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Fast and High-Quality Image Blending on Mobile Phones

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***Abstract*—We present a fast and high-quality image stitching approach for creating high-resolution and high-quality panoramic images on mobile devices. In the approach, a sequential panorama stitching procedure is created with color and luminance compensation for reducing differences between source images, fast image labeling for optimal seam finding, and gradient domain image blending for transition smoothing. The color and luminance compensation is performed in the gamma-corrected sRGB color space to avoid pixel saturation problems, optimal seams between adjacent source images are found by dynamic programming optimization for fast speed and less memory, and the source images are blended together by Poisson blending for a high blending quality. We compare results and performance with other approaches to demonstrate the advantages of our approach in mobile panorama applications.**

The main contribution of this work is studying how applying color and luminance compensation before Poisson blending improves the blending quality and processing speed of Poisson blending in long image sequences where colors and luminance vary between source images, and how it also improves the quality of image labeling. The integration of color correction, fast labeling, and Poisson blending into a sequential panorama stitching procedure allows creation of high-resolution panoramic images with large source images more quickly and using less memory. These are very important aspects for mobile devices that have limited computational power and memory resources.

I. Introduction

A panoramic image is constructed from an image sequence. Images are taken one by one with some overlapping areas between neighboring images. These overlapping areas are used to register the images so that they can be stitched into a panoramic image that covers a much wider view than each separate image. Image stitching is a very important step in creating panoramas. A simple copying and pasting of overlapping images into the final panorama produces visible artifacts in the seams due to changes of scene illumination and camera responses or spatial alignment errors.

The objective of an image stitching approach is to find optimal seams in overlapping areas of source images, merge them along with the optimal seams, and make merging artifacts invisible. We are interested in creating high-resolution and high-quality panoramic images on mobile devices. A user can capture an image sequence for a wide range of scenes with a camera phone and see a panoramic image created with the image sequence for the scenes on the phone immediately. This can provide a convenient application for mobile devices.

A. Background

As mobile phones evolve into capable computational devices equipped with high-resolution cameras and high-quality color displays, mobile image processing and mobile computational photography become more and more interesting. Many applications which could only work on computers before can now be implemented and run on mobile phones. We are building high-resolution and high-quality panoramic images on mobile devices to provide users a convenient and useful application. However, the panorama construction process requires a lot of computation. Compared with computers, mobile devices only have limited computational resources. Processing speed and memory are much lower than that of computers.

We are interested in developing a fast and high-quality image blending approach which is capable of combining a set of registered images into a composite using relatively little computation and memory, so that it can be applied on mobile devices for creating high-resolution and high-quality panoramic images.

B. Related Work

Transition smoothing and optimal seam finding are two main categories of existing methods for image stitching. Transition smoothing algorithms reduce color differences between source images for hiding seams. Recently, gradient domain image blending approaches [1], [2], [3], [4], [5] have been applied to image stitching and editing. In such algorithms, a new gradient vector field is created with combination of source image gradients, and a composite image can be recovered from the new gradient vector field by solving a Poisson equation with boundary conditions. These algorithms can adjust color differences due to illumination changes and variations in camera gains for the composite image globally, and they can produce high-quality composite images. However, memory and computational costs are high. It is difficult to process high-resolution images on mobile devices that have limited resources. Optimal seam finding algorithms [6], [7], [8], [1], [9] search for an optimal seam in the overlapping area where differences between source images are minimal. Labels for all pixels of the composite image can be created according to the optimal seam. The composite image is produced by copying corresponding pixels from the source images using labeling information.

