Development of an Optimized Flat-field Correction Algorithm for Digital Cameras

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Abstract

In this work we present an optimized linear algorithm for the spatial non-uniformity correction of a CCD color camera's imaging system, and the experimental methodology developed for its implementation. The influence of the algorithm's variables on the quality of the correction, that is, the dark image, the base correction image and the reference level, and the range of application of the correction, were assessed using a uniform radiance field provided by an integrator cube. The best spatial non-uniformity correction is achieved by having a non-zero dark image, using an image with a mean digital level placed in the linear response range of the camera as base correction image, and taking the mean digital level of the image as reference digital level. The response of a CCD color camera's imaging system to the uniform radiance field showed a high level of spatial uniformity after applying the optimized algorithm, which, also allowed to achieve a high quality spatial non-uniformity correction of captured images under different exposure conditions.

Introduction

In this work we present the optimization of a linear algorithm for the spatial non-uniformity correction of digital cameras, and the experimental methodology developed as a result. The aim of this work was to achieve the best flat field correction of a digital color camera imaging system, obtaining the most similar pixel responses over the sensor's surface when a uniform radiance field is being imaged. This allows to make the entire detection area of the sensor useful for measurement purposes, and consequently, the digital color camera imaging system to be used as a high spatial resolution instrument. Moreover, to use a digital camera image capture device as an instrument for measurement purposes its response must be a linear function of exposure within a certain range, for each of the RGB channels.

Before the application of the spatial non-uniformity correction, the contribution of different zero-mean noise components to the digitized image[1,2,3,4] of the radiance field were reduced as much as possible. After that, the spatial non-uniformity correction was carried out by applying a linear correction algorithm based on the calculation of a gain matrix and an offset matrix[6,7].

The goal of this work is the optimization of this linear algorithm allowing the use of an imaging system based on a CCD camera as an instrument for measurement purposes with high spatial resolution, being therefore a high radiometric accuracy required. This is accomplished by means of the optimization of the algorithm's variables, that is, the dark image, the base correction image and the reference level. Although the usually values of these variables used in literature provided acceptable results, the non-uniformity correction could be significantly improved by applying the linear algorithm with other values. The study of the influence of these algorithm variables in the correction and their optimum values are presented in this work together with the experimental methodology developed as a result.

This work is structured as follows: the experimental methodology developed and the material needed for its application are detailed in the Material and Method section. Next, the results of applying this experimental methodology and the new algorithm are presented in the Results section. Finally, the most relevant conclusions are discussed in the Conclusions section.

Material and Method

In order to obtain a uniform radiance field, we manufactured an integrator cube, whose sides were 50 cm long, and which had white painted walls and an 18 cm x 18 cm window of a white translucent diffuser material placed on one of its sides. A light source (PHILIPS 150 W halogen lamp) connected to a stabilized power supply (Hewlett Packard 6642A DC) for the stable illumination, and a white baffle that did not let the direct light of the lamp to reach the window, were placed inside the cube so as to achieve a highly uniform distribution of diffused light over the diffuser's translucent window. The window of the cube acted as a uniform radiance field, and had a spatial variation percentage of 0.50% over the 10 cm x 8 cm centered region that constituted the camera's viewing field. This spatial variation percentage was determined by measuring the radiance over the camera's viewing field region using a telespectroradiometer (PhotoResearch PR650 with a MS-75 objective lens, 1° aperture) (Fig. 1.).

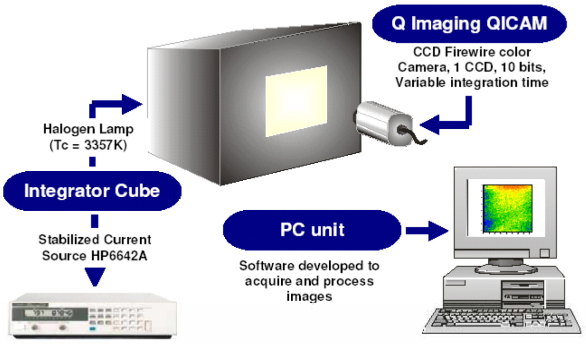


Figure 1. *Experimental set-up for the spatial characterization of a CCD camera's imaging system.*

Our image capturing system was composed of a QImaging QICAM 10-bit color CCD camera attached to a 16 mm, 1:1.4 COSMICAR Television objective lens.

