Color Correction for Mobile Panorama Imaging

Yingen Xiong and Kari Pulli
Nokia Research Center
955 Page Mill Road
Palo Alto, CA 94304, USA
{yingen.xiong, kari.pulli}@nokia.com

ABSTRACT

This paper presents a simple and efficient color and luminance compensation approach for image sequences for constructing panoramic images on mobile devices. In this approach, constant compensation coefficients for adjacent images are computed from the corresponding pixels in the overlapping areas of the adjacent images in the linearized RGB color space. A global adjustment for all compensation coefficients is performed so that the correction for each image is as small as possible. This can smooth color transition between adjacent images in the image sequence globally and reduce cumulative errors in the color correction process. The compensation coefficients, together with the global adjustment factor, are applied to correct color and luminance of source images in the image sequence before they are stitched into a panoramic image.

Our algorithm is not sensitive to the quality of spatial registration since it does not need exact pixel correspondences between the overlapped images. The computation of compensation coefficients for each adjacent image takes the gamma correction factor into account, producing better results. Running the method separately on the three channels matches the color balance that may not match due to auto-white-balancing algorithm. A global adjustment for the compensation coefficients minimizes color transitions and reduces cumulative errors. The approach is integrated into a sequential image stitching procedure and implemented in a mobile panorama system, good results have been obtained for both indoor and outdoor scenes.

Categories and Subject Descriptors

I.3 [**Computer Graphics**]: Picture/Image Generation Graphics Utilities ; I.4 [**Image Processing and Computer Vision**]: Application

General Terms

Algorithms, experimentation

Keywords

mobile imaging, mobile panorama, image stitching, color and luminance compensation, image blending, linear blending, Poisson blending, mobile image processing, mobile computational photography, panorama construction

1. INTRODUCTION

1.1 Background

Mobile phones have developed into not only efficient and convenient communication tools but also capable computational devices, equipped with high-resolution cameras and high-quality color displays. Many applications which could only work on computers before can now be implemented and run on mobile devices, such as mobile augmented reality [1], mobile image matching and recognition [2], and so on. With our panorama imaging application a user can take an image sequence from a wide range of scenes with a mobile phone and see a panoramic image created on the mobile phone immediately. The user can also send the panoramic image to his friends and upload it to website to share with other people.

Panoramic images are constructed from image sequences which are captured continuously by rotating a camera so it covers the whole scene. During image capturing, varying illumination levels in different parts of the scene lead the automatic gain control to produce different exposure levels, and automatic white balance algorithms lead to different color tones. If no further color processing is done, visible contrast or color discontinuities are likely to appear in the final panorama. Figure 1 shows an example, where the bottom shows two adjacent source images in an image sequence. From the source images we can see that the colors and luminance levels are very different. We stitch them together to create a panoramic image shown on the top of Figure 1. From the result we can see an artificial edge between the two image. In order to construct a good panoramic image with the image sequence, we need to reduce the color differences between the source images and smooth the color transition for the image sequence before stitching the source images onto the panoramic image.

1.2 Related Work

There are several approaches for color and luminance compensation for image sequences. Pham and Pringle [3] perform color correction using polynomial mapping functions. Pixel pairs in the overlapping area of two images are used to compute the parameters of the polynomial mapping func-

Figure 1: A panoramic image created by two adjacent images with differing colors and luminances.

tion. The approach can perform accurate color correction. However, since exact correspondences of pixels in both images are needed, the approach is sensitive to spatial alignment errors. As our panoramas are obtained using a handheld camera phone that might also translate between images insteady of a simple rotation around the principal point, the parallax caused by nearby objects, as well as people moving between image captures, make pixel-accurate registration impossible. According to our experiments even simple polynomial models (offset and scale) require accurate pixel correspondences for good results.

Zhang et al. [4] propose to construct a mapping function between the color histograms in the overlapping area of the source images. A color correction is performed using the mapping function for the adjacent image. Since no exact pixel correspondences are needed, the method is not sensitive to the quality of spatial alignment. However, the accuracy of color correction is not as good as with the polynomial correction.

