that is part linear, part logarithmic. The linear portion is intended for accuracy of color reproduction. It extends from black level to some threshold above the equivalent 18% gray ideal exposure point. The remaining range, from this threshold up to the clipping point, is compressed in order to preserve some of the details in the highlights. As the recovery of details in highlights is perceptual, choosing the threshold point is purely subjective and makes use of some implied assumptions about imaging systems as well as picture composing habits.

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This paper is structured as follows: Section 2 provides a brief description of lens correction problem when fall-off is significant, and lists some underling assumptions that are related to both imaging system and user practice. The algorithm is then developed to use this significant fall-off to recover some details otherwise lost in the capture of high dynamic range scenes. Section 3 details some implementation options high lighting some inherent problems that arise when nonlinear corrections are used in conjunction with linear color processing and Section 4 presents the results. Section 5, summarizes the findings and outlines future directions.

2. PROBLEM DEFINITION

The expected behavior of an imaging system is to capture (with a degree of error) a map of the radiance of a given scene.

From this point of view, the dynamic range of the captured scene should reflect the captured scene radiance. More, this correspondence is assumed to be isotropic, which in most cases it is. However, for cell-phone cameras, miniaturization has multiple side-effects, one of them being the lens fall-off magnitude which can be 50% or more, centre vs. corners.

The figure below depicts the radiance map of a scene compared to the map of the captured image.

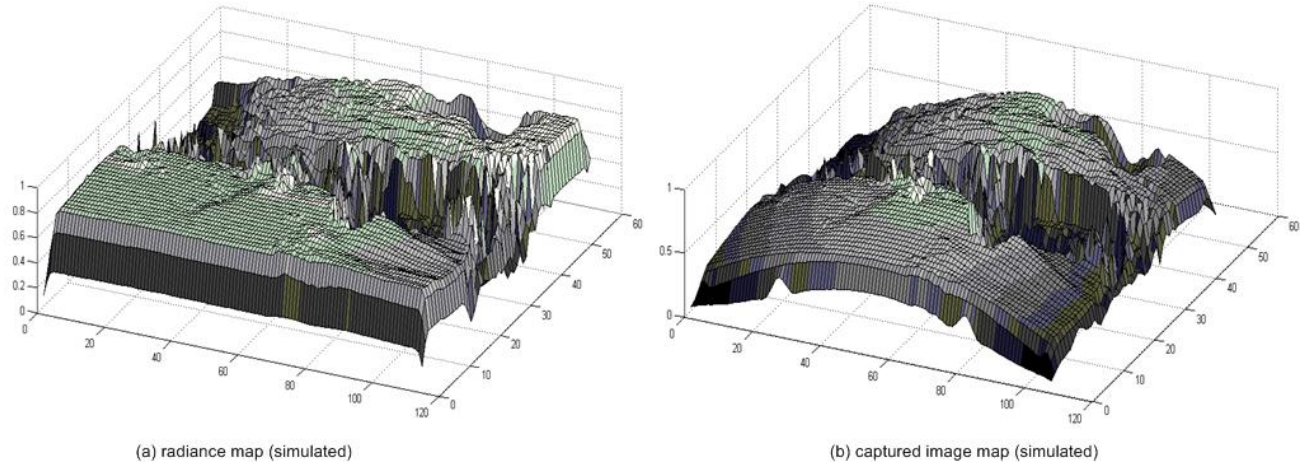


Figure 1 Radiance map of a captured scene (a) and the map of the captured image (b) – simulated data

After capture, a scene with a radiance map such as shown in Figure 1(a), would have a curved image map similar to Figure 1(b) due to lens fall off. For a small fall off (5% range), this is acceptable. However, a typical lens fall-off profile looks like Figure2 (a), where attenuation in the corners vs centre is >40%. For this case, if a linear lens correction method were used, the required correction gain map is shown in Figure2(b), where, normalizing to centre, the corners have a gain ~2x or more. Further more, when this correction is used, captured data is limited (linear correction followed by clipping) resulting in a dynamic range map that is shaped similar to Figure2(b) again. Also, SNR is degraded in a manner suggested by lens correction gain map.