The spatial non-uniformity correction of the imaging system was carried out using two images[5]: a dark image, captured under the same conditions (exposure time and temperature) as the image to be corrected and with the camera shutter closed, and an image captured from the manufactured uniform radiance field, and for different exposure levels that were modified by varying the exposure time of the CCD sensor, since the radiance level of the integrator cube was fixed.

The linear correction algorithm applied is given by the following equations[6,7]:

$$\begin{aligned} DL_c(i,j) &= O(i,j) + G(i,j)DL(i,j) \\ G(i,j) &= \frac{DL_B - DL_0}{DL_B(i,j) - DL_0(i,j)} \\ O(i,j) &= DL_0 - G(i,j)DL_0(i,j) \end{aligned} \tag{1}$$

where *$DL_c(i,j)$, $DL(i,j)$, $DL_0(i,j)$*, and *$DL_B(i,j)$* are the digital levels of the *(i,j)* pixel of the corrected image, original image, dark image, and base correction image, respectively, the term *O(i,j)* represents the (i,j) element of the correction offset matrix **O**, the term *G(i,j)* represents the the (i,j) element of the correction gain matrix **G**, and DL_0, and DL_B the reference digital level of the dark image and the base correction image, respectively.

In the linear algorithm given by Equations (1), the reference digital level and the base correction image usually used are the mean digital level of the image, and the brilliant image[6,7], which is defined as the image with the highest digital level that does not have any saturated pixels, respectively. Although the use of these values provided acceptable results, the non-uniformity correction could be significantly improved by applying the linear algorithm with other values. The variables studied and optimized in this work are the dark image, the base correction image, and the reference digital level. Once the optimized algorithm for the spatial non-uniformity correction of a CCD camera was obtained, the range of application of this spatial characterization was determined by analyzing its performance for several exposure time ranges.

The quality of the optimized algorithm's performance was evaluated in terms of the spatial non-uniformity of the digital level of an image of the uniform radiance field, which can be quantified in different ways[1]. In this work we quantified it by means of Equation (2), which will herein be referred to as the spatial non-uniformity percentage (SNUP).

$$SNUP = 100 \cdot \frac{\sigma(Mean)}{Mean} \tag{2}$$

where *Mean* represents the mean digital level over all the image pixels, and the *$\sigma(Mean)$* the standard deviation associated to it.

The offset and gain parameters of the CCD camera used were set to values that optimized the final spatial non-uniformity correction, that is, in a way that enabled the response of the RGB channels to be a linear function of the exposure over a certain exposure range, and, furthermore, that allowed to have both zero and non-zero dark images in order to determine its influence on the results.

Before the application of the spatial non-uniformity correction, the contribution of different zero-mean noise components to the digitized image of the radiance field were reduced as much as possible by analyzing the variation in the quality of the correction as a function of the number of averaged images. This analysis allowed the number of images that needed averaging to be determined.

After that, the spatial non-uniformity correction was carried out by means of the linear correction algorithm given by Equations (2).

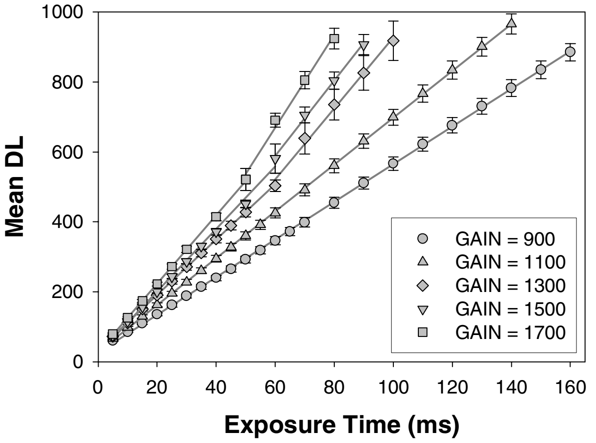
Results

Selection of gain and offset

For the imaging system analyzed, the R and G channels were more sensitive than the B channel, and showed a linear response over a certain exposure range for all the set gain and offset values. On the other hand, the B channel needed much greater exposure to reach saturation, and its response showed two linear zones with different slopes before it became saturated at certain gain and offset values. This two-slope behavior of the B channel must be avoided when one wishes to use the imaging system for measurement purposes.

