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A Comparison Study of Four Texture Synthesis Algorithms on Regular and Near-regular Textures

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CMU-RI-TR-04-01

January 2004

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Abstract

We compare the performance of four texture synthesis algorithms on synthesizing regular and near-regular textures in this report. Our results show that the near-regular texture synthesis remains to be a challenging problem. This is because a near-regular texture demonstrates both global regularity and local randomness in its texture pattern. It is difficult to preserve both properties in the synthetic textures. The comparison indicates that a specially-designed texture synthesis algorithm that respects the nature of near-regular textures can produce more faithfully synthesized textures than general purpose state of the art synthesis algorithms.

1 Introduction

Textures are conventionally classified as either regular or stochastic textures[5]. However, many real-world textures fall somewhere in-between these two extremes. Most textures, along with regular and stochastic textures, form a texture spectrum on which the structure patterns vary continuously towards randomness(Figure 1). Ideally, a good texture synthesis algorithm should be able to handle all types of textures on the spectrum; however, the performance of existing texture synthesis algorithms varies on different types of textures. Moreover, the performance of a synthesis algorithm is usually judged by examining the results visually, which could be subjective and inconsistent among different people. To better evaluate the synthesis results, an objective and consistent criterion in addition to the visual inspection would be very helpful.

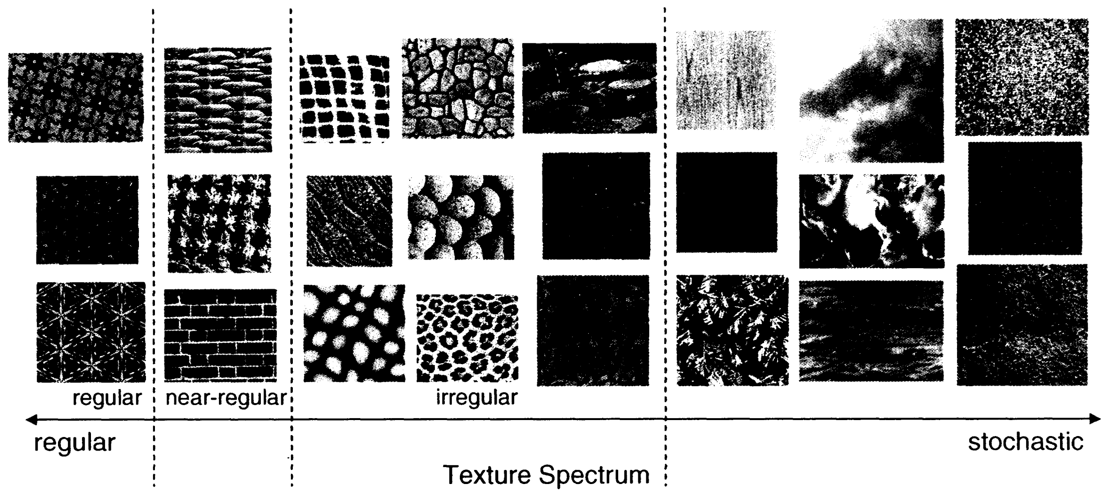


Figure 1: A texture spectrum on which textures are arranged according to the regularity of their structural variations where irregular textures refers to geometrically-irregular near-regular textures.

The goal of this report is to compare the performance of texture synthesis algorithms in a more objective and consistent way. To satisfy this goal, the testing samples should cover an appropriate scope of textures on the spectrum, and more importantly, the testing samples should also have a consistent property that is easy to verify whether the property is faithfully preserved in the synthesis process. For these reasons, we consider two particular types of textures in this report: regular and near-regular textures[13].

Regular textures are simply periodic patterns where the color/intensity and shape of all texture elements are repeating in equal intervals. That is, a texture element is a unit tile in a regular texture, which can be synthesized by tiling the space with the unit tile[1]. An example of regular textures is wallpaper. In the real-world, however, few textures are exactly regular. Most of the time, the textures we see in the real-world are near-regular, such as cloth, basket, windows, brick walls,

[1]The tile and texture element refer to the same concept and will be used interchangeably in this report.

building columns, carpet, blanket, honeycomb, etc. Near-regular textures can be considered as departures of regular textures in different space with different degree. For example, in brick wall textures, the major departure happens in the color/intensity space as the shape of each brick is regular but the color/intensity may vary. On the other hand, the perspectively-distorted window texture in Figure 2 departs mainly in the geometry space while the color/intensity of each window is almost regular. Figure 1 shows a texture spectrum where the textures are arranged according to the regularity variation in geometry space.

In this report, we will only consider a subclass of near-regular textures: **geometrically-regular near-regular textures**, of which the texture elements only vary in color/intensity space but are almost regular in geometry space. In other words, the texture elements can be defined by a regular lattice. For simplicity, we will just call geometrically-regular near-regular textures "near-regular textures (NRT)" in the rest of the report.

The global regularity of the geometrically-regular nea-regular textures is a consistent property that can be used to evaluate the synthesis results. Moreover, the departures in color/intensity space of near-regular textures provides another property to evaluate synthesis algorithms. This property is very important because preserving variations is the original purpose of texture synthesis.

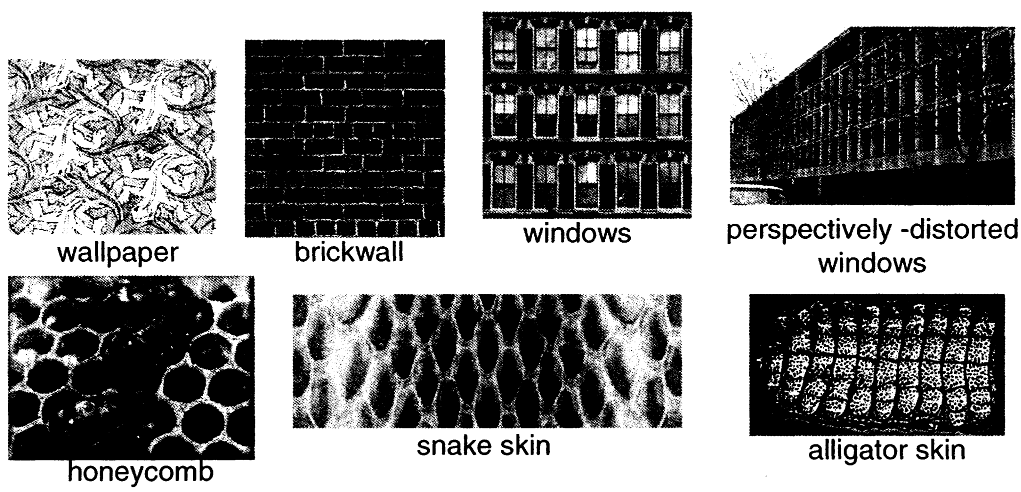


Figure 2: Examples of near-regular textures.

2 Selected texture synthesis algorithms

There are lots of work in texture synthesis that achieved impressive results in a variety of textures[1, 2, 3, 4, 5, 6, 7, 9, 14, 15, 16, 17].These algorithms can be roughly divided into two groups: the statistical-model-based approaches[2, 3, 6, 14] and image-based approaches[1, 4, 5, 7, 9, 15, 16, 17]. Statistical-model-based approaches are closely related to texture analysis and classification in that a statistical model is constructed based on the input textures and the model is used for texture analysis or synthesis. Due to their statistical nature, this type of approaches perform much better on the stochastic textures than on the structural textures. This is because the statistical-model-based approaches synthesize textures by re-sampling image pixels from a statistical model, they can not guarantee the structures in the structural textures to be preserved–the boundaries of the structures may be blurred or even broken. On the other hand, the image based approaches synthesize textures by directly copying image pixels or patches from the input texture and stitch them into the synthesized image. Because the image-based approaches try to keep the image pixels untouched as much as possible, the image details can be well preserved in the synthesized textures. However, they are local approaches in nature without special consideration given to texture's global structures. In general, the image-based approaches perform better on structural textures than the statistical-model-based approaches.

In this comparison study, we consider the image-based synthesis algorithms because we are interested in regular and near-regular texture synthesis. In particular, we compare the graph cuts approach[7], near-regular texture synthesis[13], patch-based approach[9], and regularized patch-based approach developed by one of the authors. We briefly describe these algorithms here. Readers who are interested in these algorithms are encouraged to read the original papers for details.

2.1 Graph cuts texture synthesis

Kwatra et al.[7] demonstrate a very effective general texture synthesis algorithm. Texture is synthesized by overlaying the entire input texture onto the synthetic texture at various offsets and using a graph cut algorithm to find the optimal region to add to the synthetic texture. The graph cut algorithm avoids the need for a fixed, a-priori patch size and scales well to any dimension (such as video). However, for near regular textures the choice of offsets is as important as finding low-error seams. If the input texture is copied onto the synthesized texture at an offset that is inconsistent with the periodicity of the texture, any selection of seams will still violate the global regularity of the texture. Kwatra et al. describe patch placement algorithms which do a fair job of finding low error offsets. The error is defined as the sum of squared difference (SSD) between the pixels in the overlapping region of the input texture and the texture being synthesized. They treat the input texture as a template and compute the correlation between the template and the texture being synthesized to find the low error offsets. The minimum error (or maximum correlation) offsets often, but not always, correspond to the offsets preserving the periodicity of the input texture.

2.2 Near-regular texture synthesis

Liu et al.[13] propose a texture synthesis algorithm for geometrically-regular near-regular textures[2]. The basic idea is to utilize the translational symmetry property[10][11] of a near-regular texture to find the underlying lattice structure of the texture patterns and locate the texture elements, which are called tiles, in the input texture. These "tiles" represent the smallest parallelogram-shaped region on a regular texture that can reproduce the texture patterns under the texture's trans-

[2]Although the name of the synthesis algorithm is near-regular texture synthesis, the algorithm only deals with geometrically-regular near-regular textures.

lation subgroup. For a regular texture, only one tile is needed for recovering the texture. For a near-regular texture, a set of tiles collected by sampling the input texture in a principled manner [12], are needed to preserve both the geometric regularity and color/intensity variations in the input texture. The tiles in the tile set have roughly the same size and shape but varied color/intensity. The output texture is synthesized by randomly picking a tile from the tile set and pasting the tile to the synthesizing image with overlapping on lattice points. Dynamic programming and image blending techniques are applied to the overlapping regions to stitch the tiles.

2.3 Patch-based texture synthesis

Liang et al.[9] develop a patch-based synthesis algorithm. The basic idea of the algorithm is to synthesize textures by directly copying image patches from the input texture. The major difference from other image-based approaches is that they apply a modified approximate nearest neighbor technique to speed up the searching process for the best matched patch. With the improvement on the searching speed, the algorithm can run in real-time and reach similar image quality as other image-based synthesis algorithms. Image feathering technique is used in the patch-based synthesis approach to blend the overlapping regions of patches. This might blur the overlapping region in some degree compared to the dynamic programming technique used in the near-regular texture synthesis or the graph cut technique in the graph cuts synthesis approach.