Tian et al. [5] Propose a simple linear model that computes a scale factor that matches the averages of each channel over the overlap area. The benefit of the method is that no accurate pixel correspondences are required. However, they calculate the averages in raw sRGB values, that is, in gamma-corrected RGB space, not in linear RGB. Most RGB representations use gamma correction to fit a larger (about 10 bits) dynamic range into 8 bits, for example JPG does that, and that also matches the representation better to display requirements. However, the sRGB values do not now have a linear correspondence to actual color values, and for example taking an average of pixel values in sRGB does not correspond to the average amount of light. Note that almost all most previous work, not just Tian et al., operate directly in gamma-corrected sRGB.

Ha et al. [6] perform linear correction that is otherwise quite similar to Tian et al., except that they operate in the $YCbCr$ color space.

Meunier and Borgmann [8] only consider the luminance channel to match exposures. However, rather than using the gamma-corrected values, they undo the gamma correction and calculate the averages in linear intensity. Instead of separately calculating pairwise correction factors, they formulate a global error equation that solves all the factors simultaneously. Brown and Lowe [7] use almost the same method as Meunier and Borgmann, except that they operate in non-linear gamma-corrected intensity space.

In our work, we are interested in developing a fast and efficient color and luminance compensation approach for panorama stitching to create high-resolution and high-quality panoramic images. We want to match the exposure levels of different auto-exposed images. We also want to match the color balances which often differ from image to image depending on the overall image content and the auto-white-balance algorithm used. We compute separate adjustment factors for each of the R, G, and B channels, but we calculate the averages in linear RGB rather than in gamma-corrected sRGB. We also have a simple way of calculating a global correction factor that aims to minimize the magnitudes of the per-image correction factors. Our method is low computational and memory complexity, and has been implemented on a panorama image capture and creation system running on a mobile phone.

1.3 Organization of the Paper

In Section 2 we introduce the work flow of our approach. The details of the color and luminance compensation approach are described in Section 3. A sequential panorama stitching process using the color correction approach is explained in Section 4. Applications and result analysis are discussed in Section 5. A summary of the paper is given in Section 6.

2. WORK FLOW OF THE APPROACH

Figure 2 shows the work flow of our method. The color correction process is integrated into a sequential image stitching procedure which includes two parts. The first part is the computation of color correction coefficients. The second part is color correction and image stitching.

The image stitching procedure starts with setting the stitching order of the source images by sorting their offsets and allocating memory space for the final panoramic image I_c. After loading the first source image S_1 and setting the initial parameters, we start the first part with loading the next source image S_2.

The color and luminance correction coefficients for the current source image S_i are computed with the sum of pixel values in the overlapping area between the current image S_i and the previous image S_{i-1} in the linear RGB color space. In this way, we can obtain color correction coefficients for all source images. We perform global adjustment for these coefficients in the whole image sequence to further smooth color transition for the panoramic image and reduce the likelihood of correction coefficients over-exposing and thus saturating the images. The global adjustment g_c can be obtained by minimizing an objective function which makes the color correction for each source image as small as possible.

After obtaining the color correction coefficients and the global adjustment factor, we perform color correction for each source image with these coefficients and stitch them onto the final panoramic image sequentially. After all source images are processed, we can obtain the final panoramic