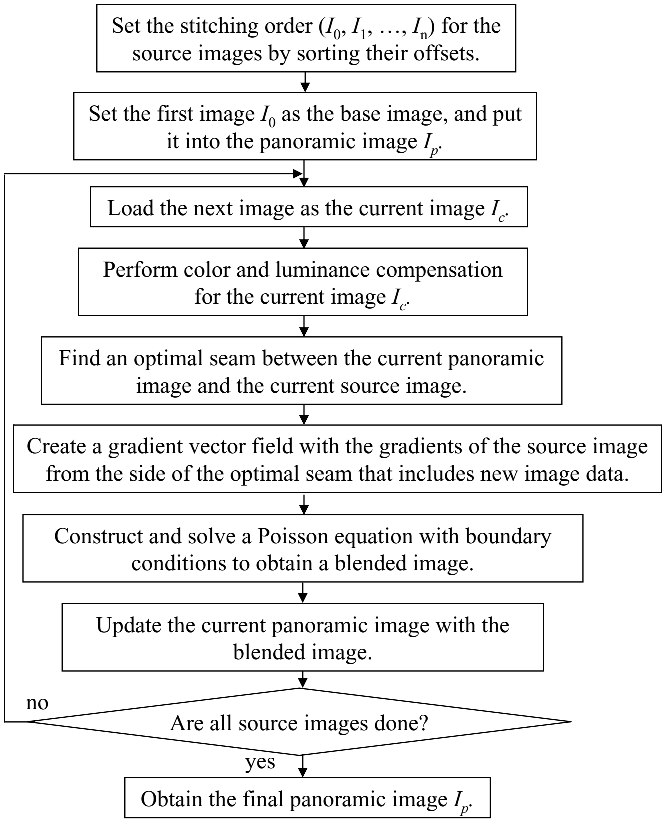

Fig. 1. Work flow of the fast and high-quality image blending approach for creating panoramic images.

In this paper, we develop a fast and high-quality image blending approach based on our previous work in color correction [10], fast labeling [11], and gradient domain image blending [12] for creating high-quality and high-resolution panoramic images on mobile devices. We focus on integrating the color correction, fast labeling, and Poisson blending processes into a sequential panorama stitching procedure, improving the blending quality and processing speed of Poisson blending with color and luminance compensation in applications of long image sequences with very different colors and luminance between the source images, improving the quality of image labeling with color correction. We compare results and performance with graph cut and Poisson blending approaches to show advantages of the proposed approach. We implement our method in a mobile panorama imaging system. Good performance has been obtained in tests and applications for both indoor and outdoor scenes.

C. Organization of the Paper

In Section II, we introduce the work flow of our approach. The details of the fast and high-quality image blending approach for producing mobile panoramic images are described in Section III. Applications and result analysis are discussed in Section IV. A summary of the paper is given in Section V.

II. Summary of Our Approach

Figure 1 shows details of the sequential panorama stitching procedure with the fast and high-quality image blending approach which includes color correction, optimal seam finding, and transition smoothing processes. The procedure starts with setting the stitching order $(I_0, I_1, \ldots, I_n)$ of the source images in the image sequence by sorting their offsets.

After allocating memory space for the composite image I_p, we put the first image I_0 into the composite image as the base image. We continue the stitching process by inputting the next source image as the current image I_c. We perform color and luminance compensation in the gamma-corrected RGB color space for the current image to reduce the color differences between images I_c and I_p. After locating the overlapping area between the current composite image I_p and the current image I_c, we find an optimal seam with dynamic programming optimization in the overlapping area and create labeling with the optimal seam information. A gradient vector field is created with the gradients of images in the overlapping area and the gradients of the rest of the current source image. A blended image can be recovered from the gradient vector field by constructing and solving a Poisson equation with boundary conditions. We update the current composite image I_p with the blended image. We load the next source image to replace the current source image I_c to continue the panorama stitching process. Once all source images are processed, we obtain the final panoramic image I_p.

In practice, at the beginning of the image stitching process, we find the image with the best color and luminance distribution and use its colors and luminances as is for the first source image. In this way, we can make the stitching process roughly independent of stitching directions.

During panorama stitching, we only need to keep the current source image I_c and the composite image I_p in memory, which enables us to process large images with limited computational resources in our mobile panorama system.

III. Fast Image Stitching

Our approach combines optimal seam finding and transition smoothing processes to create panoramic images. During image stitching, dynamic programming is used for optimal seam finding, Poisson blending for transition smoothing, and color correction to speed up the blending process and to improve qualities of seam finding and image blending. Here, we explain these processes in detail.

Changes in camera responses and scene illumination in different view angles of the camera lead to differences in color and luminance of the captured images. Artifacts in the overlapping areas of the images may be created during panorama stitching. It is necessary to perform color and luminance compensation for the source images to reduce the differences to make image blending simple.

In an image sequence $I_0, I_1, \ldots, I_i, \ldots, I_n$, I_{i-1} and I_i are adjacent images. I^o_{i-1} and I^o_i contain the image data in the overlapping area between the two adjacent images. We compute a color correction coefficient for image I_i in the gamma-corrected sRGB color space as

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

where $P_{c,i}(p)$ is the color value of pixel p in color channel c in image I_i^o; γ is a gamma coefficient. Usually we set $\gamma = 2.2$. For the first image I_0, we set $\alpha_{c,0}$ to 1.