Patch placement in the patch-based approach is very different from that in the near-regular texture synthesis. In patch-based approach, the patch shape is a rectangle and the patch is pasted in a scan-line order. Additionally, the patch size and placement offset are arbitrarily defined by a user. They may not match the lattice structure of the input near-regular texture.

2.4 Regularized patch-based texture synthesis

We develop a regularized patch-based texture synthesis algorithm to deal with near-regular textures[3] in which each texture element may not be well circumscribed by parallelogram. We allow the parallelograms on a regular lattice to be deformed to quadrilaterals so that the texture elements can be separated by the deformed lattice. In other words, we deform a geometrically-irregular near-regular texture to a geometrically-regular near-regular texture. We then apply a modified patch-based approach to synthesize the geometrically-regular texture. Our modification to the patch-based approach allows the patch to paste along the lattice axis direction and allow the patch shape to be a parallelogram other than an arbitrary rectangle. The patch-size and lattice construction vectors are provided by a user who identifies the underlying lattice structure of the input near-regular texture. A synthesized inverse deformation is used to warp the synthesized regular texture to a near-regular texture. We describe the details of the algorithm in the appendix.

[3]Strictly speaking, the algorithm can handle a near-regular texture which has both geometric variation and color/intensity variation. Since we only compare the synthesis performance on geometrically-regular near-regular textures in this study, the capability of the algorithm to handle the geometrically-irregular textures would not be addressed in this report.

	Graph cuts	**Near-regular synthesis**	**Regularized patch-based**	**Patch-based**
Patch shape/size	input texture image	tile shape/size from translational symmetry analysis	user identified lattice, quadrilateral patch	user defined, rectangular patch patch
Patch placement	random or maximal correlation locations	lattice points	lattice points	patch grids
Patch stitching	graph cut & blending	dynamic programming & blending	image-feathering	image-feathering

Table 1: Summary of four synthesis algorithms. A *patch* is a 2D sample of neighboring pixels extracted from the input texture image. *Patch shape/size* refers to how the shape and size of the region are determined when extracting image pixels from the input texture, while *patch placement* and *stitching* refer to how the patches are placed and stitched in the synthesized texture.

To conclude this section, we summarize these four algorithms in Table 1. We compare the patch shape/size determination, patch placement, and patch stitching methods used in these algorithms where a *patch* is a 2D sample of neighboring pixels extracted from the input texture. *Patch shape/size* refers to how the shape and size of the region are determined when extracting image pixels from the input texture, while *patch placement* and *stitching* refer to how the patches are placed and stitched in the synthesized texture.

3 Results

We compare the synthesis results by the four algorithms on regular textures (Figure 3-7) and near-regular textures (Figure 8-45). In addition, we include the synthesis results by the *image quilting* approach[4] whenever the same input texture has been tested in their published paper on website[4](Figure 16, 18, 22, 27, 35, 36). Among the six testing textures, two synthesized results of image quilting preserves the global regularity(Figure 22 and 27). For the convenience of comparison, we summarize the synthesis performance of these four algorithms on regular textures in Table 2 and near-regular textures in Table 3. These two tables record whether the global regularity is preserved in the synthesized texture.

From Table 2, we find that all four algorithms can handle the regular textures very well, but they perform quite differently on near-regular textures from the results shown in Table 3. It may not be surprising that the near-regular texture synthesis algorithm performs best among the four because it is specially designed for near-regular texture synthesis. The graph cuts approach and patch-based approach do not preserve the global regularity well most of the time. This is because these two algorithms do not explicitly model the underlying lattice structure of the input texture and use it in the synthesis process. An interesting comparison is the patch-based approach and

[4]http://www.cs.berkeley.edu/ efros/research/quilting.html.

Textures	Description	**Graph cuts**	**Near-regular synthesis**	**Regularized patch-based**	**Patch-based**
Figure 3	wallpaper	✓	✓	✓	✓
Figure 4	wallpaper	✓	✓	✓	✓
Figure 5	wallpaper	✓	✓	✓	✓
Figure 6	jigsaw puzzle	✓	✓	✓	✓
Figure 7	pavement tiles	✓	✓	✓	✓
success rate	preserved/total	100%	100%	100%	100%

Table 2: Comparison of preservation of global regularity in regular textures where ✓denotes the regularity is preserved.

regularized patch-based approach. Because the later utilizes a user-specified lattice of the input texture in the synthesis process, it preserves the global regularity much better than the patch-based approach.

Although the graph cuts approach does not utilize the lattice structure in synthesis process, it still performs well on a few near-regular textures and much better than the patch-based approach(Table 3). The reason for this is that the algorithm incorporates a correlation technique to determine the best pasting location so that the underlying periodicity, if existing, can be preserved. This correlation-based patch placement works well on regular textures and some near-regular textures; however, for near-regular textures in which the color/intensity of texture elements is not regular, the correlation technique can not guarantee the regularity to be maintained globally. This is especially true when the input texture contains an interlocked structure, like woven fabric or brick walls (Figure 23, 28, 34, 36, 37, 38, 40, 41). Figure 46 shows several synthesis results of a brick wall texture by different patch placement settings in the graph cuts. This example shows that the correlation technique can not work well on discovering the regularity of near-regular textures in this brick wall texture. The synthesis result of the same texture by the near-regular synthesis approach is shown in Figure 36.

A limitation of the near-regular texture synthesis algorithm is that the input texture sample contains at least two complete tiles so that the underlying lattice and the tile set is well defined. If no complete tile exists in the texture, the algorithm can not produce good results. This is the situation in Figure 31 where the input texture contains the overlapping of two periodic patterns (squares and hexagon net), but the sampling area is too small to have a complete tile that covers a full period of the composed periodic pattern[5]. In the near-regular texture synthesis result, the algorithm preserves the square pattern because it demonstrates stronger periodicity–the hexagon net is discontinuous between squares. Another failure example of the near-regular texture synthesis algorithm is the thin line jigsaw puzzle texture in Figure 33. In this case, the input texture dose not contain a complete tile either. This can be observed from the upper-right image in which the pattern in the circled region only appears once in the texture.

[5]In fact, it is not guaranteed that a two-dimensional pattern composed of two periodic two-dimensional patterns remains to be a periodic pattern.

Textures	Description	**Graph cuts**	**Near-regular synthesis**	**Regularized patch-based**	**Patch-based**
Figure 8	punched card	✓	✓	✓	×
Figure 9	hexagonal net	✓	✓	✓	✓
Figure 10	metal	×	✓	✓	×
Figure 11	ceramic tiles	✓	✓	✓	×
Figure 12	fish tiles	✓	✓	✓	×
Figure 13	wall	✓	✓	✓	×
Figure 14	squares	×	✓	✓	×
Figure 15	pavement tiles	×	✓	×	×
Figure 16	cans	✓	✓	✓	×
Figure 17	swirl	✓	✓	✓	×
Figure 18	fabric	×	✓	✓	×
Figure 19	fabric	✓	✓	✓	✓
Figure 20	fabric	✓	✓	✓	✓
Figure 21	fabric	✓	✓	✓	✓
Figure 22	knot mat	✓	✓	✓	×
Figure 23	fabric	×	✓	×	×
Figure 24	fabric	✓	✓	✓	×
Figure 25	toothpastes	✓	✓	✓	✓
Figure 26	windows	✓	✓	✓	×
Figure 27	windows	✓	✓	✓	×
Figure 28	fabric	×	✓	✓	×
Figure 29	basket	✓	✓	×	×
Figure 30	fabric	✓	✓	N/A	N/A
Figure 31	squares&hexagons	×	×	N/A	N/A
Figure 32	mosaic	×	✓	N/A	N/A
Figure 33	jigsaw puzzle	✓	×	N/A	N/A
Figure 34	fabric	×	✓	N/A	N/A
Figure 35	biscuit	×	✓	N/A	N/A
Figure 36	brick wall	×	✓	N/A	N/A
Figure 37	brick wall	×	✓	N/A	N/A
Figure 38	brick wall	×	✓	N/A	N/A
Figure 39	brick wall	✓	✓	N/A	N/A
Figure 40	brick wall	×	✓	N/A	N/A
Figure 41	brick wall	×	✓	N/A	N/A
Figure 42	carpet	✓	✓	N/A	N/A
Figure 43	rug	×	✓	N/A	N/A
Figure 44	rug	×	✓	N/A	N/A
Figure 45	cans	×	✓	N/A	N/A
success rate	preserved/total	53%	95%	86%	23%

Table 3: Comparison of preservation of global regularity in near-regular textures where ✓denotes the regularity is preserved and × denotes not preserved.

4 Conclusion

In this report, we compare the performance of four texture synthesis algorithms on regular and near-regular textures. Because of the global regularity property of the regular and near-regular textures, we are able to provide a more consistent and objective criterion to evaluate the synthesis results.

The comparison study shows that near-regular texture synthesis remains to be a challenging issue to several state-of-the-art algorithms, such as the graph cuts[7], patch-based[9], and image quilting methods[4]. The results from the regularized patch-based approach and the near-regular texture synthesis approach show that the global regularity of the near-regular textures can be better preserved if the synthesis algorithm analyzes the underlying lattice structure and utilizes this information in the synthesis process. In fact, the synthesis results by the near-regular texture synthesis algorithm demonstrate that both the global regularity and local randomness of a near-regular texture can be faithfully preserved.

Acknowledgment

The authors would like to thank Yanghai Tsin for providing his code on an earlier version of near-regular texture synthesis. This research is partially funded by an NSF grant #IIS-0099597. Regularized-Patch-based method was implemented when Wu was an intern at Microsoft Research Asia, under the joint advising of Drs. Liu and Shum.