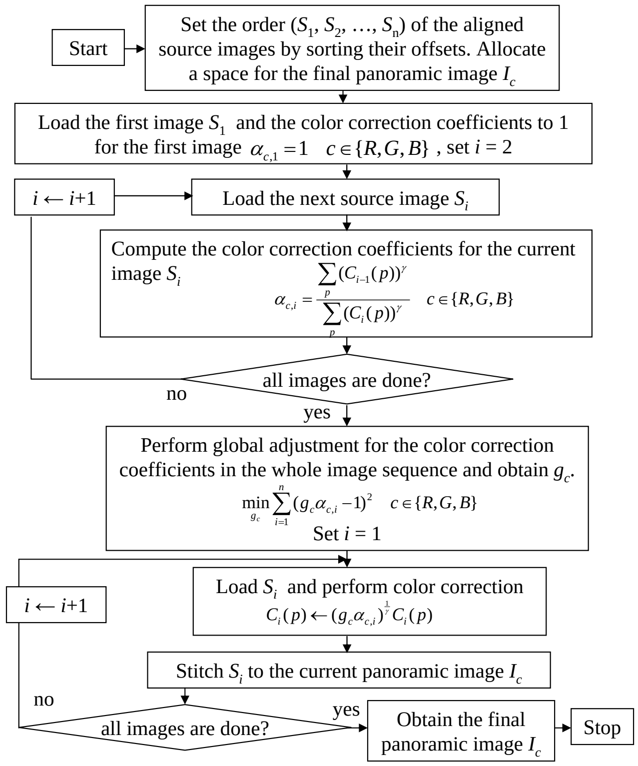


Figure 2: Work flow of sequential image stitching with the color correction approach.

image.

3. COLOR AND LUMINANCE COMPENSATION

Suppose S_k^o and S_j^o are the overlapping areas of two adjacent images S_k and S_j. The color transformation between images S_k^o and S_j^o can be modeled by a linear mapping,

$$C_{c,j}(p) = \beta C_{c,k}(p) \quad c \in \{R, G, B\} \tag{1}$$

where

$C_{c,j}(p)$ and $C_{c,k}(p)$ are color values at pixel p in overlapped images S_k^o and S_j^o;

β is a mapping coefficient.

The linear correction for color and luminance can be expressed by a diagonal model,

$$S_j^o = S_k^o \, M \tag{2}$$

where M is a transform matrix

$$M = \begin{bmatrix} \alpha_R & & \\ & \alpha_G & \\ & & \alpha_B \end{bmatrix} \tag{3}$$

where α_R, α_G, and α_B are color correction coefficients for channel R, G, and B respectively:

$$\alpha_c = \frac{\overline{C_{c,k}}}{\overline{C_{c,j}}} \quad c \in \{R, G, B\} \tag{4}$$

where $\overline{C_{c,k}}$ and $\overline{C_{c,j}}$ are mean values of R, G, and B of S_k^o and S_j^o. That is, the αs match the average colors over the overlap area for each channel.

Equation 3 is called the diagonal model. With this model, color correction for the adjacent image can be performed for R, G, and B channels separately by

$$C_c(p) \leftarrow \alpha_c C_c(p) \quad c \in \{R, G, B\} \tag{5}$$

where $C_c(p)$ is the color value at pixel p in color channel c.

The diagonal model is a simple and fast color correction approach. It has the advantage that no pixel-accurate registration is required, and we can simultaneously match different exposure levels as well as different overall color balance. There are a couple of problems, however. The first one is that calculating an average over gamma-corrected pixel values does not have a clear physical meaning, so the resulting correction factors more easily lead to pixel value saturation or loss of contrast. Additionally, if the correction factors are calculated one after other, the cumulative effect is even more likely to lead to pixel saturation or loss of contrast.

We want to have the same effect as if we did all our calculations in linear light color space. However, we don't want to first linearize each pixel, and then after all processing reapply the gamma correction. We also want to minimize the magnitude of each correction factor.

This is how we can calculate appropriate correction factors in linear color space. For an image sequence $S_1, S_2, \ldots, S_i, \ldots, S_n$, suppose S_{i-1} and S_i are two adjacent images. S_{i-1}^o and S_i^o are images in the overlapping area between the two adjacent images. We compute a correction coefficient for image S_i as

$$\alpha_{c,i} = \frac{\sum_p (C_{c,i-1}(p))^\gamma}{\sum_p (C_{c,i}(p))^\gamma} \quad c \in \{R, G, B\} \quad (i = 2, 3, \ldots, n) \tag{6}$$

where

$C_{c,i}(p)$ is the gamma-corrected color value of pixel p in color channel c in image S_i^o;

γ is a gamma coefficient that transforms gamma-corrected values to linear color (we use 2.2 throughout).