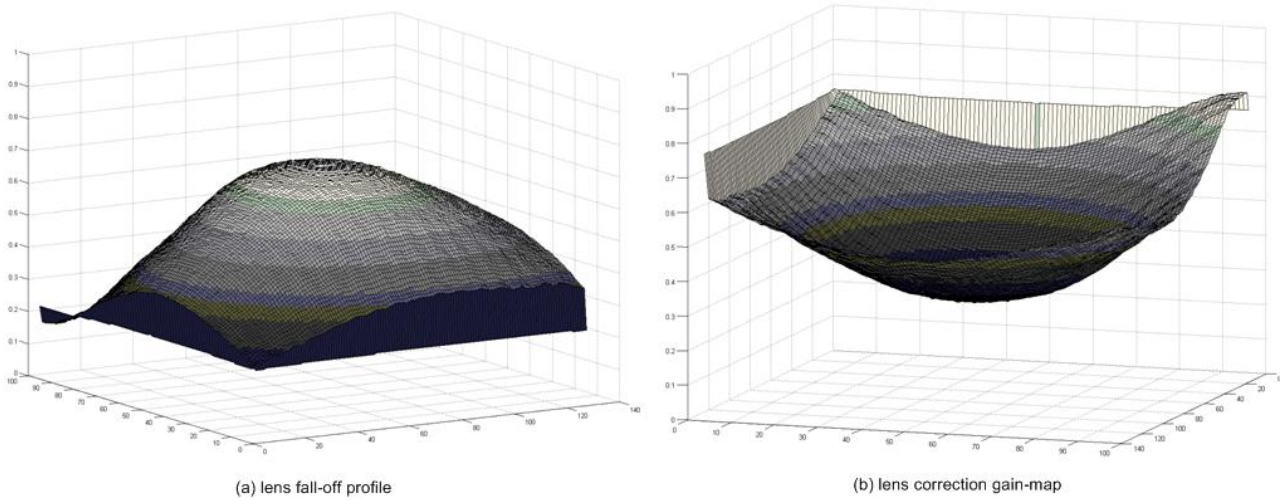


Figure 2 Lens fall-off (a) and linear lens correction map – real data

When the whole imaging chain is considered, the captured image often ends up like the following Figure:

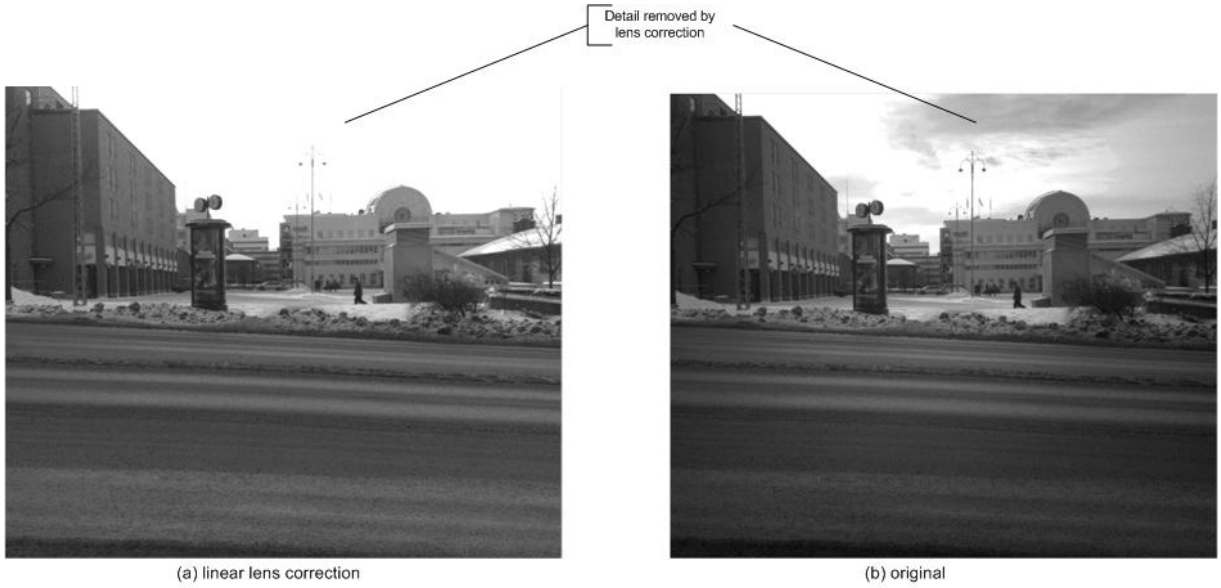


Figure 3 Intensity distribution: (a) linear lens corrected image (b) original – real data

This situation arises when high-dynamic range scenes are captured with lenses that have significant fall-off. Details in the original that are lost would not be there in the first place if lens fall-off would have been insignificant (since the dynamic range map of the camera is almost flat in that case).

2.1 System level and casual photographer underlying assumptions

Regardless of the type of auto-exposure implemented, as the goal is to get as much information as possible form the scene, significant lens fall-off will allow sensor to acquire more information from scene (which in some cases makes a difference). The difference is based on several observations:

1. a user will capture a scene having the light source off to the side rather than in centre;
2. usually the centre has a med to low light response compared to the corners, as in most cases the centre is a reflective object with some details;

Those observations would lead to the conclusion that in most cases, the user required sensitivity response of the camera can be lower in the centre than in the corners. Of course, these are habitual observations and in a high-performance system that is required to be accurate, a linear and isotropic relation between scene radiance and captured image dynamic range and intensity is at least desired.

In the case of a casual photographer, the captured scene will sometimes have the radiance distribution anisotropic, further more, it's likely to have increasing radiance towards the edges of the framed scene, in which case, a significant fall-off could be useful because it would allow capture of a higher radiance towards edges vs. centre. In this case, a linear lens correction would remove all the extra detail by clipping the intensity values to max. (see the intensity map in Figure4):