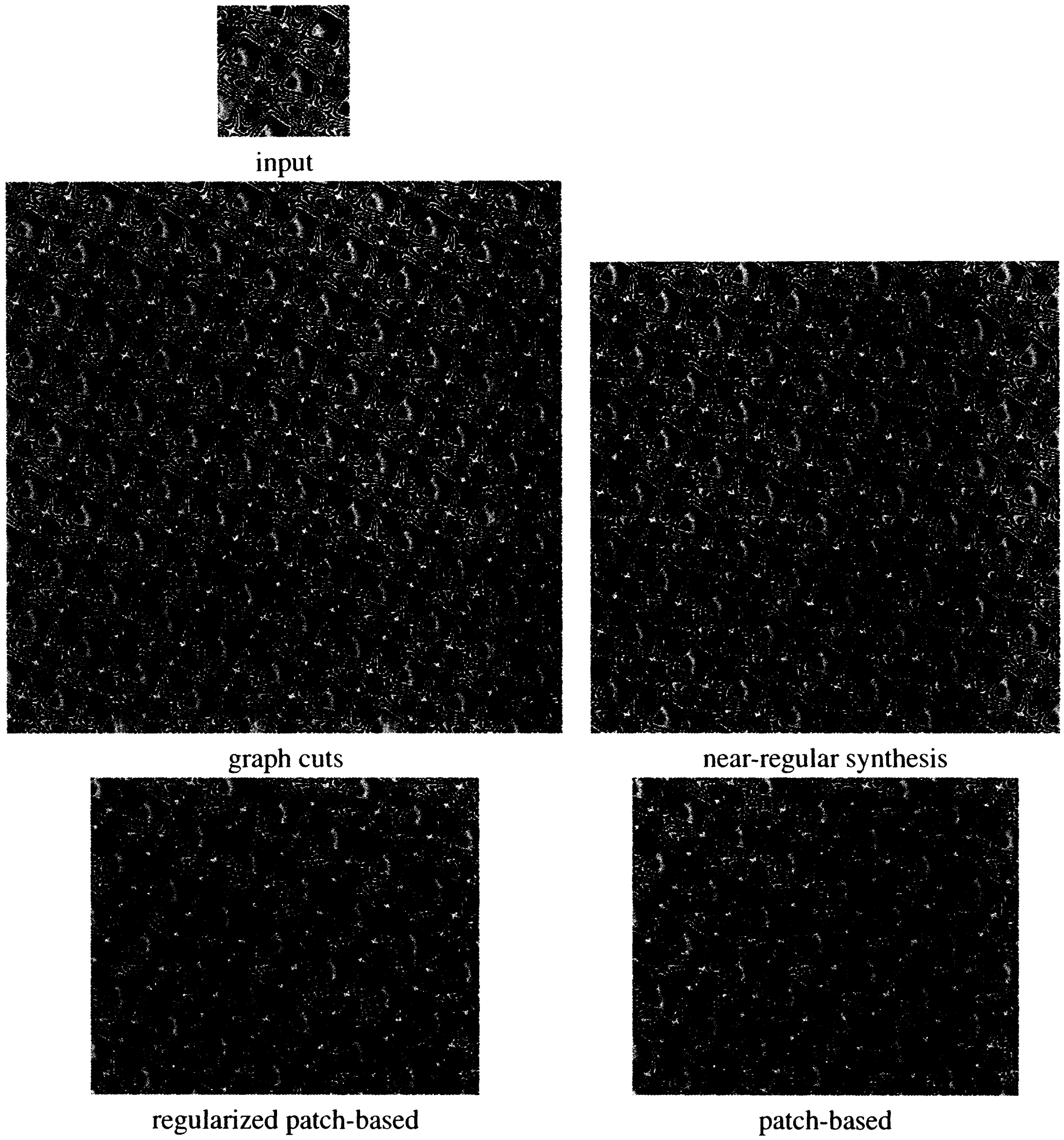


Figure 3: Synthesis results of a wallpaper texture.

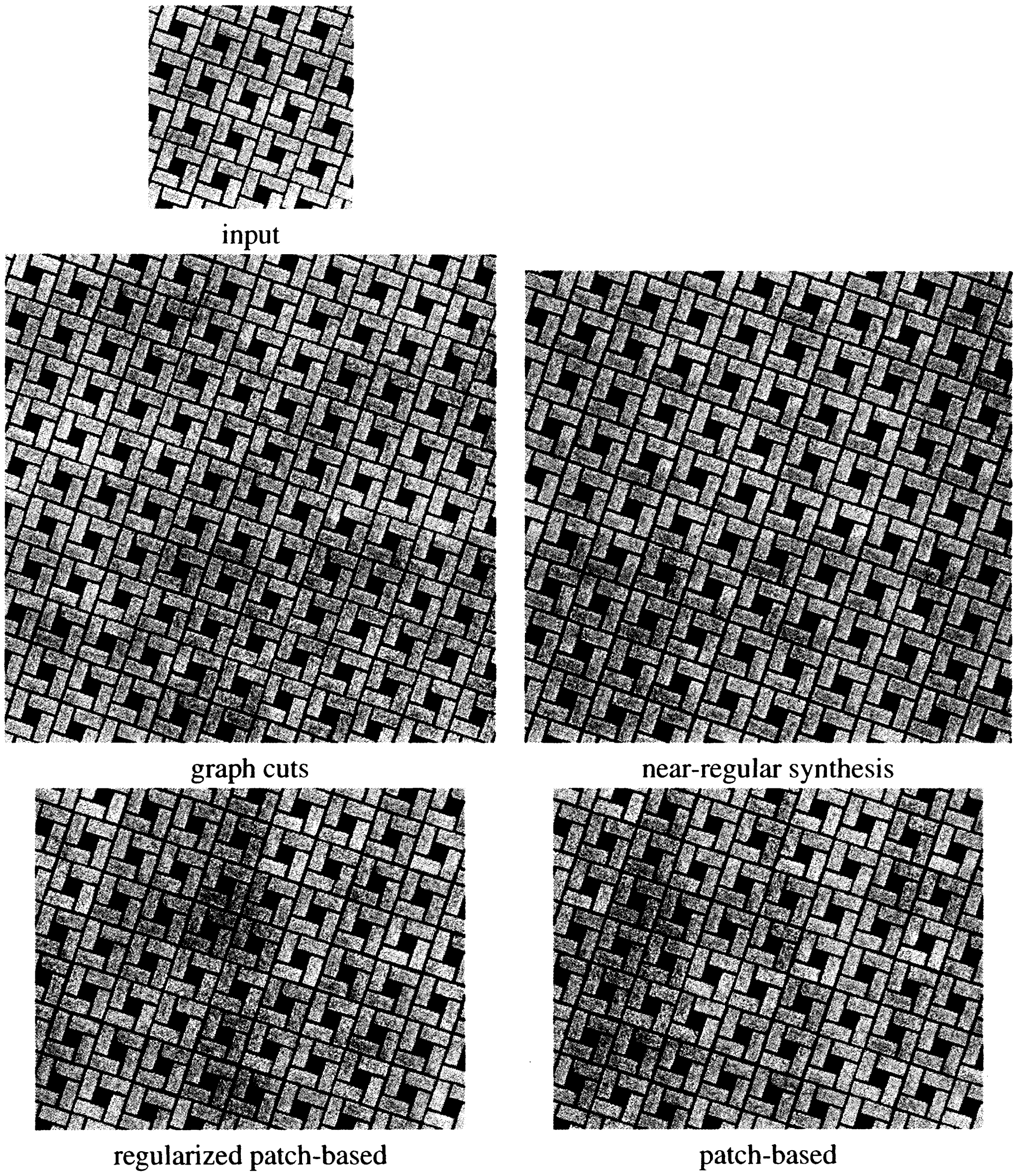


Figure 4: Synthesis results of a wallpaper texture.

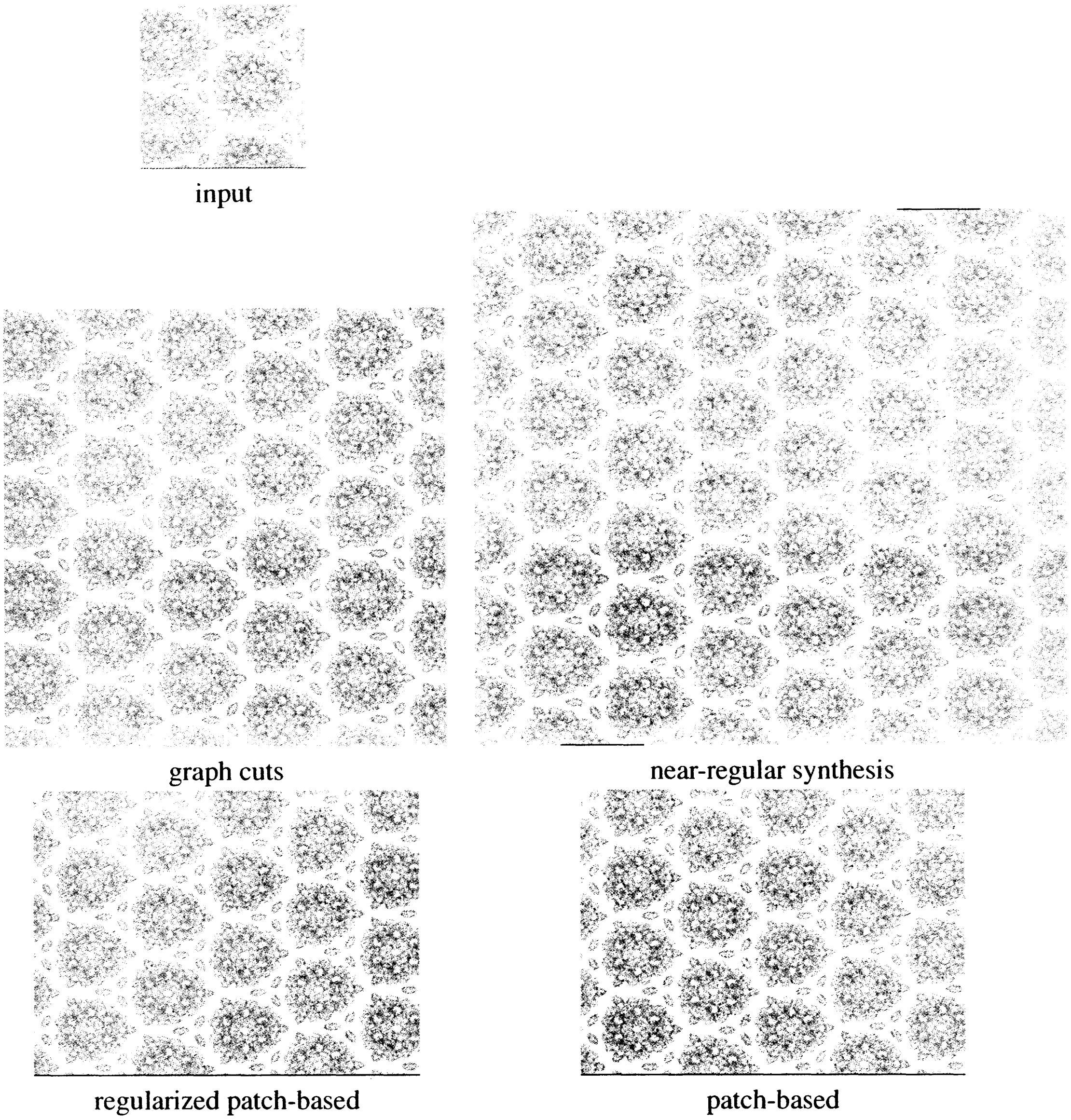


Figure 5: Synthesis results of a wallpaper texture.