We can simply leave the first image as it is, and correct the next one in relation to the first one, and so on. That is, the gain compensation coefficient for the first image is set to one, i.e.,

$$\alpha_{c,1} = 1 \quad c \in \{R, G, B\}. \tag{7}$$

To avoid cumulative errors, we want to adjust the color for each image as little as possible to avoid image saturation, and create the following objective function

$$\min_{g_c} \sum_{i}^{n} (g_c \alpha_{c,i} - 1)^2 \quad c \in \{R, G, B\} \tag{8}$$

where

g_c is a global compensation coefficient for color channel c;

n is number of images;

$\alpha_{c,i}$ is a correction coefficient for image i, channel c.

This is a quadratic function in the adjustment parameter g_c which can be solved in closed form by setting the derivative

Figure 3: Top: Input images with corrected colors. Middle: Simple merging with optimal cut and alpha blending. Bottom: Complex merging with optimal cut and Poisson blending.

to 0, yielding

$$g_c = \frac{\sum_{i=1}^{n} a_{c,i}}{\sum_{i=1}^{n} a_{c,i}^2} \quad c \in \{R, G, B\} \quad (i = 1, 2, \ldots, n) \tag{9}$$

With the correction coefficients, we perform color compensation for the whole image S_i. If we first undo gamma correction, apply a multiplicative correction, and then move back to gamma-corrected space, the operation is $(\alpha\ C_{c,i}^{\gamma})^{1/\gamma} = \alpha^{1/\gamma}\ C_{c,i}$, that is, it's enough to simply change the correction factor. Using this idea with both α_c's and g_c we get

$$C_{c,i}(p) \leftarrow (g_c \alpha_{c,i})^{\frac{1}{\gamma}} C_{c,i}(p) \quad c \in \{R, G, B\} \quad (i = 1, 2, \ldots, n) \tag{10}$$

where $C_{c,i}(p)$ is the color value of pixel p in image S_i in color channel $c \in \{R, G, B\}$.

The above description simply chooses the illumination level and color balance of the first image as the basis and modifies others. In practice we first analyze all the images, and choose the one with best color distribution as the basis, say image i, set $\alpha_{c,i} = 1$ (instead of $\alpha_{c,1}$), and calculate $\alpha_{c,j}$ with $j \neq i$, and g_c.

Figure 3 shows the results of color and luminance compensation for the images shown in Figure 1. The top row shows the color corrected source images and the middle figure shows the panoramic image created by the image stitching process with the color corrected images and a simple linear image blending described in Section 4. By comparing with the original result shown in Figure 1 we can see that the color differences between the two images are reduced and color transition in the panoramic image is smoothed. However, since the original source images are too different, the stitching artifacts can not be totally removed by the color correction and the simple blending process. Some differences across the seam can still be seen. In this case, more intensive image blending is required to remove the artifacts. Figure 3 (bottom) shows a panoramic image created by the stitching process with the color correction approach presented in this section and Poisson blending [9]. From the result we can see that all stitching artifacts are removed.

These two images come from an image sequence with 17 source images shown in Figure 4 (b). A panoramic image shown in Figure 4 (d) is created from the image sequence by the stitching process with the color correction approach. We can see that the approach performs a good color and luminance correction for the image sequence and makes seams between adjacent images minimally visible.

4. PANORAMA STITCHING

We stitch the images to a panoramic image by using the first image in a sequence as the base image, and add the rest one at a time. In order to stitch the current source image S_i onto the panoramic image I_c, we first perform color correction for S_i and find an optimal seam in the overlapping area between S_i and I_c, and then we cut the overlapping area along with the seam and merge the cut area and other parts of S_i onto I_c to update it.

After stitching the current source image S_i onto the panoramic image I_c, we input the next source image S_{i+1} as the current one and stitch it onto the updated panoramic image I_c. We repeat the process until all source images are stitched.

In order to further smooth the color transition between adjacent images, we perform a linear blending in the areas along the seams with a width δ in each side. Of course, we can also integrate other intensive image blending approaches into the stitching process, however, more computational and memory costs will be needed.

5. APPLICATIONS AND RESULT ANALYSIS

The proposed color and luminance compensation approach is implemented in a mobile panorama system for producing high-resolution panoramic images on mobile devices. In order to evaluate performance of the approach, we compare the results obtained by this approach with the ones obtained by the diagonal model [5] calculated in gamma-corrected sRGB. The approach has been tested in different scenes with different conditions. Good performance has been obtained for both indoor and outdoor scenes. In this section, we present some example applications and results which are obtained on Nokia N95 8GB mobile phones with an ARM 11 332 MHz processor and 128 MB RAM. It can also be run on other mobile devices. In these applications, the size of source images in image sequences is 1024×768.

