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Technical Section

On pixel-based texture synthesis by non-parametric sampling

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Abstract

In this paper, we propose a pixel-based method for texture synthesis with non-parametric sampling. On top of the general framework of pixel-based approaches, our method has three distinguishing features: window size estimation, seed point planting, and iterative refinement. The size of a window is estimated to capture the structural components of the dominant scale embedded in the texture sample. To guide the pixel sampling process at the initial iteration, a grid of seed points are sampled from the example texture. Finally, an iterative refinement scheme is adopted to diffuse the non-stationarity artifact over the entire texture. Our objective is to enhance texture quality as much as possible with a minor sacrifice in efficiency in order to support our conjecture that the pixel-based approach would yield high quality images.
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1. Introduction

Texture synthesis by example has recently been investigated extensively in computer vision and computer graphics. This problem is stated as follows: Given a texture sample, synthesize a (tilable) new texture of an arbitrary size such that it is perceptually similar to the texture sample. The notion of perceptual similarity is well explained in [1,2]. Rich results have been reported as solutions to the texture synthesis problem [2–7]. In particular, pixel-based, non-parametric methods [1–3] have drawn much attention.

Relying on a simple strategy of copying one pixel at a time, these techniques have demonstrated their surprising capability of synthesizing a wide variety of high quality textures ranging from regular to stochastic. However, resulting textures have sometimes shown visual artifacts such as "blurring" and "garbage growing" [1–3]. That is, a pixel-based method has a tendency to blur features or to grow small-scale structures in synthesized textures. As pointed out in [8], such a method also suffers from heavy searching time in sampling the pixel values from the input sample texture.

To remedy those drawbacks in both texture quality and time efficiency, patch-based methods have been proposed [4,6,8]. Unlike pixel-based methods, patch-based methods copy a patch of pixels at a time to show real-time performance in texture synthesis. Moreover, by copying a cluster of spatially coherent pixels simultaneously, the latter methods apparently remove visual artifacts such as blurring and garbage growing. However, a closer look at the resulting textures sometimes reveals at least two new types of artifacts, instead: texture discontinuity and repetition. The discontinuity artifact is caused when a texture sample exhibits a smooth spatial variation with no high-frequency components. The other artifact is observed when a verbatim copy of a patch in the texture sample is transferred to a synthesized texture. Both of these artifacts may result from the lack of randomness of the patch-based copying strategy.

To introduce enough randomness into a texture while adopting the patch-based strategy, either patches must be sufficiently small and irregular, or patch-copying operations must be repeated sufficiently often to eventually

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remove all seams and patch repetitions. Then, the limiting behavior would be reduced to that of a pixel-based scheme. This conjecture naturally raises an interesting question: Are problems such as blurring and garbage growing indeed inherent in pixel-based schemes? As expected, our answer is negative as we will explain in later sections.

In this paper, our objective is to show that pixel-based schemes can avoid the alleged artifacts while still preserving their inherent framework. On top of the general framework of the pixel-based paradigm, our method is equipped with three distinguishing features: window size estimation, seed point planting, and iterative refinement. To capture the structure of a texture, the scale of a dominant texture component is automatically estimated to obtain the window size, which has been manually specified in previous pixel-based methods [1–3]. To provide a landmark for pixel sampling at the initial iteration, a grid of seed points are sampled from an example texture and planted onto the output texture. Finally, the method refines the output texture by iteratively diffusing non-stationarity artifacts over the entire output texture region.

The remainder of this paper is organized as follows: after reviewing related work in Section 2, we present a novel texture synthesis method in Section 3. We show experimental results in Section 4. Finally, Sections 5 and 6 provide discussion and conclusions, respectively.

2. Related work

Rich results have been reported in texture analysis and synthesis. For our purposes, we focus on research results on example-based texture synthesis by non-parametric sampling, which are directly related to our work. In non-parametric sampling, a texture is implicitly modeled by a collection of examplars, instead of explicitly giving its parameters [6]. Methods in this category model an (infinite) texture by Markov random fields (MRFs). A texture is synthesized by simply copying pixels from a texture sample based on their local similarity. An underlying assumption is that the finite texture sample reflects the statistical properties of an MRF such as stationarity and locality. Depending on the method of copying pixels from the texture sample, we distinguish two classes of methods.

2.1. Pixel-based methods

This class of methods adopts the strategy of copying one pixel at a time. Efros and Leung [1] initiated this strategy and demonstrated its power of probability sampling by synthesizing high quality results for a broad range of texture samples. They also reported their experience that the method sometimes causes visual artifacts such as garbage growing and verbatim copying. We believe that these artifacts result from two reasons: for the former artifact, non-parametric sampling with partial neighbors of a pixel might not be sufficient to capture large-scale structures of a texture sample. For the latter artifact, the window size probably might be too large to introduce enough randomness. In addition, the method required heavy computation time because of exhaustive pixel searching.

Wei and Levoy [2] tried to improve the previous method [1] in at least two directions: to guide the pixel sampling process beyond the already-generated neighbors of each pixel, they proposed a multi-resolution scheme. This scheme also exhibited the effect of enlarging the window size. In fact, exploiting the full neighbors at coarser levels, their method sampled some types of structural components relatively well, even with a small window size. To accelerate the pixel searching process, they adopted a heuristic called tree-structured vector quantization (TSVQ). Although the TSVQ greatly enhanced time efficiency, it also brought in the blurring artifact, which may obscure the quality enhancement obtained from the multi-resolution searching. Later, Wei pointed out that this method demonstrates patch-copying behavior [9]. When the window size gets larger, neighboring pixels in the output texture tend to be sampled from spatially coherent source locations. This observation provides an insight on the relationship between pixel-based and patch-based methods.

Ashikhmin [3] exploited spatial coherency to remedy the blurring artifact observed in a texture generated by the method of Wei and Levoy. The latter method tries to sample a better pixel from scratch at every pixel to be synthesized. The search domain covers the entire texture sample although it is reduced quickly, thanks to the TSVQ technique. Ashikhmin restricted the search domain based on the observation that the pixel to be synthesized has a tendency to be spatially coherent with its already-generated neighbors. Therefore, given their positions in the texture sample, the candidates can be found by properly shifting these positions according to their displacements with respect to this pixel. Thus, Ashikhmin's method tends to show a patch-copying behavior and solves the blurring artifact as intended. This method also exhibited better time efficiency than that of Wei and Levoy even without employing the TSVQ acceleration. However, for smooth textures such as clouds and waves, the method sometimes introduced visual artifacts such as discontinuity and garbage growing, due to its restricted search space.

2.2. Patch-based methods

Unlike pixel-based methods, patch-based methods copy a patch of pixels at a time. These methods exploit spatial coherency in one form or another to accelerate their synthesis performances as well as to enhance texture quality. In this sense, Ashikhmin's work [3] can be considered as a "bridge" to the patch-copying paradigm although Xu et al. [10] used texture patches even earlier for texture synthesis.

Efros and Freeman [4] presented a patch-based method called "image quilting." They observed that, in pixel-based texture synthesis, much effort is wasted on searching pixels, the positions of which can be derived trivially from their

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