To produce a non-zero dark image, the offset value must be higher than 1100, and in order to generate a linear zone with a unique slope for the camera's response in the B channel, the gain parameter value must be less than 1200 (Figure 2.). The camera settings selected for a zero dark image were a gain value of 1000 and an offset value of 850. In order to have a non-zero dark image, an offset value of 1400 and a gain value of 1000 were selected. These values led to a dark image with a mean digital level of 35, which is approximately a 4% of the maximum useful (linear response zone) digital level of the 10-bit camera. These gain and offset parameter values produce the best spatially corrected images.

Figure 2. Mean digital level (DL) of images from a uniform radiance field for the B channel versus exposure time for different gain values and offset fixed at 1400.



Number of images

In order to determine the number of images to be averaged, the variation of the SNUP of the resulting image was analyzed as a function of the number of averaged images (Table 1.).

Although increasing the number of averaged images progressively improved the spatial uniformity, an increase higher than 20 did not lead to an outstanding improvement in the spatial uniformity. Therefore, from this point on, an image will refer to the image resulting from averaging 20 individual, successively captured images.

Table 1. SNUP values and SNUP reduction percentages (red. %) for the image resulting from averaging as function of the number of averaged images (Av. Im.), for the RGB camera channels.

Av. Im.	R Channel		G Channel		B Channel	
	SNUP	red. %	SNUP	red. %	SNUP	red. %
1	2.6644	-	3.1353	-	3.0815	-
10	2.4957	6.33	3.0850	1.60	2.5654	16.75
20	2.4871	0.34	3.0813	0.12	2.5345	1.20
30	2.4815	0.23	3.0793	0.06	2.5238	0.42
40	2.4805	0.04	3.0790	0.01	2.5156	0.32
50	2.4791	0.06	3.0776	0.05	2.5121	0.14
60	2.4770	0.08	3.0758	0.06	2.5069	0.21

Influence of dark image, base correction image, and reference digital level

The linear spatial non-uniformity correction algorithm given by Equations (2) was applied to images captured with the two above mentioned camera gain and offset values. We used the image with a mean digital level placed in the middle of the useful linear response range of the camera as the base correction image, and the mean digital level of the image as the reference digital level.

In order to analyze the influence of having a zero or a non-zero dark image, the spatial non-uniformity correction quality of several corrected images was compared by means of the SNUP (Table 2.). The use of a non-zero dark image improved the spatial non-uniformity correction from a 21% up to a 66%, depending on the color channel, with respect to corrected images obtained with a zero dark image. Consequently, in order to obtain images with high spatial non-uniformity correction, it is essential to work with gain and offset values which produce non-zero dark images.

Table 2. Mean SNUP values of images over the camera's useful linear response range for zero dark image (ZDI) and non-zero dark image (NZDI) gain and offset settings and for the RGB camera channels.

	R Channel	G Channel	B Channel
ZDI	0.5162	0.5096	1.8431
NZDI	0.4064	0.3589	0.6280

Regarding the influence of the base correction image on the quality of the spatial non-uniformity correction, several images were selected: the brilliant image; the central image, whose mean digital level is placed in the middle of the useful linear response range of the CCD camera's imaging system; and the extreme image, whose mean digital level is placed in the end of the useful linear response range of the. In this case, the mean digital level of the image was also taken as the reference digital level. As can be seen in Table 3., both using the central and the extreme images as base correction images led to a clear improvement in the quality of the spatial non-uniformity correction. The best correction is commonly achieved by using the central image, obtaining an improvement of the spatial non-uniformity correction of a 41% for the R channel, and of a 29% for the G channel. For the B channel, the results obtained using the different images selected as base correction image were quite similar. This result is probably due to the fact that the B channel's response shows two linear zones. Although we modified the gain and offset values in order to obtain a unique slope, this linear behavior was observed when the average over the entire image was considered. However, the linearity of the response of each pixel individually was not assured and, consequently, it would affect the results.