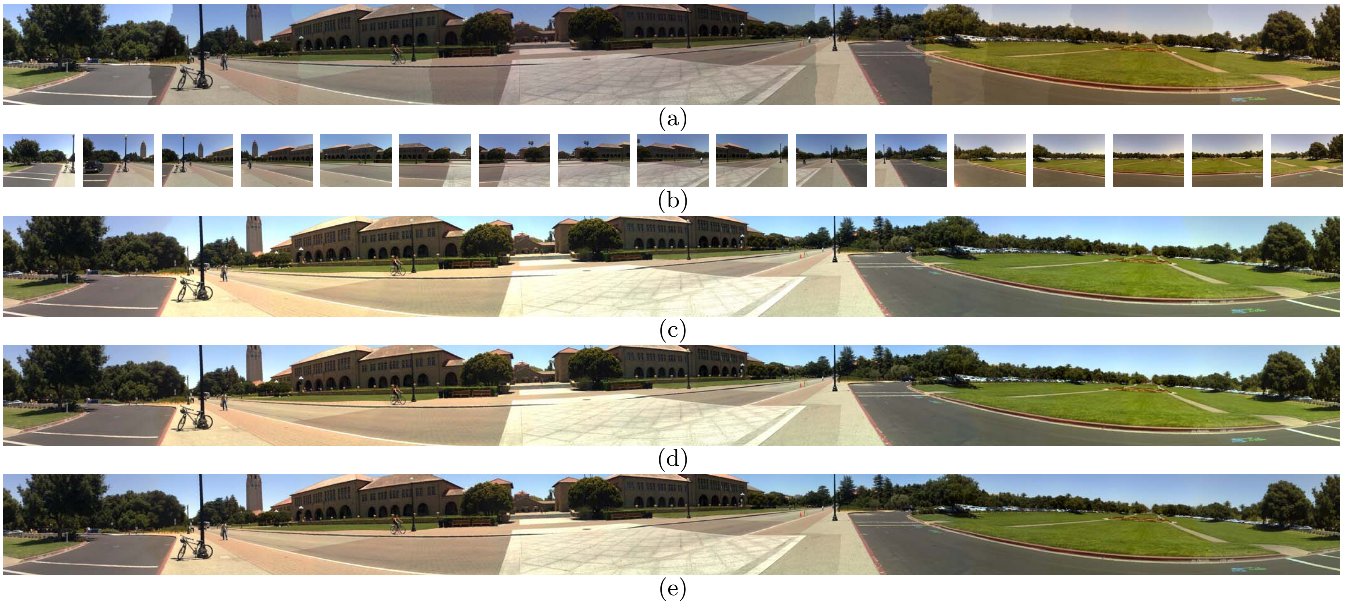


Figure 4: Panoramic images constructed with different color correction processes from 17 1024×768 images for an outdoor scene. (a) No color color correction. (b) Source images. (c) Correction factors calculated without considering gamma. (d) Correction factors calculated in linear RGB. (e) Linear RGB and global correction: our complete method.

5.1 Application to an outdoor scene

Figure 4 shows our stitching method applied to an outdoor scene. From the long image sequence with 17 source images shown in Figure 4 (b) we can see that the color and luminance of the source images are very different, especially between images 12 and 13. Figure 4 (a) shows the panoramic image constructed with the original source images. From the result we can see the seams between adjacent images clearly. The panoramic image is pretty unrealistic. A color and luminance compensation process is needed to construct good panoramic images.

Figure 4 (c) shows a panoramic image produced by the stitching process with color correction using the averages calculated in sRGB. Comparing with the original panorama shown in Figure 4 (a), we can see that the differences of color and luminance between the source images are reduced. However, the color changed too much, which makes the result still look unrealistic. During color and luminance correction, the pixels in the result image are easily saturated, which is the main reason for why the result looks unrealistic. Since there are cumulative errors during the color correction processing, the longer the image sequence is, the worse the result.