To avoid cumulative errors, we perform a global adjustment for color and luminance in the whole image sequence,

$$\min_{g_c} \sum_{i=0}^{n} (g_c \alpha_{c,i} - 1)^2, \quad c \in \{R, G, B\}, \tag{2}$$

where g_c is a global compensation factor for color channel c.

With the correction coefficients and the global compensation factor, we can perform color compensation for image I_i,

$$P_{c,i}(p) \leftarrow (g_c \alpha_{c,i})^{\frac{1}{\gamma}} P_{c,i}(p), \;\; c \in \{R, G, B\} \;\; (i = 0, 1, \ldots, n) \tag{3}$$

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

In order to set a good basis for the color correction process, we search for an image I_b which has the best color and luminance distribution in the image sequence and use it to adjust the color and luminance of the first image I_0. By this way, we can make the color correction process roughly independent of stitching directions.

We want to merge two adjacent images together along with a seam where the differences between these two images are minimal. This way we avoid stitching images where the objects have real or apparent (due to parallax) motion between images. We apply dynamic programming to find an optimal seam between the two images and merge them together.

Suppose I_p^o and I_c^o are images in the overlapping area between the current panoramic image I_p and the current source image I_c. We compute a squared difference s between I_p^o and I_c^o as an error surface,

$$s = (I_p^o - I_c^o)^2. \tag{4}$$

We find the minimal cost path through the surface by scanning it row by row and computing a cumulative minimum squared difference S for all paths,

$$\begin{aligned} &S(r, c) = s(r, c) \\ &+ \min(S(r-1, c-1), S(r-1, c), S(r-1, c+1)) \end{aligned} \tag{5}$$

where $r = 2, \ldots, n_r$ and $c = 2, \ldots, n_c$ are the indices of the row and column of the error surface respectively. The optimal path can be obtained by tracing back the paths with a minimal cost from bottom to top by dynamic programming. We use it as an optimal seam to merge the two images and create labeling.

When the adjacent images are too different for the optimal seam finding process to find an ideal seam, stitching artifacts might still be visible. In this case, a transition smoothing process is needed to reduce the differences between source images and remove the artifacts. In our approach, we use Poisson blending for transition smoothing.

Since the source images are already processed by color correction, the differences between them are reduced, which can make blending easy and speed up the blending process.

In Poisson blending, we create a gradient vector field (G_x, G_y) with gradients of source images. In the sequential image stitching procedure, the gradient vector field is created with gradients of overlapping images between the current panoramic image I_p and the current source image I_c and the rest of gradients of the current source image I_c. A divergence vector field can be computed from the gradient vector field,

$$div(G) = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}. \tag{6}$$

We use the divergence vector as a guidance to construct a Poisson equation

$$\nabla^2 I(x, y) = div(G), \tag{7}$$

where ∇^2 is the Laplacian operator

$$\nabla^2 I(x, y) = \frac{\partial^2 I(x, y)}{\partial x^2} + \frac{\partial^2 I(x, y)}{\partial y^2}. \tag{8}$$

Equation 7 is a linear partial differential equation. In order to solve this equation, we use the Neumann boundary conditions and to use its discretized form:

$$\begin{aligned} &I(x+1, y) + I(x-1, y) + I(x, y+1) + I(x, y-1) - 4I(x, y) \\ &= G_x(x, y) - G_x(x-1, y) + G_y(x, y) - G_y(x, y-1). \end{aligned} \tag{9}$$

IV. Applications and Result Analysis

The fast image stitching procedure is implemented in our mobile panorama system for creating high-resolution and high-quality panoramic images. In order to evaluate its performance, we also implemented a commonly used stitching approach which applies graph cut and Poisson blending globally over the whole image sequence [12]. We compare the results and performance of the two stitching approaches to demonstrate the advantages of the fast stitching approach in processing speed and memory consumption which are very important for mobile applications. Good performance has been obtained with both indoor and outdoor scenes. In this section, we present some example applications and results which are obtained by running the approach on Nokia N95 8GB mobile phone 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. We have also tested it with larger source images. The results are satisfying.

A. *Applications of color correction*

We have tested the effect of color correction to the optimal seam finding process. Figure 2 shows one of the results. Figure 2 shows a short image sequence with three source images with very different colors and luminance and moving objects in the scene. Figure 2 top row shows the panoramic images created without and with color correction processing. From the results we can see that the optimal seams are different in these two

Fig. 2. Effect of color correction to optimal seam finding.