Table 3. Exposure time corresponding to each base correction image, and mean SNUP values for the RGB camera channels of the spatially corrected images over the camera's useful linear response range, using the brilliant image (BI), the central image (CI), and the extreme image (EI) as the base correction image in the linear spatial non-uniformity correction algorithm.

	R Channel		G Channel		B Channel	
	t_{exp} (ms)	Mean SNUP	t_{exp} (ms)	Mean SNUP	t_{exp} (ms)	Mean SNUP
BI	60	0.6914	55	0.5081	155	0.5816
CI	30	0.4064	30	0.3589	80	0.6280
EI	55	0.4307	50	0.3669	150	0.6133

Although it may be thought that taking the brilliant image as the base correction image enabled the full response range of the camera to become involved, this image is placed in the beginning of the saturation zone of the camera response, and this could be the reason why the brilliant image led to worse results than the central and extreme images, which were both in the linear response range. From this point on, the base correction image is taken to be the central image.

Finally, with respect to the influence of the reference digital level on the quality of the spatial non-uniformity correction, as for the base correction image, several values were taken as the reference digital level: the mean digital level, the mode of all the pixel digital levels of an image, and the digital level corresponding to the central pixel of the image. The central images for each RGB channel were taken as base correction images.

Table 4. Mean SNUP values for the RGB camera channels of spatially corrected images, using the mean digital level (Mean DL) of the image, the mode of all the pixel digital levels (Mode DL), and the digital level of the central pixel (Central DL) as the reference digital level in the linear spatial non-uniformity correction algorithm.

	R Channel	G Channel	B Channel
Mean DL	0.4064	0.3589	0.6280
Mode DL	0.4064	0.3596	0.6289
Central DL	0.4071	0.3606	0.6323

The results obtained in terms of the spatial non-uniformity correction quality were very similar for all the reference digital levels considered (Table 4.). The results corresponding to the mean and mode digital levels were practically identical and slightly better than those obtained for the central digital level.

This could be due to the statistical nature of these two reference digital levels, since they are related to the digital level value distribution of an image. From this point on, the mean digital level is taken as the reference digital level in the linear spatial non-uniformity correction algorithm, since it is usually used as reference digital level in the literature.

Range of application of the spatial characterization

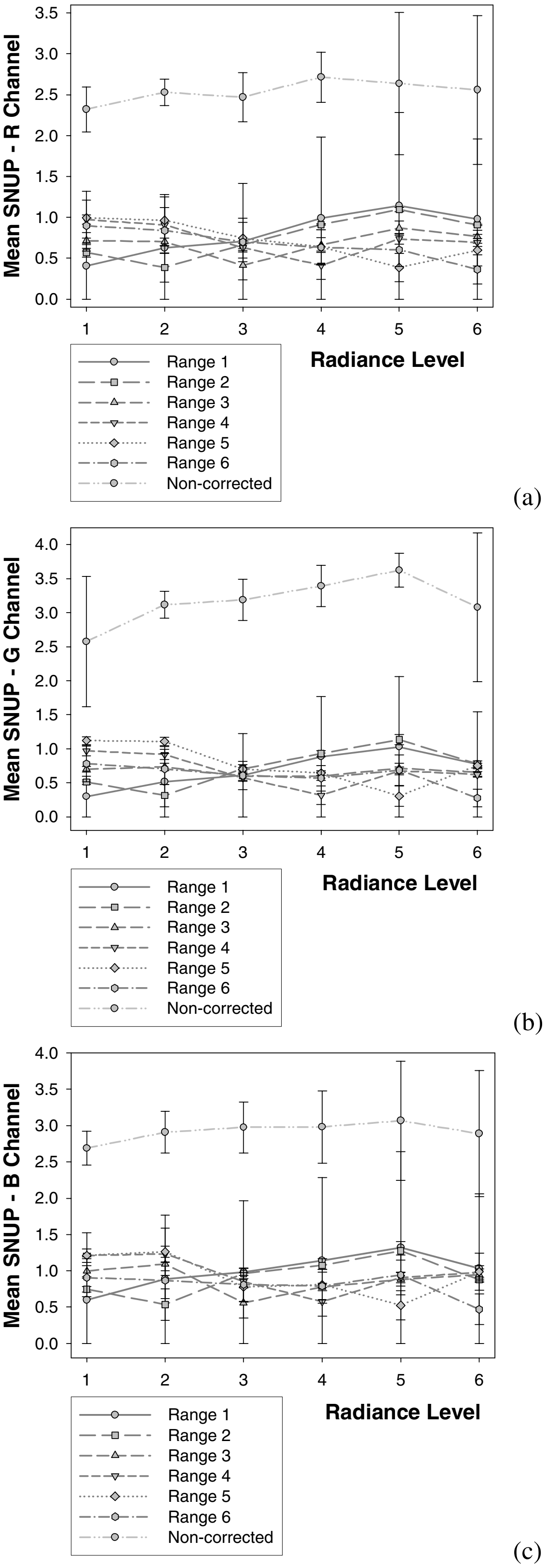
Up to this point, the illumination conditions were fixed and, as a consequence, the exposure time range in which the camera's linear response was useful was also fixed, depending on the gain and offset settings. However, the exposure time range can change depending on the image captured.

