Improved Resolution Synthesis for Image Interpolation[1]

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Abstract

The Resolution Synthesis algorithm (ResSynth or RS) is an image interpolation algorithm which computes the minimum mean-squared error estimate of the high-resolution image, given the low-resolution image. ResSynth produces sharper images than the commonly used Bilinear and Bicubic interpolation; and it is computationally efficient. However, the original ResSynth algorithm has some deficiencies, which are: 1) it tends to aggravate noise and JPEG artifacts in the image; 2) it produces halos around strong edges in the image; 3) it occasionally generates "color sprinkles" - pixel errors around the edges. To overcome these problems, we developed the New ResSynth algorithm based on the original algorithm. New ResSynth significantly improves the quality of the interpolated images.

Introduction

Interpolation is the process of estimating the intermediate values of a continuous event from discrete samples [1]. Image interpolation is a fundamental image processing operation. It is used to enhance the resolution of an image, or simply put, scale up an image. It is widely adopted in printers, cameras, scanners, as well as image processing softwares, etc. The booming of digital technologies has made the demand for premium quality interpolation algorithms higher than ever. However sharpness of edges and freedom from artifacts remain the two main challenges for interpolation algorithms. Interpolated images are prone to blurry edges, lack of detail, and aggravated artifacts. Computational efficiency is also an important consideration in image interpolation.

Many interpolation algorithms have been proposed over the years. There are two major categories of interpolation algorithms: the linear filtering approach and the non-linear filtering approach. In linear filtering approach, the interpolated image is a linear function of the original sampling data. The key element is the interpolation kernel function, which is used to approximate the missing high resolution image data. The best known linear-filtering interpolation kernel functions are the family of B-spline functions [2] and the cubic convolution function [1]. The zeroth order B-spline (also known as pixel replication or nearest neighbors) and first order B-spline (Bilinear) interpolations are both very efficient algorithms, but the interpolated images appear blocky and/or blurry. The cubic B-spline significantly improves the image quality, at the expense of increased computation. The cubic convolution algorithm is a variation of the cubic B-spline interpolator. It is a very popular interpolation algorithm because of its relatively high quality and reasonable efficiency. Since the linear filtering approach in general is not good at edge and detail rendering, many non-linear interpolation algorithms have been developed in recent years. These algorithms adopt locally adaptive filtering to render sharper images. One approach in the non-linear category is the edge-directed interpolation [3, 4, 5]. Edge information is extracted from the image and used to guide interpolation, for instance, to avoid averaging across edges. Another approach is the model-based interpolation method [6, 7]. These algorithms employ stochastic models for the image data, and estimate optimal high resolution image data or optimal interpolation filters with a well-defined cost function.

[1] Research supported by the Hewlett-Packard Company

The goal of our paper is to improve an existing algorithm which belongs to the model based non-linear interpolation method–the ResSynth algorithm [6, 8, 9, 10, 11]. Compared with Bicubic interpolation (the best quality interpolation method in Photoshop 6.0, which adopts the cubic convolution algorithm), ResSynth produces significantly sharper edges and better textures and detail.

The structure of this paper is as follows. In the remainder of this section, we will introduce the ResSynth algorithm, and then point out the major deficiencies in ResSynth. In the next three sections, we will cover our solutions to these problems, i.e. the New ResSynth algorithm, the results, and the conclusions of our research. In the results section, we present interpolation results from New ResSynth, along with those from ResSynth for comparison.

What is Resolution Synthesis (ResSynth)

ResSynth computes the minimum mean squared error (MMSE) estimate of the high resolution image, given the low resolution image. It employs a multivariate Gaussian mixture model for the image data. It works by first classifying the pixel being interpolated based on a local activity measure computed from the image data in a window centered at this pixel, and then applying interpolation filters that are optimized for the selected class. Classification is done by computing probabilities of class membership in a Gaussian mixture model. The parameters for the classification and interpolation filters are obtained by an off-line training procedure using the expectation-maximization (EM) algorithm. For details of this algorithm, please refer to [6].