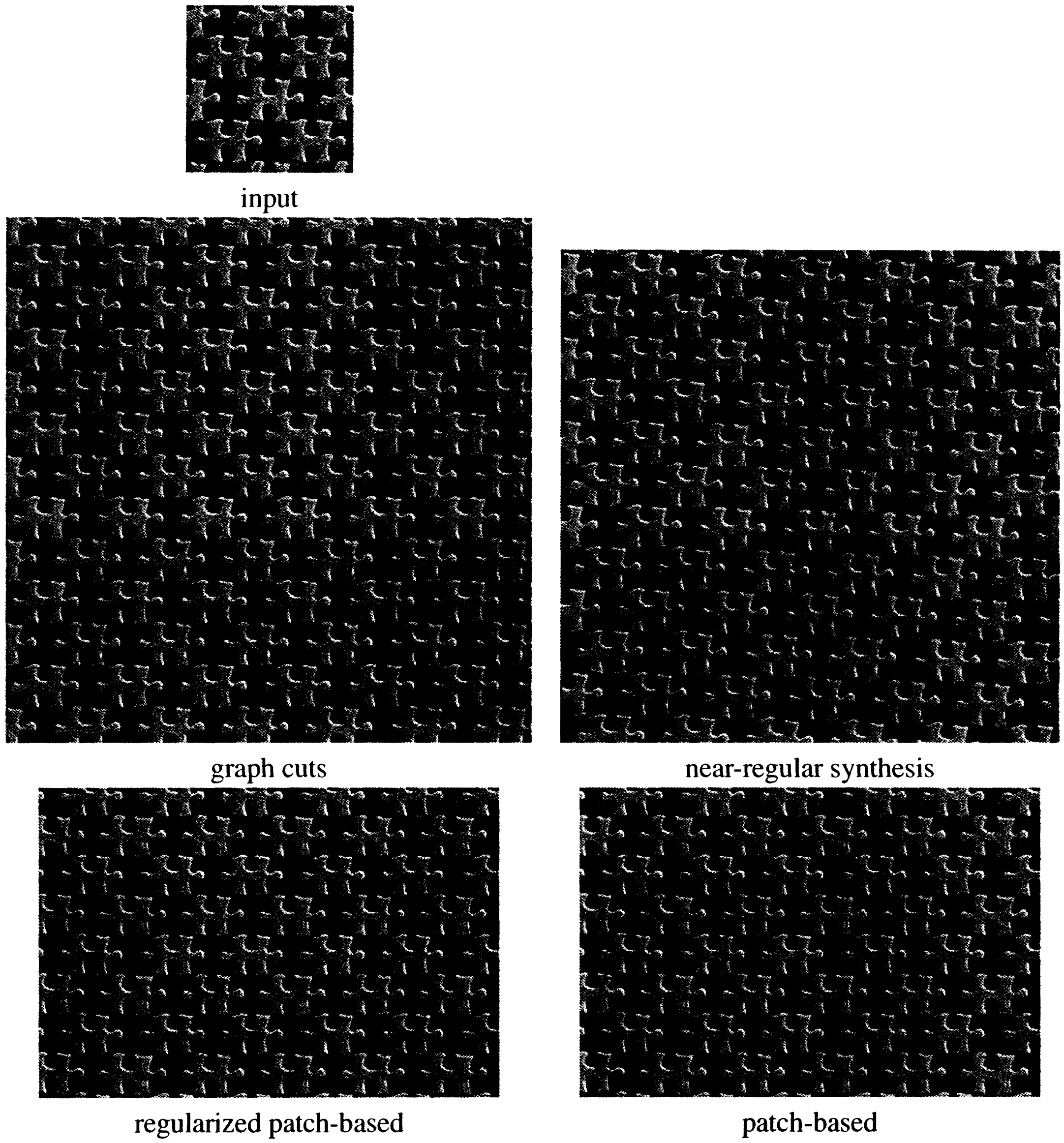
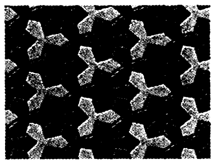
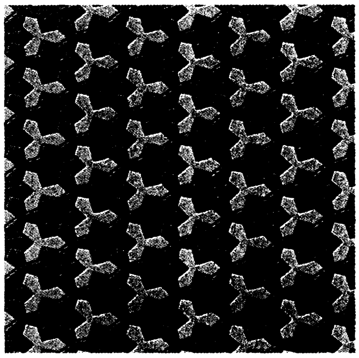


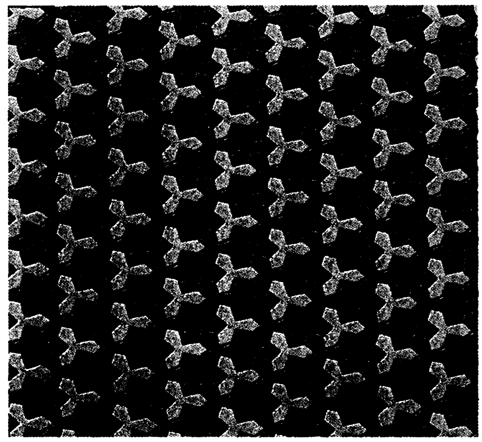
Figure 6: Synthesis results of a jigsaw puzzle texture.



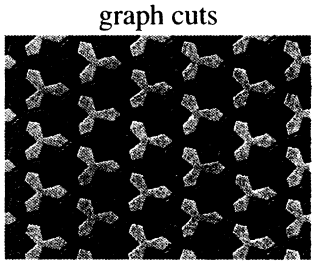
input



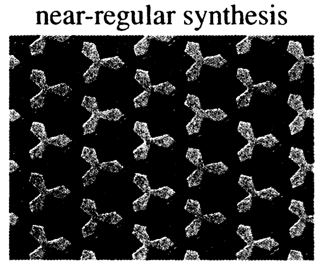
graph cuts



near-regular synthesis



regularized patch-based



patch-based

Figure 7: Synthesis results of a pavement tile texture.

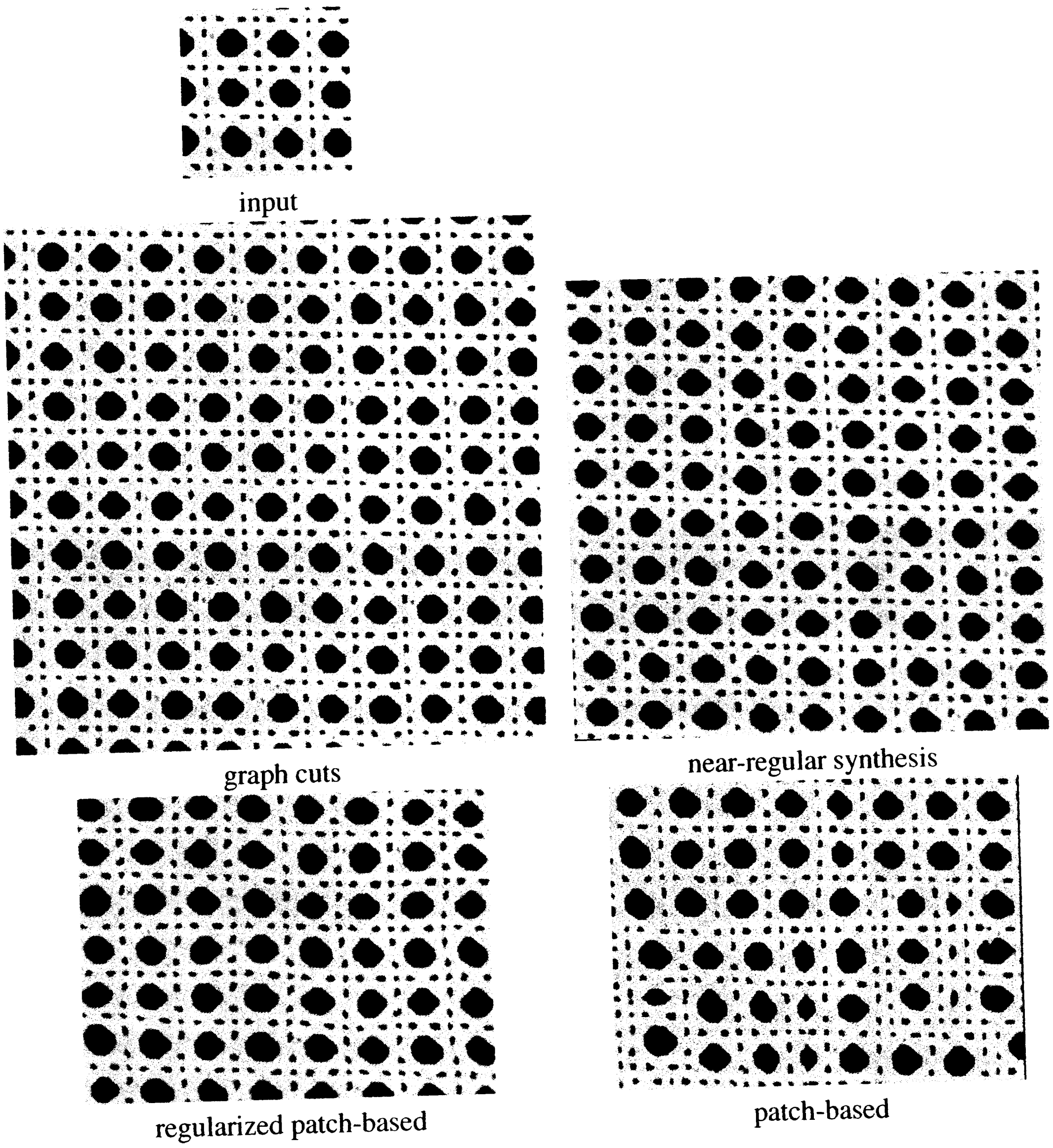


Figure 8: Synthesis results of a punched card texture. Global regularity is not preserved in the patch-based result.