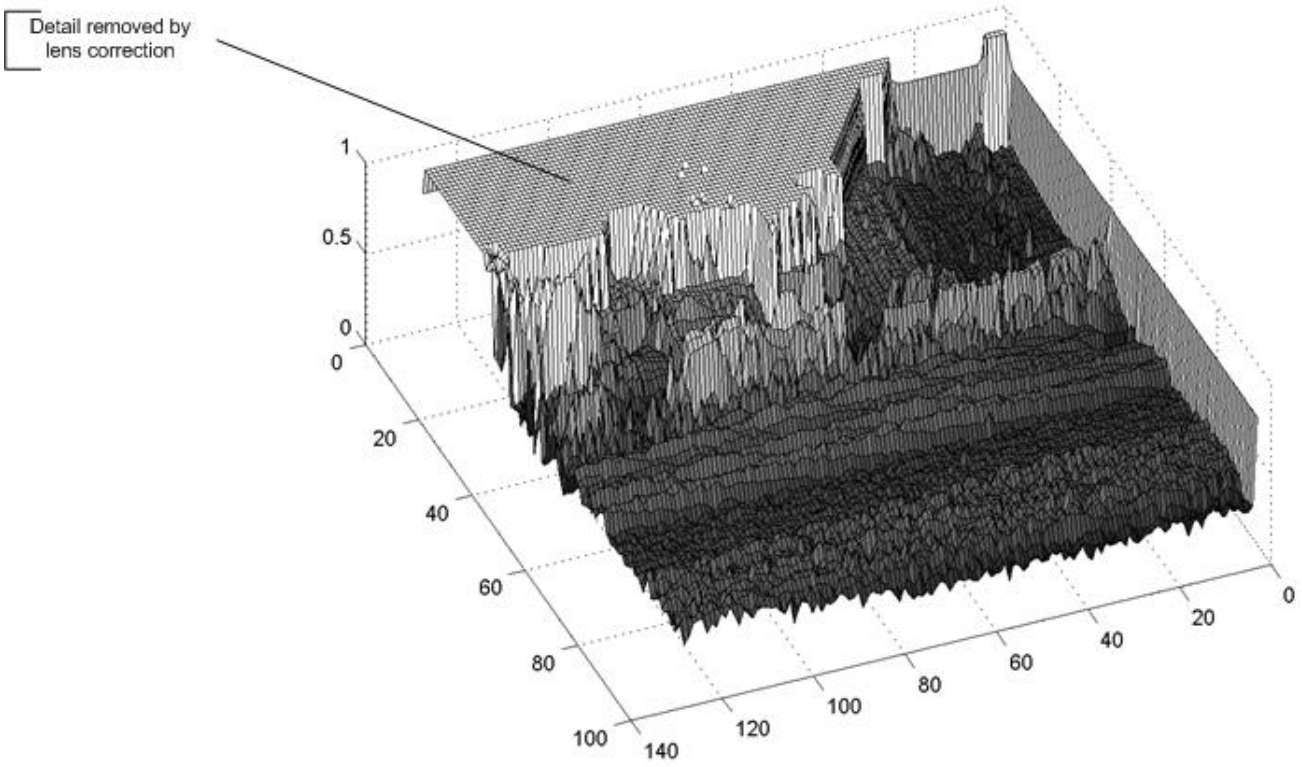


Figure 4 Captured scene intensity map after linear lens correction

Also, using an error propagation formula[3], one can easily show that the noise distribution of the captured and corrected image is no longer isotropic, which in turn has other undesired effects: anisotropic resultant PSF, MTF and also dynamic-range limitations. The dynamic range limitation is a direct result of clipping in linear lens correction.

2.2 Proposed Algorithm

To alleviate this problem, instead of linear lens correction, a more complex correction is proposed. For each point the correction has the form:

$$F(x,y,v)=\begin{cases} G(x,y)*v & if \quad G(x,y)*v < Luma \\ H(x,y,v) & if \quad G(x,y)*v \geq Luma \end{cases}$$ where

v is the pixel value at coordinates x,y while *Luma* is the luminance threshold value used to differentiate between the linear and logarithmic regions of correction. Choosing the optimum point for *Luma* is subjective as it's a balance that allows details in the highlights to be preserved at similar perceptual contrast for both centre of image and corners. We found that the following criteria yielded reasonable results: if the corrected pixel value using the linear part of correction is below 18% gray exposure point plus a headroom of 30%, then no compression is needed, else compression needs to be applied;

For the linear lens correction function $G(x,y)$ we used a function in form of a gain map, applied as $P_{xy}^{o} = P_{xy}^{i} \cdot g_{xy}$ (1);

For the logarithmic compression function $H(x,y,v)$ we used an isotropic compression function $H(x,y,v)=a(x,y)\cdot\ln(\frac{1}{v}+b(x,y))+c(x,y)$ (2).

To build a continuous pixel transfer function, the following conditions need to be met:

$H(x,y,1)=1$ or in other words, the compression function should map 1 to 1;

$H(x,y,Luma)=G(x,y,Luma)$ i.e. $F(x,y,v)$ should be continuous in Luma;

$H'(x,y,Luma)=G'(x,y,Luma)$ in order for the tangent of $F(x,y,v)$ to be continuous in Luma;

Also, F(x,y,v) needs to be monotonic increasingly and concave, to accomplish compression.