Instead of using a fixed interpolation function at each pixel, ResSynth filters are locally adaptive and optimized. Thus ResSynth is able to render significantly sharper edges and better detail than the popular Bilinear and Bicubic interpolation algorithms [6]. ResSynth can interpolate images for any integer factors. However, since it is primarily used for $2\times$ interpolation, i.e. double size in both dimensions, we will focus on $2\times$ interpolation as well.

The Problems of ResSynth

Despite its advantages, ResSynth has some major deficiencies: 1. it produces halo around edges; 2. it tends to aggravate noise and JPEG artifacts; 3. it occasionally produces color sprinkles–isolated pixel errors near edges. Halo and aggravated artifacts are commonly seen in many interpolation algorithms. Figure 3 (b), Figure 3 (d), Figure 4 (b), and Figure 5 (b) are examples illustrating the aforementioned deficiencies.

The Solution - New ResSynth

To overcome these deficiencies, we developed the New ResSynth algorithm based on the original algorithm. Our objectives are: 1. remove halos and color sprinkles; 2. reduce noise and JPEG artifacts; 3. at the same time, it is very important that New ResSynth should preserve, as much as possible, the image sharpness in ResSynth. This makes it a challenging problem to solve. The traditional way to reduce noise is using a low pass filter, such as a Gaussian filter. However we find that with a sufficient amount of filtering to reduce the noise to an acceptable level, the images are significantly blurred. Moreover low pass filters are not very effective at removing halos and JPEG artifacts. Another challenge in solving this problem lies in the efficiency requirement. Any significant increase of computation time is undesirable. With these goals and requirements in mind, we solve the problems in ResSynth with three major procedures. We denote the modified ResSynth algorithm as New ResSynth.

First, we use a new strategy to generate training images, and re-train the filter parameters with the new training image data. The original cluster parameters and filter parameters are trained with a set of low resolution images and the corresponding high resolution images. The low resolution images are obtained by block-averaging the original high resolution images. The high resolution training images are the original high resolution images sharpened with an unsharp mask filter before training. This training strategy leads to interpolation filters with a built-in sharpening effect. It produces sharp interpolated images. On the other hand, it aggravates artifacts and makes the images look noisy. Our new training strategy uses JPEG-compressed low resolution images and the corresponding high resolution original images as the training images. As a result, the new interpolation filters generate images that are not only less noisy, but also have fewer JPEG artifacts. The interpolation filters are trained to suppress JPEG artifacts. The greater the amount of JPEG compression applied to the low resolution images, the smoother the interpolated images are. After experimenting with many different settings of the training images, we choose to apply Photoshop JPEG compression level 7, for the best balance among sharpness, noise, and JPEG artifacts. The idea of training with JPEG compressed images was first described in [6].

However, after the first step, the halo problem still exists. By manipulating with the training strategy itself, we cannot get images that are both sufficiently sharp and halo-free, since filters trained on natural images tend to produce overshoot and undershoot at the edges to create an impression of sharpness, which causes halo. Therefore, as the second step, we add a constraint to fundamentally remove halos. Considering that in natural images, there should not be any overshoot or undershoot, we prescribe that no interpolated pixel value can exceed the maximal and minimal value of its 3×3 low resolution neighborhood. This procedure effectively eliminates halos. It is illustrated with Fig. 1.

Finally, as the third step, median filtering is applied to the interpolated pixels to clean up color sprinkles. The median filter is known for its effectiveness in removing outliers. However, a conventional square mask median filter, as shown in Fig. 2 (a), erodes corners, which leads to noticeable artifacts for text/graphics. Therefore, we use a cross mask median filter, as shown in Fig. 2 (b). It has two advantages over the conventional median filter: first, it preserves corners; second, it requires less computation. Suppose that the current low resolution pixel is L[0,0], after interpolation, four high resolution pixels are generated: H[0,0], H[0,1], H[1,0], and H[1,1]. Median filter is then applied to high resolution pixels H[-1,0], H[-1,1], H[0,-1], and H[0,0]. (Note that H[-1,0], H[-1,1], and H[0,-1] are generated by previous low resolution pixels.) This makes each high resolution pixel be median-filtered once and only once, in a causal manner.