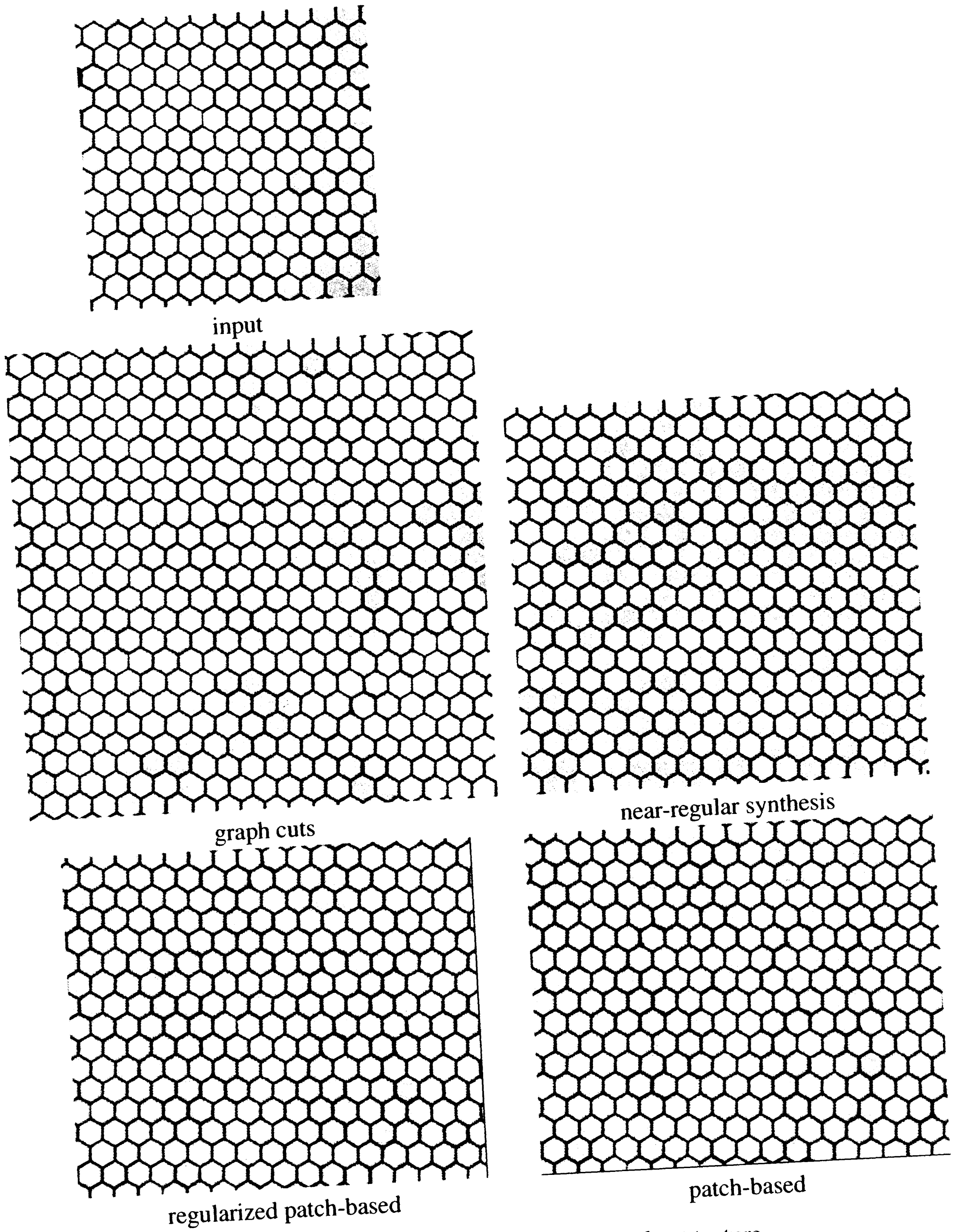


Figure 9: Synthesis results of a hexagonal net texture.

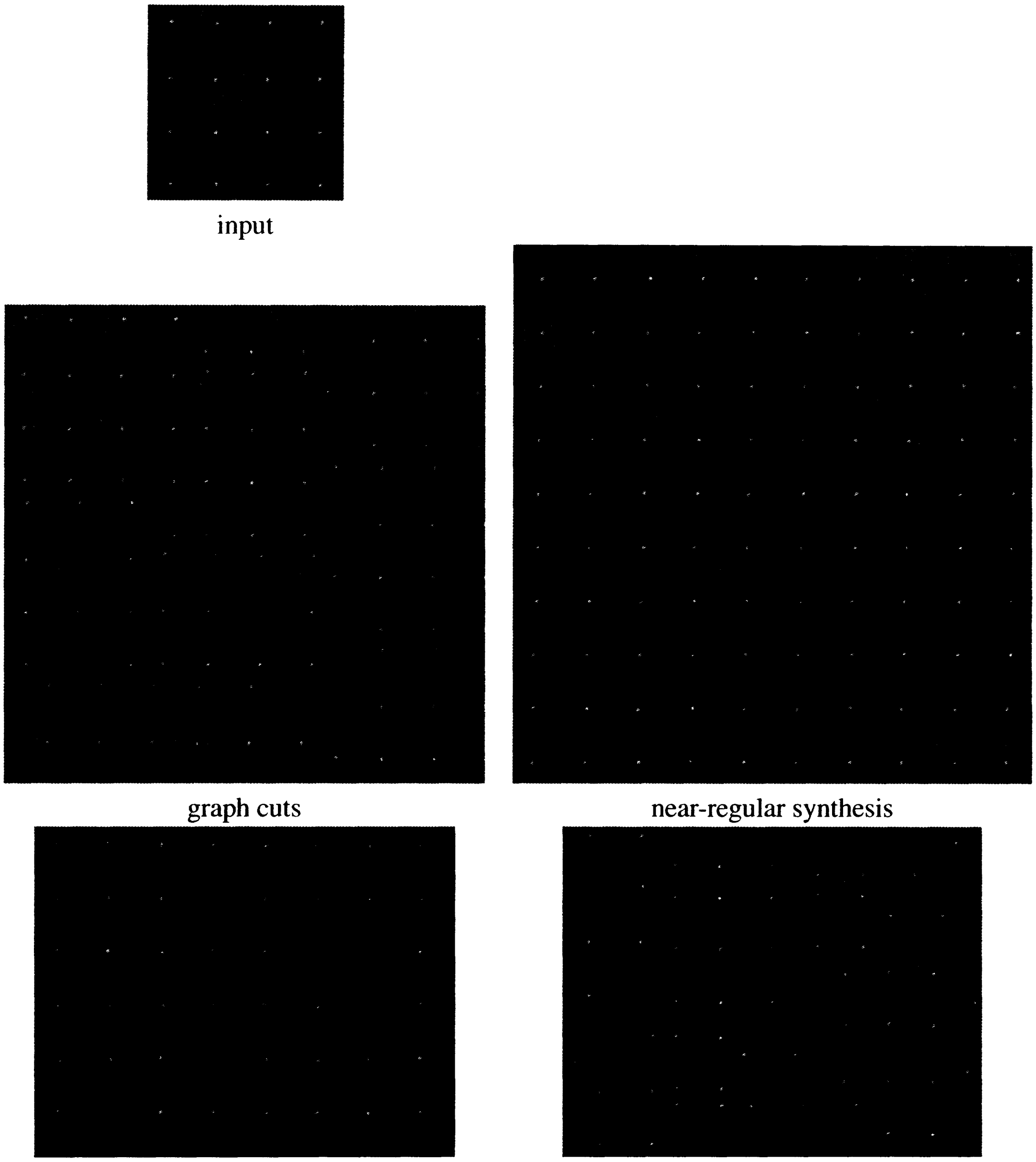


Figure 10: Synthesis results of a metal texture. Global regularity is not preserved in the graph cuts and patch-based results.

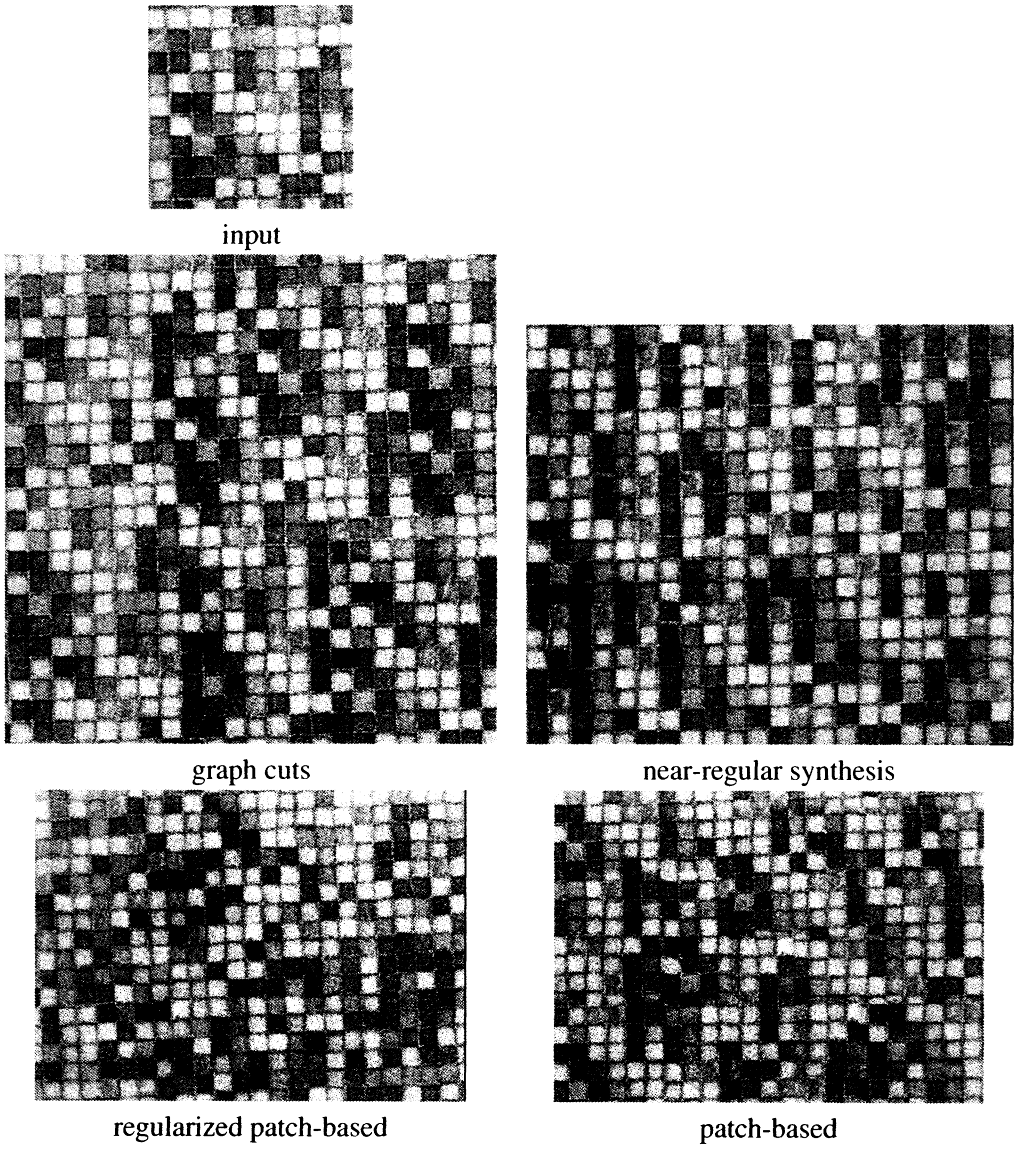
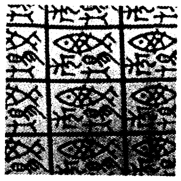
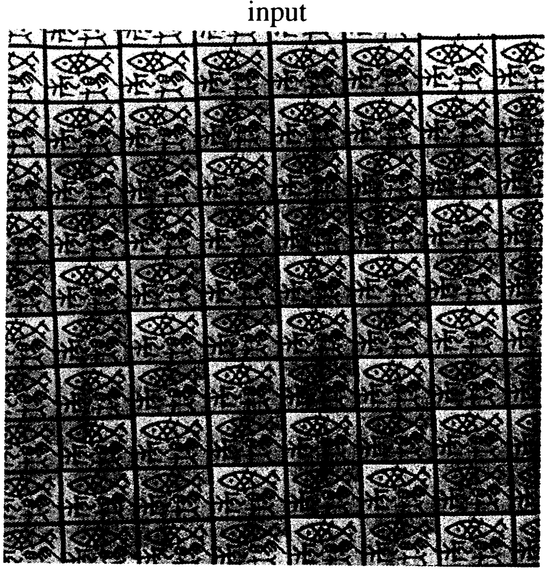