Fig. 3. Effect of color correction to image blending quality.

cases. According to our tests, the seams found with the color correction process are better than the ones without the color correction process. After color correction, the optimal seam finding process can find corresponding pixels which have real minimal differences as seams. Our conclusion is that color correction can improve the quality of optimal seam finding.

We have also tested the effect of color correction to the quality of image blending. Figure 3 shows one of the results. There are three source images with very different colors and luminance in the image sequence shown in Figure 3, especially between the first and the second images. Figure 3 top row shows panoramic images by Poisson blending without and with color correction processing. To compare the results, we set the iteration number to 20 for the Poisson solver for both cases in the test. From the results we can see that the color transition of Figure 3 top right is much better than Figure 3 top left. The image blending with color correction processing has higher quality. According to our tests, the longer the image sequences, the more important is the color correction. Our conclusion is that color correction can improve image blending quality, especially for long image sequences.

B. Applications to long image sequences

We compare results and performance obtained from the fast blending approach proposed in this paper and the global image blending approach [12]. Figure 4 shows some results.

First, we compare the optimal seam finding processes in both approaches. Figure 4 (a) shows the optimal seams created by graph cut optimization in the global blending approach, seam finding takes 531.2 seconds. Figure 4 (b) shows the optimal seams created by dynamic programming in the fast blending approach, seam finding only takes 6.56 seconds. The latter one is about 81 times faster than the previous. According to our tests, the longer the image sequences, the bigger the time savings of the proposed approach is. Further, the graph cut approach needs to keep all source images in memory to find all optimal seams for the whole image sequence at the same time, while our method only needs to keep one source image in memory. In this way, we can process larger and greater number of source images to create high-resolution panoramic images on devices with limited amount of RAM, such as mobile phones. Both approaches can find proper seams to avoid ghosting problems.

Then, we compare the whole image stitching process. In the global image blending approach, the stitching process includes labeling and Poisson blending. The approach uses global blending process. All source images are kept in memory and a global optimal solution is found by solving a Poisson equation with boundary conditions. Figure 4 (c) shows the panoramic image created by the stitching process. It takes 675.56 seconds. Figure 4 (d) shows the result obtain by the fast blending approach which includes color correction, optimal seam finding, and Poisson blending. As described in previous section, these processes are integrated in a sequential stitching procedure that only needs to keep one source image in memory during stitching. The stitching process takes 67.48 seconds. The fast blending approach is about 10 times faster than the global image blending approach. From the images (c) and (d) we can see that the color transition in image (d) is better than in image (c). The visual quality of image (d) is also better. Our conclusion is that color correction can improve the quality of panorama stitching and speed up the stitching process. The longer the image sequences, the more important is the color correction processing.

Figure 5 shows an application of the fast stitching approach to a long image sequence captured in an indoor scene. From the result we can see that the fast blending approach also works well for indoor scenes.

V. Conclusions and Discussion

We presented a fast and high-quality image blending approach and implemented it in a mobile panorama imaging system for creating high-resolution and high-quality panoramic images on mobile devices. The approach integrates color correction, fast labeling, and gradient domain image blending into a sequential panorama stitching procedure for creating panoramic images on systems with limited memory resources. It uses color and luminance compensation to improve the blending quality and reduce computational iterations of Poisson blending and to improve the quality of optimal seam finding. According to our tests, the combination of Poisson blending with color correction has a higher blending quality and the optimal seam finding process can find better seams with color corrected source images.

We compared the results and performance with other approaches in applications for long image sequences with very different colors and luminance between the source images. For the application of an image sequence with 13 source images, the proposed approach is about 10 times faster and the color