Figure 4 (e) shows the panoramic image constructed with the color and luminance compensation calculated in linear RGB, our method. From the result we can see that the color transition is more natural than in the result created with the diagonal model. The colors from left to right looks more reasonable than Figure 4 (c). Although the color in the sky changed a lot in the source image sequence, it is smoothed in the panoramic image and it does not change much from left to right, which expresses that the global adjustment functions well in the correction approach. Since gamma correction is taken into account when we computed the compensation coefficient for each source image, the properties of mapping function for color correction are much better than that of diagonal model and the pixel color values are not so easily saturated as when the direct sRGB values are used.

Figure 4 (d) shows the panoramic image constructed with our color and luminance compensation approach without global adjustment. By comparing with Figure 4 (c), pixels are not so easily saturated in areas such as the ground near the bicycle, the sky next to the light pole, and the sky near the tower, and so on, demonstrating that taking gamma correction should be taken into account during the calculations. By comparing with Figure 4 (e), both images are similar on the left side. However, the image in Figure 4 (d) becomes brighter from left to right which is caused by the accumulative errors. These errors are corrected in the image in Figure 4 (e) by the global adjustment process.

5.2 Application to an indoor scene

An application for an indoor scene is shown in Figure 5. The original image sequence is shown in Figure 5 (c). From the image sequence we can see that the colors and luminances between adjacent images are different, especially between the third and fourth, as well as between the fifth and sixth images. First, we stitch the source images together without the color and luminance compensation process to created a panoramic image shown in Figure 5 (a). From the result we can see that artificial edges can be seen between adjacent images due to the differences of color and luminance.

Then, we stitch the source images together with the color and luminance compensation process proposed in this paper to create a panoramic image shown in Figure 5 (b). From the result we can see that the artificial edges between adjacent images are removed. The differences between source images are smoothed. From the results we can see that the approach

(a)

(b)

(c)

Figure 5: Panoramic images produced with 7 1024×768 source images in an indoor scene before and after color and luminance compensation, respectively.

works well for color and luminance correction.

5.3 More comparisons to other approaches

We perform more comparisons with stitching results obtained by running several approaches on mobile phones. Figure 6 shows an example. The image sequence is shown in Figure 6 (d). There are 11 source images in this image sequence. The colors and luminances between these images are very different. This is a difficult case for panorama stitching. Figure 6 (a) shows the panoramic image created by the image stitching process using the diagonal model described at the beginning of Section 3. Again, from the result we can see that pixels can be easily saturated, such as the sidewalk of the fountain, the water in the center, the sky close to the fountain, the road in front of the building, and so on. On the other hand, from the result created by the stitching process with our color correction approach shown in Figure 6 (c) we can see that these saturating problems are solved. More details and textures can be seen on the sidewalk of the fountain, the road in front of the building, the sky, the water of the fountain. The color of the building is more natural. This is the main advantage of our approach by performing color correction using linearized RGB values and using the global adjustment to reduce cumulative errors in the color correction process. Figure 6 (b) shows the result produced by the stitching process with Poisson blending [9] and the source images without color correction. By comparing Figure 6 (c) with Figure 6 (b) we can see that the visual quality of these two images is similar, except that the sky in the Figure 6 (b) is little bit darker that in the Figure 6 (c). However, the computational cost of the color correction approach is much less that that of the Poisson blending approach. The color correction approach is much faster in the stitching process. According to our tests, the longer the image sequences are, the more important it is to use the global adjustment term, especially with 360° panoramic images.

We present further examples in Figure 7 to show that the approach works well for image sequences with very different color and luminance between source images. All of these results are obtained by running the approach on a Nokia N95 8GB mobile phone. Figures 7 (a) and (b) show panoramic images created on sunny days. Due to the differences of the sunshine and view angles of the camera, the color and luminance of source images in the image sequences are very different. The approach can correct the differences and produce reasonable panoramic images. Figure 7 (c) shows the panoramic image created in the evening. The colors and luminances in source images are very different, yet the approach still creates a satisfying panoramic image.