Or in our case (using functions (1) and (2)):

$a\cdot\ln(b+1)+c=1$ (3)

$$a\cdot\ln(\frac{1}{luma}+b)+c=luma\cdot g_{xy} \quad (4)$$

$$\frac{a\cdot b}{1+luma\cdot b}-\frac{a}{luma}=g_{xy} \quad (5)$$

Where *luma* is the inflexion point threshold (input pixel value) and g_{xy} is the lens correction gain map value at points x,y. Using these conditions, the logarithmic compression function $H(x,y,v)$ can be fully defined. To illustrate the

difference between a linear lens correction function and the proposed function, transfer characteristics for two pixels, one in centre of correction and one at the extreme, are shown in the following diagram:

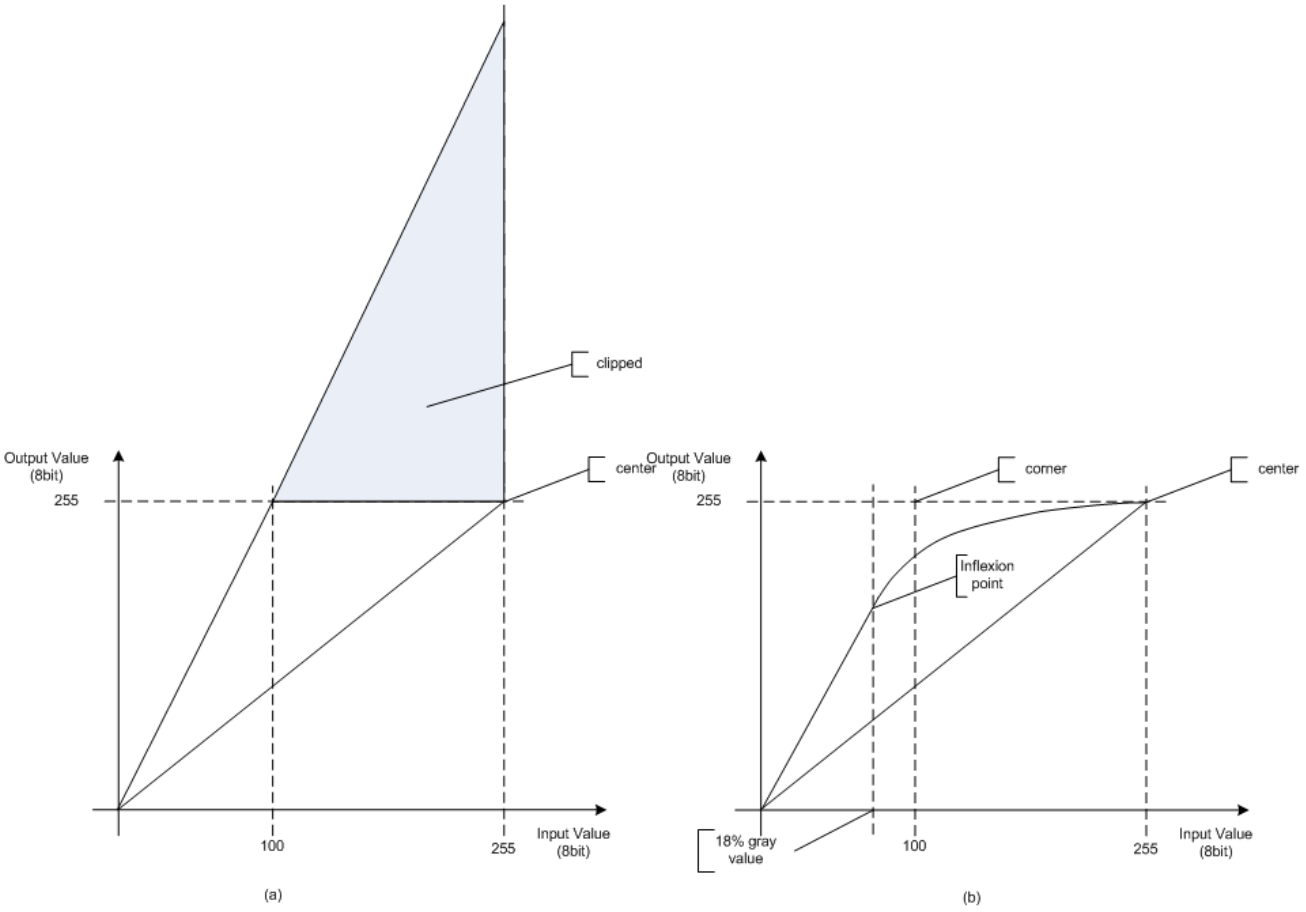


Figure 5 transfer characteristics for (a) linear lens correction (b) proposed lens correction