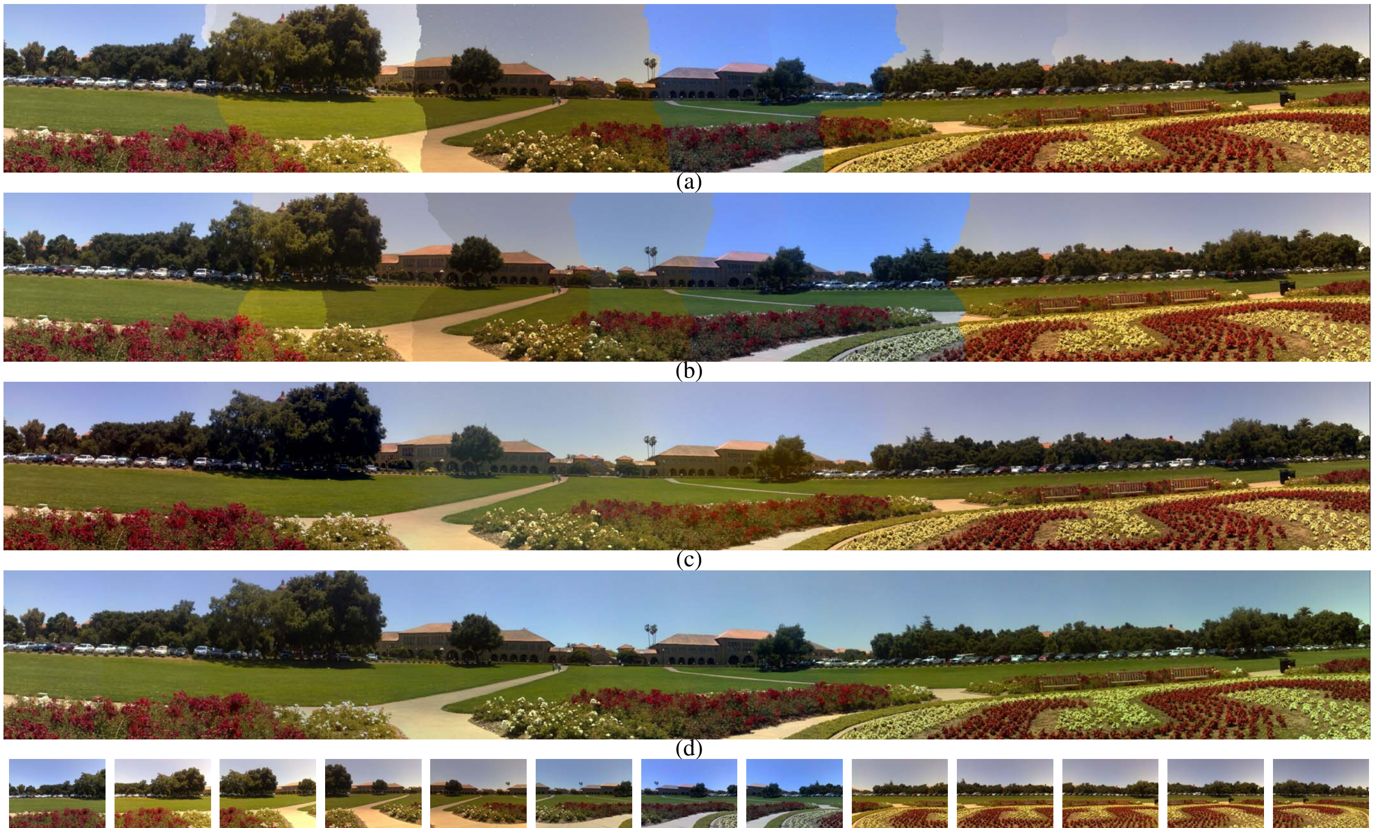

Fig. 4. Comparison of panoramic images produced by different approaches with 13 1024×768 images with very different colors and luminance.

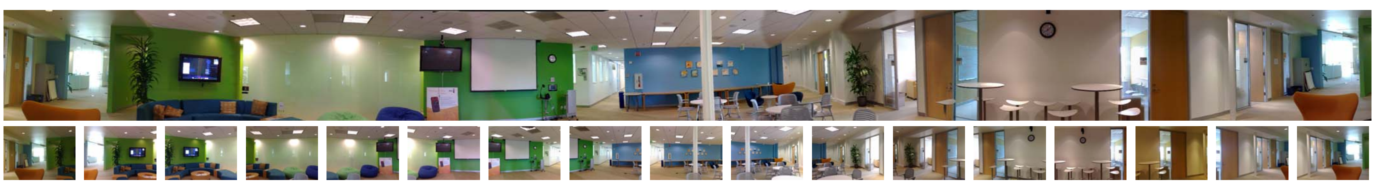

Fig. 5. A panoramic image created by the fast stitching approach with 17 1024×768 images.

transition of the result image is better. Our tests also show that the longer the image sequences, the more important is the color correction processing.

The approach has been tested and applied to different image sequences. Good performance has been obtained in both indoor and outdoor scenes.

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