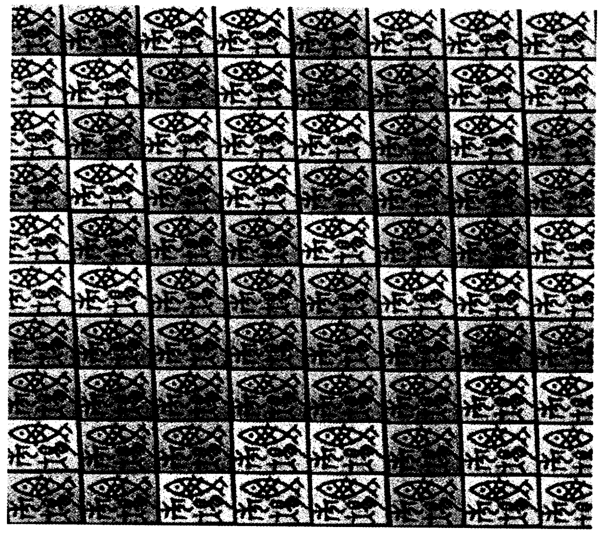
Figure 11: Synthesis results of a ceramic tile texture. The result by the patch-based approach does not preserve the regularity of the tile size in middle part of the bottom rows.



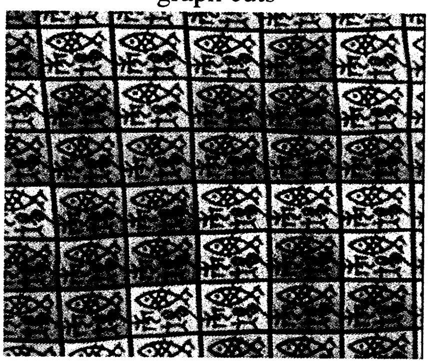
input



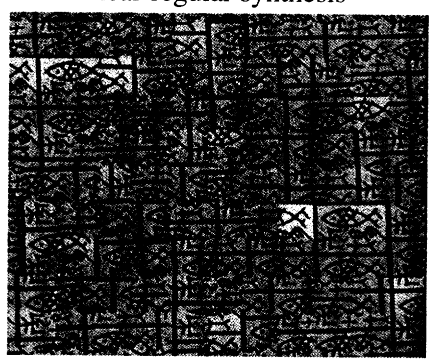
graph cuts



near-regular synthesis



regularized patch-based



patch-based

Figure 12: Synthesis results of a fish tile texture. The patch-based result does not preserve the global regularity.

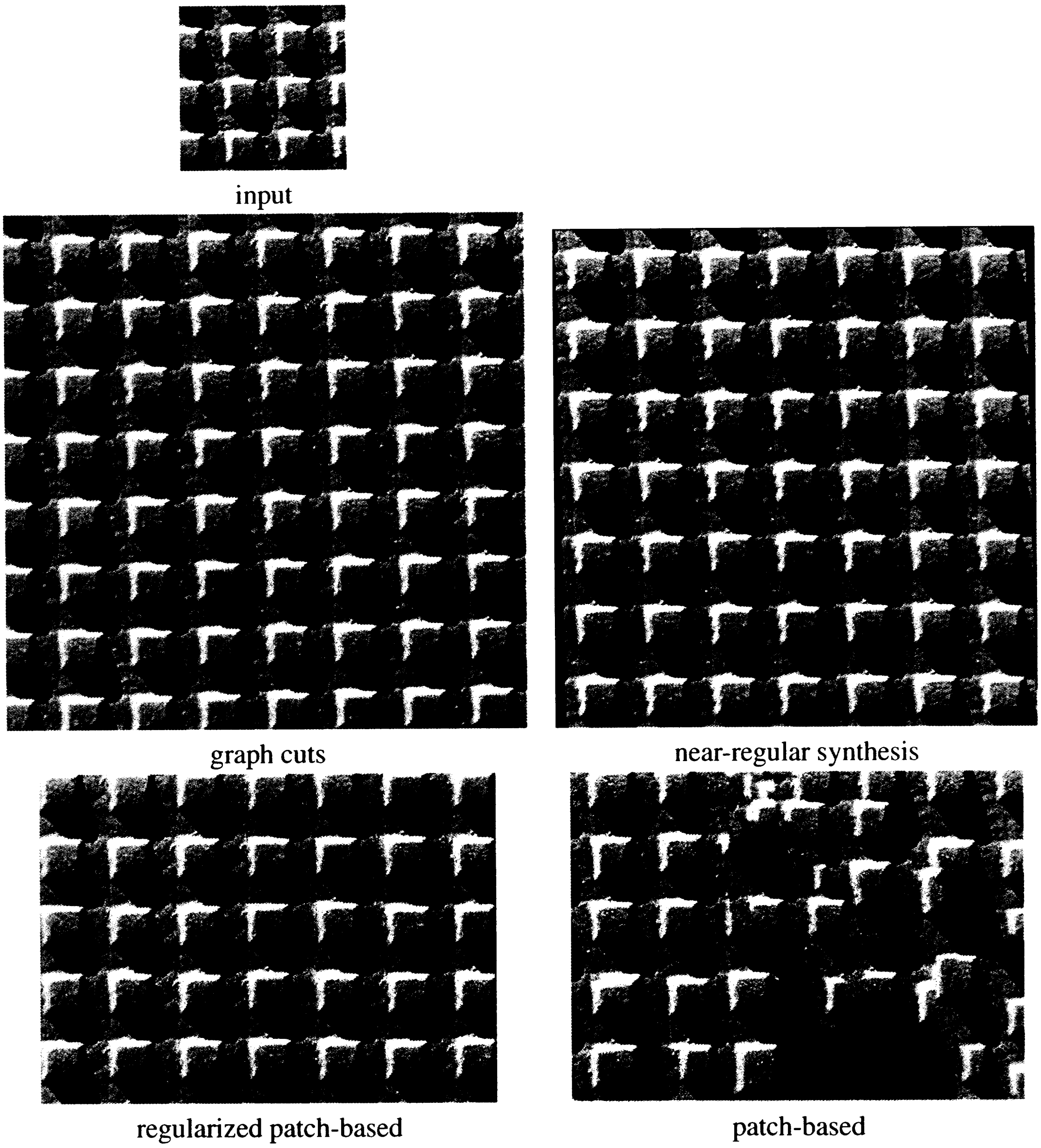


Figure 13: Synthesis results of a wall texture. The patch-based result does not preserve the global regularity.

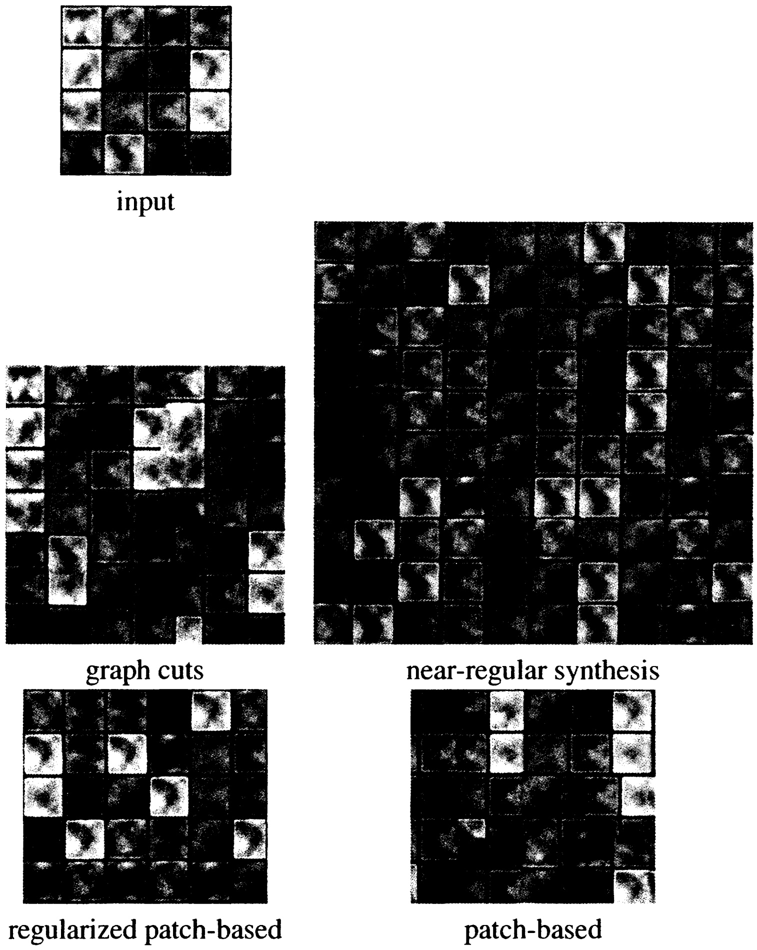


Figure 14: Synthesis results of a texture of squares. There are mixed squares in the graph cuts and patch-based results.