The optimized algorithm for spatial characterization (Equations (2)) depends fundamentally on the correction gain matrix. This is the why assessing the application of the optimized algorithm to spatial characterization involves determining whether a correction gain matrix calculated for certain fixed illumination conditions and, consequently, a fixed exposure time range, leads to high quality spatial non-uniformity correction when it is used to correct an image captured in any other exposure time range, beyond the useful linear response range of the camera.

In order to check the application of the optimized algorithm, several groups of images of a uniform radiance field were captured for several radiance levels by varying the current intensity applied to the halogen lamp. For each radiance level (exposure time range) a correction gain matrix was calculated, and used to correct the groups of images corresponding either to its own radiance level or to the rest of the radiance levels considered. The radiance levels were selected on the basis of the exposure time ranges associated with them (Table 5.), and corresponded to the useful linear response ranges of the CCD camera's imaging system for each channel. From this point on, radiance level will mean the corresponding exposure time range of the RGB channel responses, instead of the numerical radiance level itself.

Table 5. Radiance and exposure time range (useful linear response range) for each RGB channels, corresponding to the six radiance levels (RL) considered.

		Exposure Time Range (ms)		
RL	**Radiance ($W/sr{\cdot}m^2$)**	**R Channel**	**G Channel**	**B Channel**
1	5.2630	5 – 60	5 – 50	10 – 160
2	3.8460	10 – 80	10 – 80	10 – 225
3	2.6620	10 – 100	10 – 100	50 – 400
4	1.7580	25 – 175	25 – 175	50 – 700
5	1.0920	25 – 300	25 – 300	100 – 1300
6	0.6303	50 – 500	100 – 700	200 – 2500



(a)

(b)

(c)

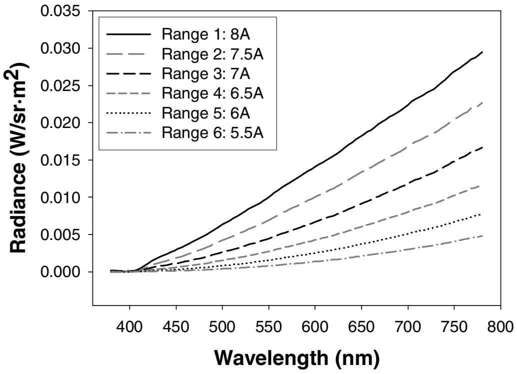
Figure 3. Mean SNUP, and standard deviation of the Mean SNUP (error bars) of each radiance level (Range 1 to 6), as a function of the radiance level of each one of the correction gain matrixes used in the optimized algorithm for the spatial non-uniformity correction applied, for the (a) R, (b) G, and (c) B camera channels.