As it can be seen, image data out of lens correction range is discarded if a purely linear lens correction is used. Of course, as it was pointed out in introduction, if the correction is small (<5%) the data loss is not noticeable. However, for a small-factor cell-phone camera, image data loss can be severe. The proposed solution recovers part of that image information, but makes color processing more complicated, as imaging pipelines typically use linear color processing[4,5].

3. IMPLEMENTATION

Most implementations for color image processing in adjunct to this type of lens correction face the challenge of applying a non linear correction in color channels that are processed in a linear fashion. Usually, this is the case when lens correction is applied before any color processing at the beginning of image chain. The other option is to apply lens correction after normal color processing (which usually is impractical since lens fall-off is different in each color plane).

The two implementations investigated are:

1. lens correction applied in color domain, after color processing as illustrated in Figure 6;

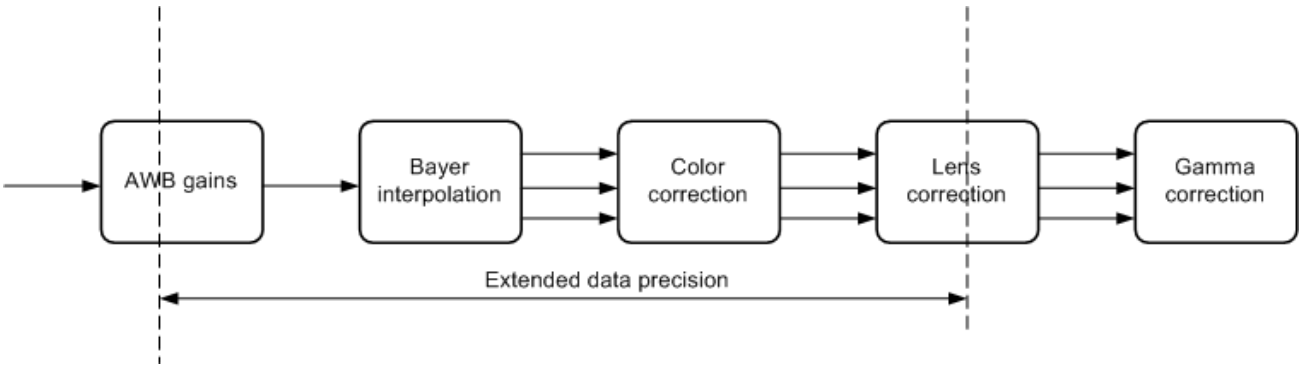


Figure 6 Proposed lens correction in color domain implementation

2. linear portion of the lens correction is done in the raw domain, followed by regular linear color processing using extended depth so data is not clipped, after which color processing and the compression portion of lens correction is applied, as illustrated in Figure 7;