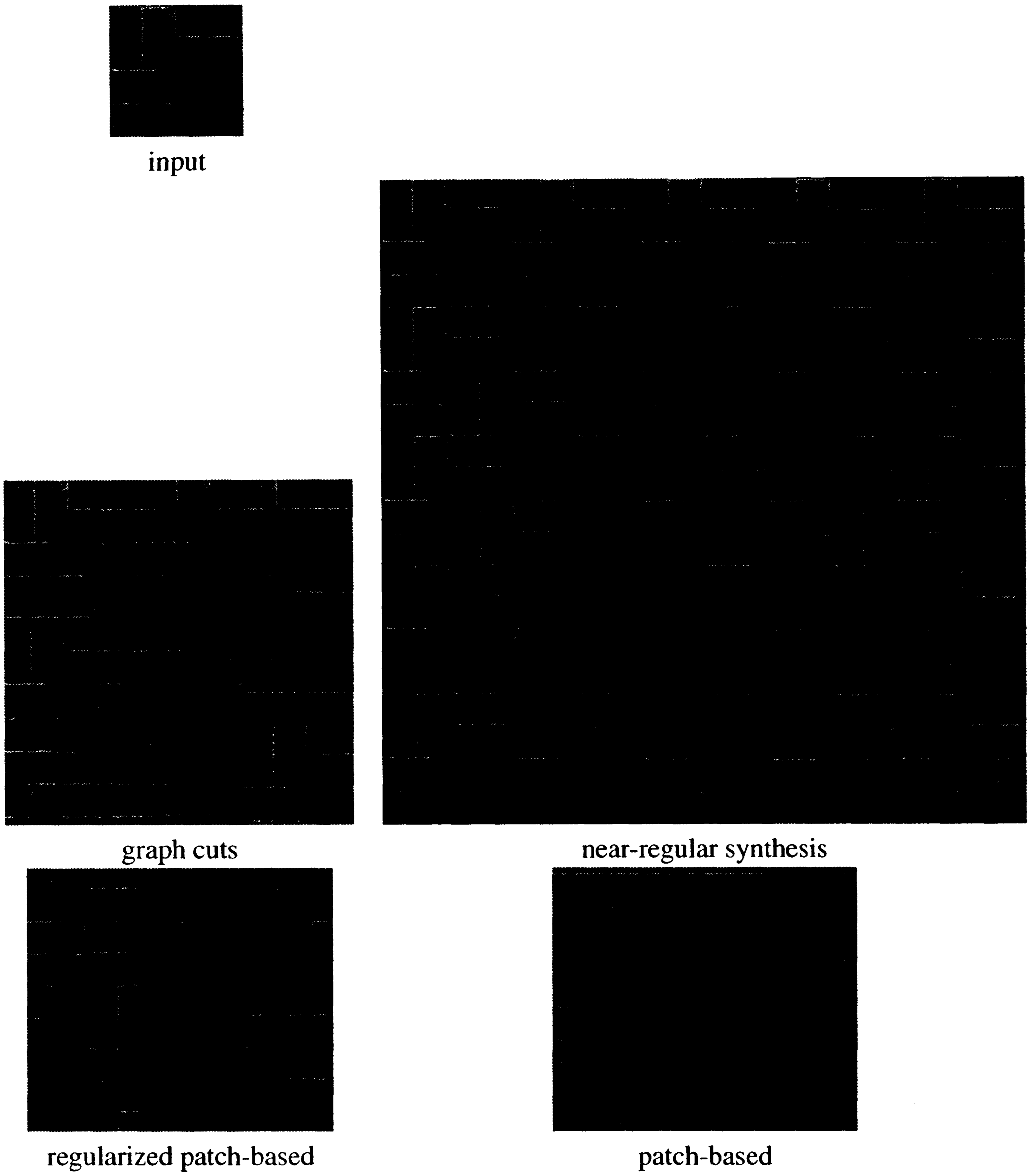


Figure 15: Synthesis results of a pavement tile texture. The near-regular synthesis result preserves the global regularity–the square and vertical/horizontal line pattern.

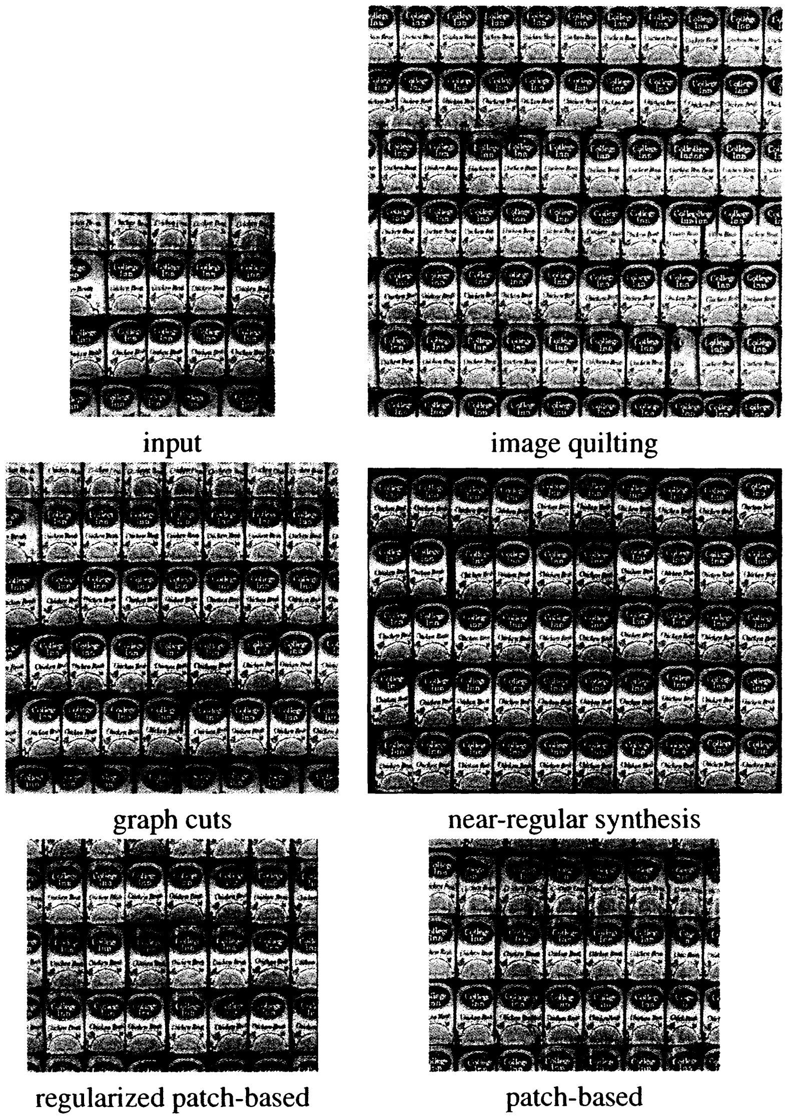


Figure 16: Synthesis results of a texture of cans. Global regularity is not preserved in the patch-based and image quilting results. The cans in the third column of the patch-based result and the third column from the right of the image quilting approach are not synthesized correctly.

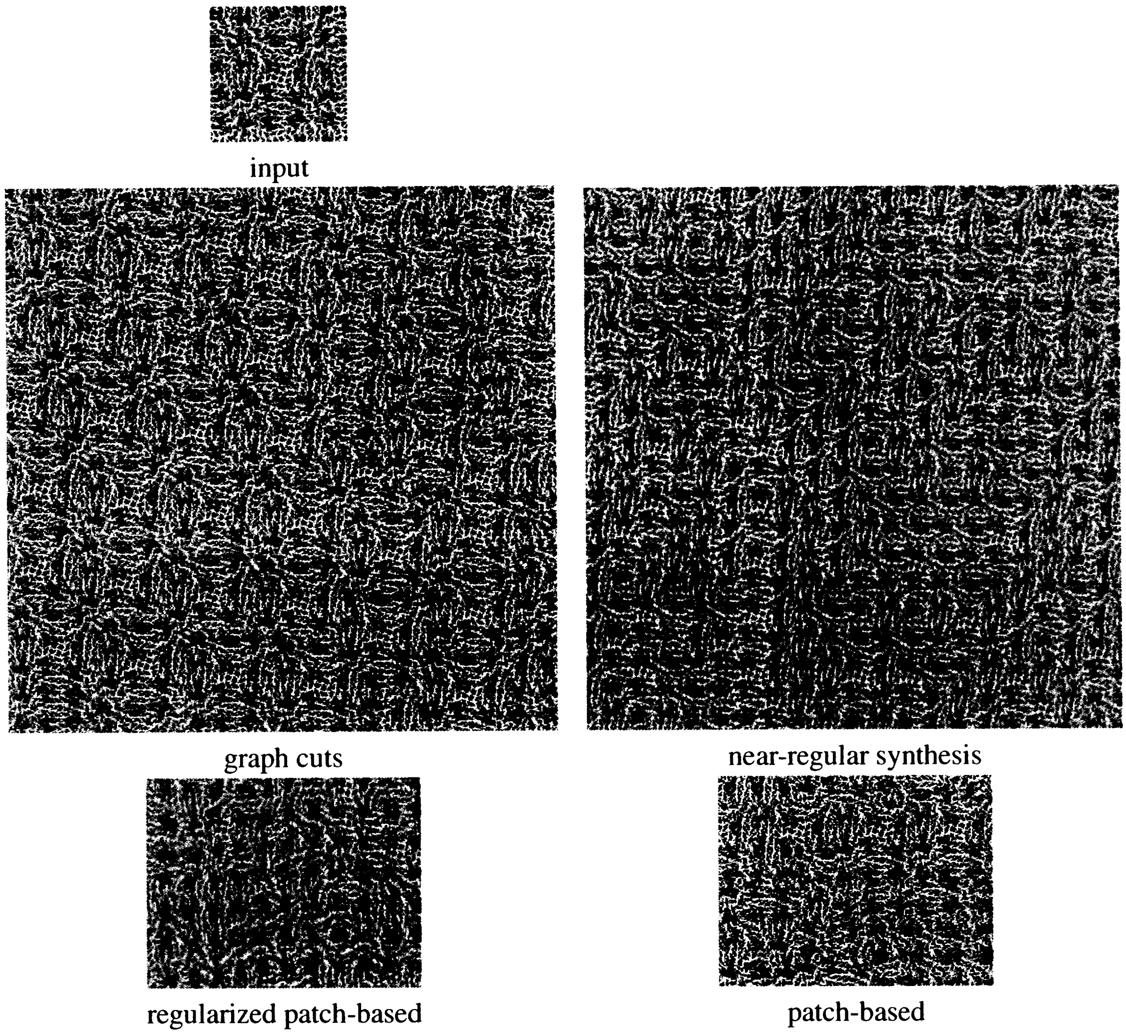


Figure 17: Synthesis results of a swirl texture. The regularity is not preserved in the bottom rows of the patch-based synthesis result.