The mean SNUP obtained for each radiance level (Range 1 to 6) as a function of the radiance level of each correction gain matrix used, are shown for the different radiance levels in Figure 3., for the RGB channels. The mean SNUP of the original, non-corrected images for the different radiance levels are also shown.

The best results were obtained when images corresponding to a radiance level were corrected using the correction gain matrix calculated for the same radiance level or for the closest radiance levels. High radiance levels, corresponding to low exposure time ranges, led to better results than lower ones. In spite of this, if one compares the mean SNUP of the corrected images of different radiance levels using the gain correction matrixes calculated for all the radiance levels to the mean SNUP of the non-corrected images for the same radiance levels, one can see that the calculation of a correction gain matrix at a certain radiance level, preferably a high radiance level, and, consequently, a certain exposure time range of the RGB channels, preferably a low exposure time range, would be sufficient to achieve a high quality spatial non-uniformity correction of images when the optimized linear spatial non-uniformity correction algorithm is applied to them using this gain matrix.

Obtaining different radiance levels by varying the current intensity applied to the halogen lamp considerably modified the radiance spectrum of the incident light in the CCD camera's imaging system (Fig. 4.). Therefore, the fact that high quality spatial non-uniformity correction of images is achieved for different exposure time ranges proves that the correction performed by this optimized algorithm is independent of changes in the radiance spectrum of the incident light, and that the algorithm may be successfully applied in a wide range of exposure conditions.

Figure 4. *Radiance spectrum of the incident light in the CCD camera's imaging system. Different radiance levels are achieved by varying the intensity of the current applied to the light source.*



Conclusions

In this work we present an optimized linear algorithm for the spatial non-uniformity correction of a CCD camera's imaging system and the experimental method designed for its implementation.

In order to use a CCD image capture device as an instrument for measurement purposes its response must be a linear function of exposure within a certain range, for each of the RGB channels. Therefore, all the settings of our imaging system (exposure time range, gain, offset, …) were chosen so that this linear behavior was ensured.

Previously to the application of the non-uniformity correction, the contribution of the different zero-mean noise components was minimized by averaging a certain number of images. It was found that an average of 20 images was sufficient to attenuate the effect of these components on the image.

Although the linear correction algorithm considered in this work is widely found in the literature, it is always applied using the mean digital level and the brilliant image as the reference digital level and the base correction image, respectively. These results can be considerably improved with the use of other values. In this work, we carried out the optimization of this spatial non-uniformity correction by studying the influence on the correction of the dark image, the base correction image, and the reference digital level.

In order to obtain the best spatial non-uniformity correction quality, it is necessary to have a non-zero dark image, and to use the central image, i.e. the image with a mean digital level placed in the middle of the useful linear response range of the camera, as the base correction image. With regard to the reference digital level, the mean and the mode of all the pixel digital levels of an image gave practically identical results. Because the mean digital level of the image is the most commonly used, in this work, it was taken as the reference digital level.

Finally, the application of the optimized algorithm was assessed by capturing groups of images for different radiance levels, calculating the correction gain matrix for each radiance level, and correcting the images of all the radiance level groups with the correction gain matrixes calculated for each radiance level. The best results were obtained when images corresponding to a radiance level were corrected using the gain matrix calculated for the same radiance level or for the closest ones. In spite of this, the comparison between the mean SNUP of corrected and non-corrected images showed up that the calculation of a unique correction gain matrix at a certain radiance level would be sufficient to achieve a high quality spatial non-uniformity correction of images of different radiance levels. High radiance levels corresponding to low exposure time ranges were preferred for calculating the gain correction matrix, since these led to better results than low levels.

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Author Biography

Marta de Lasarte completed her BSc Degree in Physics at the Autonomous University of Barcelona (Spain) in 2004 and received the 2004 year Extraordinary Award of Degree End from the Autonomous University of Barcelona. She is currently enrolled in the PhD program in Optical Engineering at the Technical University of Catalonia, having received a PhD grant from the Ministerio de Educación, Ciencia y Deportes of Spain. Her work focuses on color imaging (device *calibration and characterization, color management) and industrial colorimetry.*

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