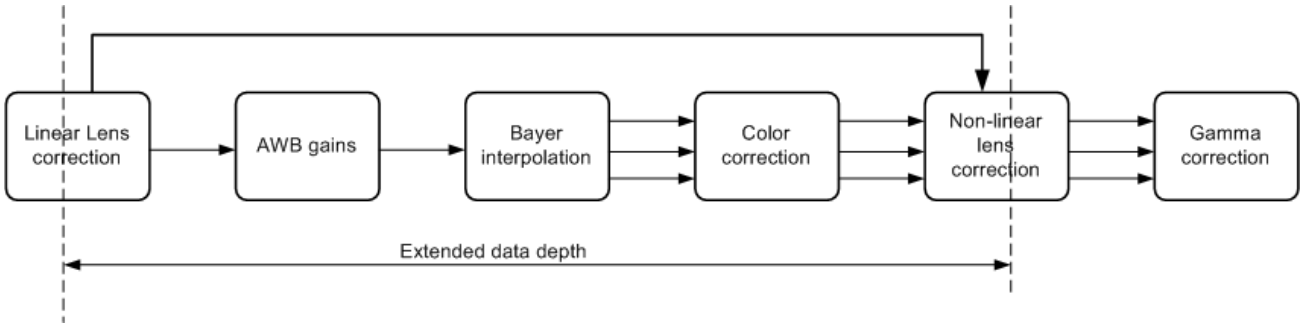


Figure 7 Proposed lens correction in raw domain implementation

In the luminance (monochrome) domain, both implementations offer similar results if the lens fall-off has no hue-shading. Unfortunately, this is not the case in reality, as the modules that we have investigated exhibited various hue-shading profiles that require independent gain-maps per color plane.

To find the required a,b,c coefficients for the logarithmic compression function (2) in a practical implementation, equations (3), (4), (5) are equivalent to:

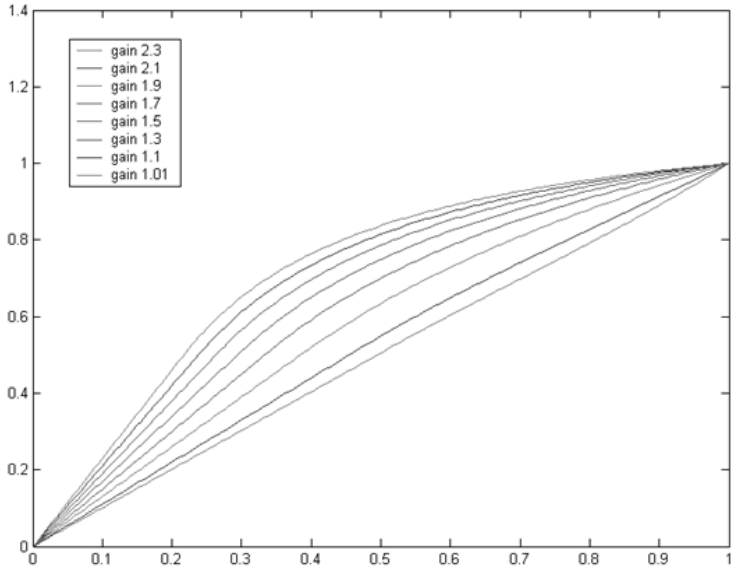
$$c = 1 - a \cdot \ln(b+1)$$

$$a = \frac{g_{xy}}{\frac{1}{\frac{1}{b} + luma} - \frac{1}{luma}}$$

And for b we have the following equation:

$$\frac{g_{xy} \cdot luma \cdot (1 + b \cdot luma)}{b - (1 + b \cdot luma)} \cdot \ln\left(\frac{luma \cdot (b+1)}{luma \cdot b + 1}\right) + g_{xy} \cdot luma - 1 = 0 \quad (6)$$

As the compression function is dependant of gain, solving (6) numerically for PLuma=130/255 – note that $luma = \frac{PLuma}{g_{xy}}$, the following family of transfer curves is obtained (we used Newton method considering the precision issues as outlined in[6]):



gain	b
2.3	5.375
2.1	3.829
1.9	2.518
1.7	1.435
1.5	0.568
1.3	-0.098
1.1	-0.5695
1.01	-0.7219