6. CONCLUSIONS AND DISCUSSION

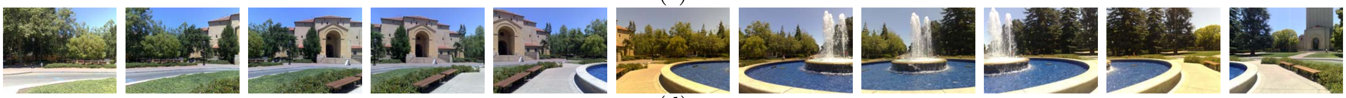
In this paper, we presented a simple and efficient approach of color and luminance compensation for image sequences and implemented it to produce high-resolution and high-quality panoramic images on mobile devices. By comparing with the approach that calculates averages of gamma-corrected sRGB values, we have shown the importance of operating in linear RGB instead. The global operation can adjust color and luminance in the whole panoramic image, making the changes in each image as small as possible and reducing cumulative errors in the color correction process.

The approach shows good performance in both indoor and

(a)

(b)

(c)



(d)

Figure 6: Panoramic images constructed with different approaches from 11 1024×768 source images for an outdoor scene.

(a)

(b)

(c)

Figure 7: More panoramic images created with our algorithm.

outdoor scenes. It always tries to keep balance of color and luminance in the whole panoramic image. The approach works well for both long and short image sequences.

By integrating a sequential panorama stitching procedure with the color correction approach, we can create high-resolution and high-quality panoramic images. The approach is simple and robust, and has been implemented on a mobile phone, and it has produced good results with many different scenes and different illumination conditions.

7. REFERENCES

[1] Gabriel Takacs, Vijay Chandrasekhar, Natasha Gelfand, Yingen Xiong, Wei-Chao Chen, Thanos Bismpigiannis, Radek Grzeszczuk, Kari Pulli, and Bernd Girod, "Outdoors augmented reality on mobile phone using loxel-based visual feature organization," in *MIR '08: Proceeding of the 1st ACM international conference on Multimedia information retrieval*, New York, NY, USA, 2008, pp. 427–434, ACM.

[2] David Chen, Sam S. Tsai, Vijay Chandrasekhar, Gabriel Takacs, Jatinder Singh, and Bernd Girod, "Robust image retrieval using multiview scalable vocabulary trees," in *Visual Communications and Image Processing 2009*, Majid Rabbani and Robert L. Stevenson, Eds. 2009, vol. 7257, p. 72570V, SPIE.

[3] B. Pham and G. Pringle, "Color correction for an image sequence," *Computer Graphics and Applications, IEEE*, vol. 15, no. 3, pp. 38–42, May 1995.

[4] Zhang Maojun, Xie Jingni, Li Yunhao, and Wu Defeng, "Color histogram correction for panoramic images," in *Virtual Systems and Multimedia, 2001. Proceedings. Seventh International Conference on*, 2001, pp. 328–331.

[5] Gui Yun Tian, D. Gledhill, D. Taylor, and D. Clarke, "Colour correction for panoramic imaging," in *Information Visualisation, 2002. Proceedings. Sixth International Conference on*, 2002, pp. 483–488.

[6] Seong Jong Ha, Hyung Koo, Sang Hwa Lee, Nam Ik Cho, and Soo Kyun Kim, "Panorama mosaic optimization for mobile camera systems," *Consumer Electronics, IEEE Transactions on*, vol. 53, no. 4, pp. 1217–1225, Nov. 2007.

[7] M. Brown and D. G. Lowe, "Automatic Panoramic Image Stitching using Invariant Features," in *International Journal of Computer Vision*, 2006, vol. 74, no. 1, pp. 59–73.

[8] Laurent Meunier and Moritz Borgmann, "High-resolution panoramas using image mosaicing," in *http://scien.stanford.edu/class/ee368/projects2000/project13/* , Stanford, 2000, Stanford.

[9] Yingen Xiong and Kari Pulli, "Gradient domain image blending and implementation on mobile devices," in *MobiCase'09: Proceedings of The First Annual International Conference on Mobile Computing, Applications, and Services*, San Diego, CA, USA, 2009, Springer-Verlag New York, Inc.