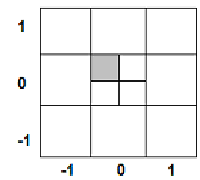
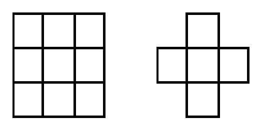


Figure 1. *Halo removal: when the current low resolution pixel L[0,0] is interpolated into high resolution pixels, each high resolution pixel is clipped to the maximal (or minimal) pixel values in the 3×3 low resolution neighborhood centered at L[0,0], if it exceeds the maximum (or minimum).*



(a) (b)

Figure 2. *Median filter masks (a) The square-shaped mask of a median filter (b) The cross-shaped mask used in New ResSynth*

The Results

The results of New ResSynth are shown in the next several figures[2]. First we compare ResSynth with New ResSynth for the problematic images demonstrated earlier. In Fig. 3, (a) is the original image. (b) is the result from interpolating 2× by ResSynth. As we can see, there are opponent color halos around the edges of the text. (c) is the result from New ResSynth. New ResSynth has removed the opponent color halo that appears in (b). Because of the new training strategy, New ResSynth also suppresses background noise. (b) also contains color sprinkles, but they are difficult to detect here because the halos dominate the perception. After the halos in (b) are removed by the halo-removal procedure described in the previous section, the color sprinkles become more noticeable. For instance, Fig. 3 (d) is the close-up of the upper stroke of the green letter "C" after halo-removal, but before median filtering. We can see some green pixels near the green edges on the brown background. This is an example of "color sprinkles". Figure 3 (e) shows the result from New ResSynth, i.e. (d) after cross-mask median filtering. Color sprinkles are removed. In Fig. 4, (a) is the original image, (b) is the result of interpolating (a) 2× by ResSynth. The noise in the face area becomes quite objectionable. (c) is the result from New ResSynth. New ResSynth

[2] Figures in the PDF file may contain artifacts introduced by the PDF converter. For best comparison of the results, please refer to the hard copy of this paper in the conference proceedings or contact the author (bz@purdue.edu) for the PS version of the paper.

significantly reduces noise in the interpolated image. In Fig. 5, (a) is the original image, (b) is the result of interpolating (a) 2× by ResSynth. JPEG artifacts in the image are aggravated in (b). (c) is the result from New ResSynth. JPEG artifacts are significantly reduced. For instance, look at the areas around the red characters on the yellow background, in the upper body of the woman, around the face of the man, etc. Overall, New ResSynth produces much cleaner images with less noise and fewer JPEG artifacts.

Finally, let us take a look at the edges rendered by New ResSynth and ResSynth. As mentioned earlier, it is important that New ResSynth do not significantly compromise edge sharpness in an attempt to reduce noise and JPEG artifacts. Figure 6 contains close-up edges interpolated by ResSynth and New ResSynth, shown in (b) and (c) respectively. There are less halo and noise around the edges in (c); while the edges in (c) are as crisp as those in (b). The smooth areas in (c) are also less noisy.

Conclusions

In this paper, we describe the deficiencies in the original resolution synthesis algorithm–ResSynth. To solve these problems, we modified ResSynth with three major procedures. Detailed accounts of these procedures are given. We show that this New ResSynth algorithm has successfully removed halo, reduced noise and JPEG artifacts in the interpolated images, while preserving edge crispness and details. New ResSynth demonstrates a significant improvement of image quality over ResSynth for a wide range of images, including both pictorial images and text/graphic images.

Acknowledgments

The authors would like to thank Dr. C. Brian Atkins for his valuable help during the course of this research work.

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