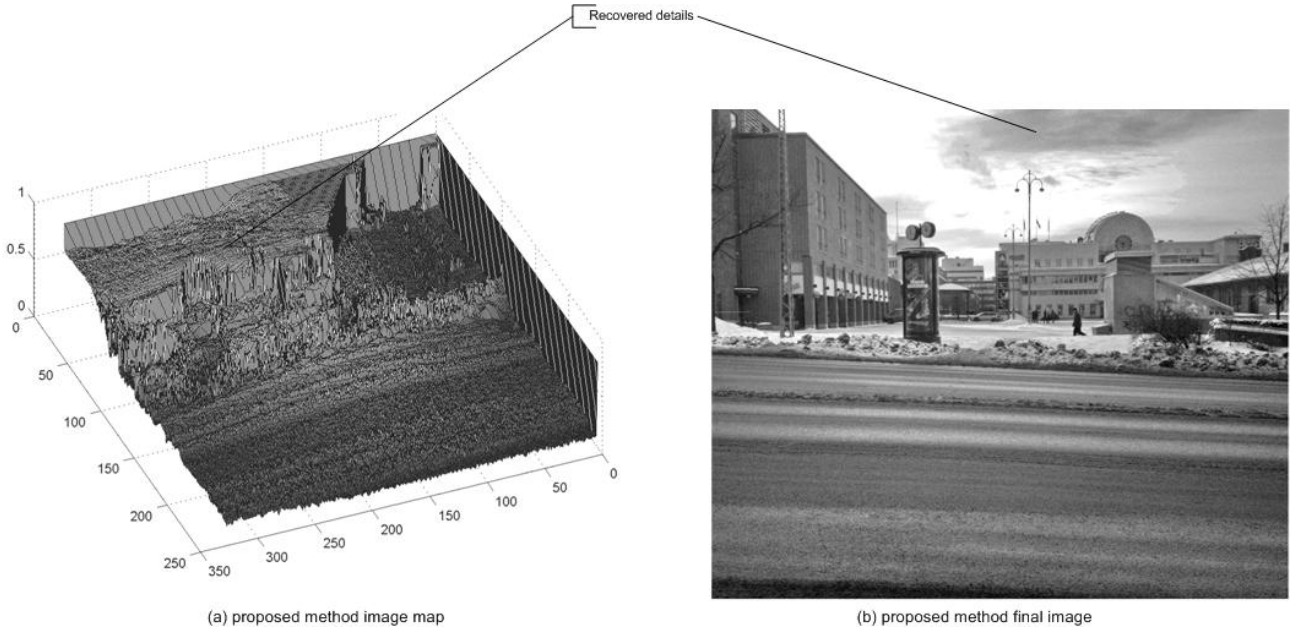
Figure 8 Example family of transfer characteristics for discrete values of gain

For practical implementation, we used a look-up table that would allow a one iteration of Newton method to solve (6) following the guidelines outlined in[7].

4. RESULTS

To illustrate the results of the proposed method, several scenes were investigated, and for each, intensity maps were generated. As the improvement is mostly perceptual, since the recovered details in highlights (see Figure8 – b) are non-linear, the image improvement is subjective, although quite visible, as it can be seen by comparing Figure3(a) with Figure9(b).

As some of the details are captured from the original scene, a map of captured dynamic range in the image would be significantly flatter than Figure2 (a).



(a) proposed method image map (b) proposed method final image

Figure 9 Proposed method (a) image map (b) final image

5. CONCLUSIONS AND FUTURE WORK

A new method for lens correction was proposed that uses the significant lens fall-off usually present in cell-phone cameras to restore some of the dynamic range which is lost if a linear lens correction is used, due to the fact that regions that have high intensity end up by being clipped. As the proposed solution uses a non-linear compression region in the transfer characteristic of the proposed lens correction function, it restores some of the details that would be otherwise lost, but the recovered data is subjective therefore the improvement is mostly perceptual. As a consequence, the threshold for the inflection point on the transfer characteristic was chosen on subjective basis. A suitable compression function was shown to be logarithmic of the form $a \cdot \ln(\frac{1}{v} + b) + c$ and it's effectiveness illustrated. A method to determine a,b,c was provided. Results show recovery of details in high-dynamic range scenes that otherwise would have been lost, therefore the dynamic range of the captured image is improved toward the corners. The proposed method makes use of implicit system level assumptions as well as typical scene compositions (outlined in 1.1). If those assumptions are not met, the method would correct the captured image same as a linear lens correction, since the logarithmic compression

part of the pixel transfer characteristics would not be used. Future work will consist of exploration of different compression functions as well as hardware and software implementation of the method.

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