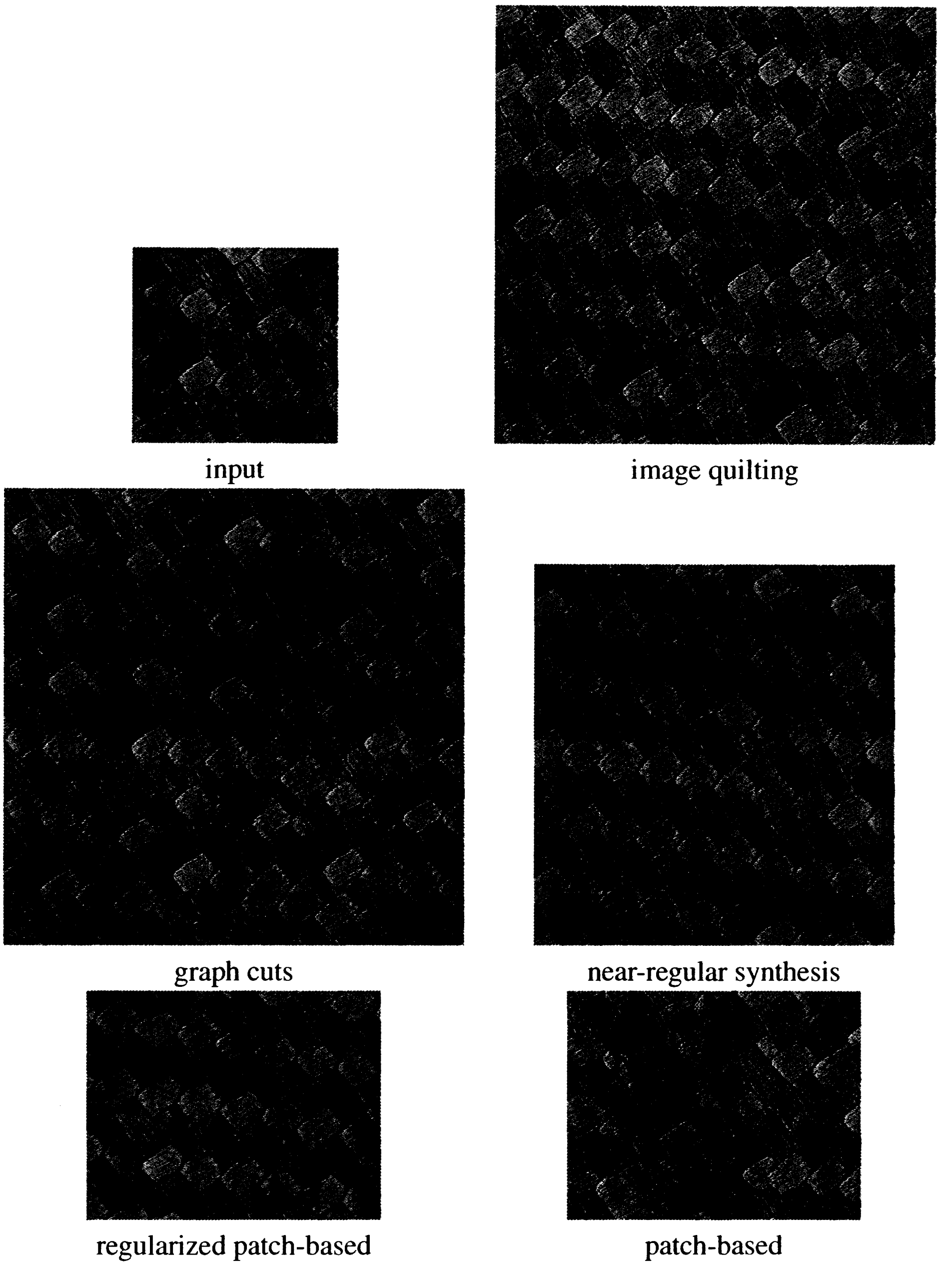


Figure 18: Synthesis results of a fabric texture. Global regularity is not preserved in the graph cuts, patch-based, and image quilting approach. The interwoven structure is not maintained in the lower-left portion of the graph cuts and the central bottom part of the image quilting approach.

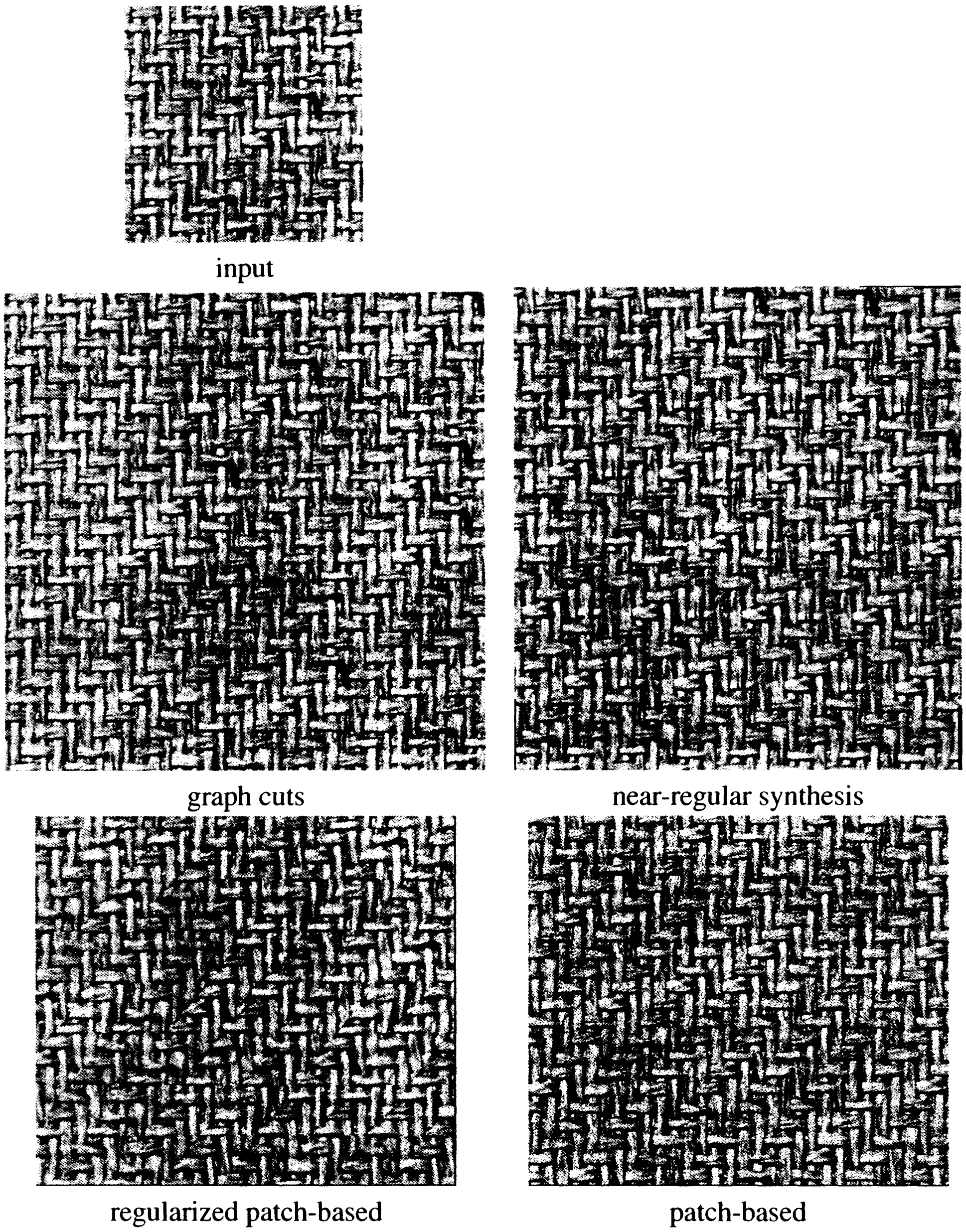


Figure 19: Synthesis results of a fabric texture.

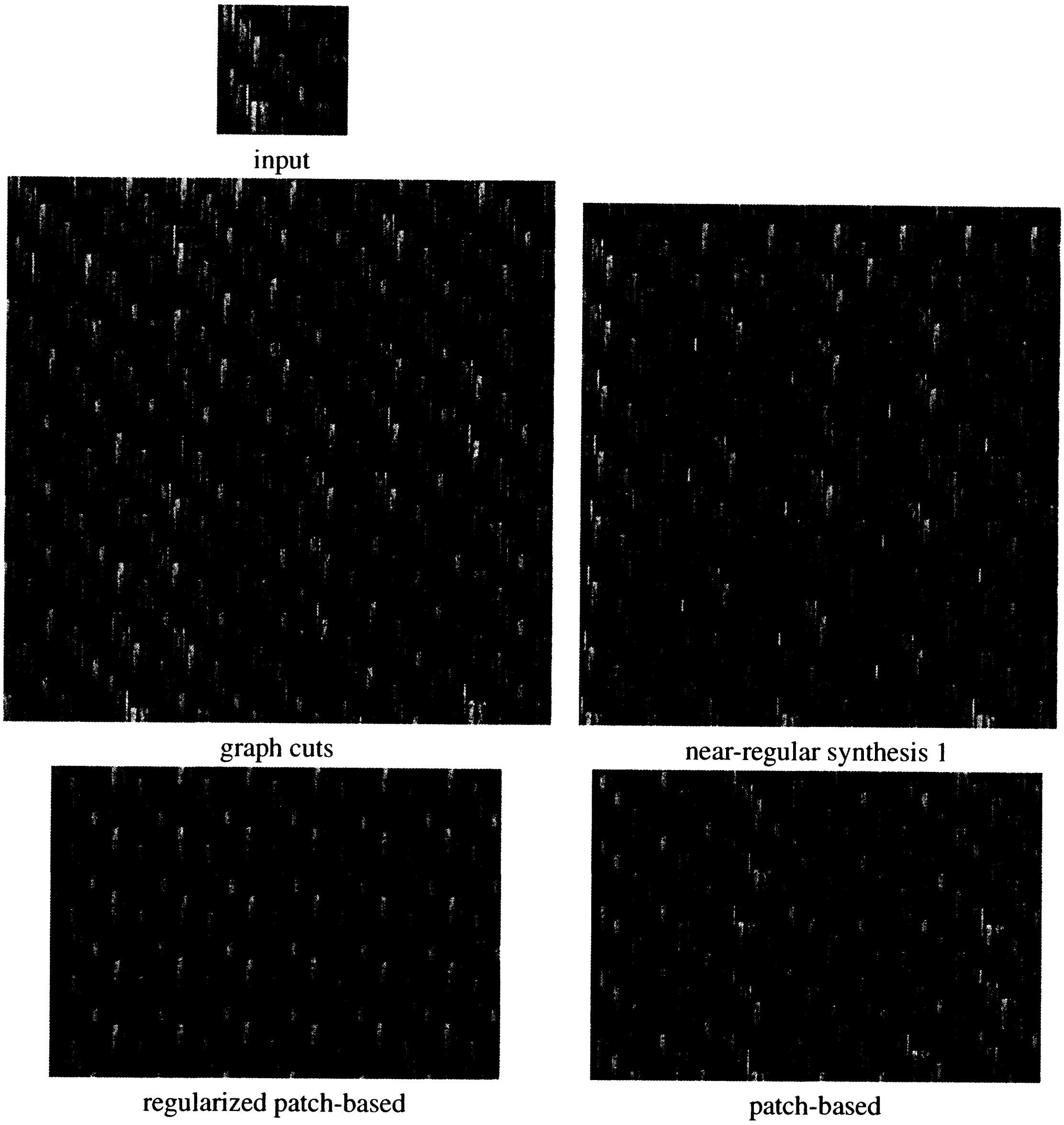


Figure 20: Synthesis results of a fabric texture.

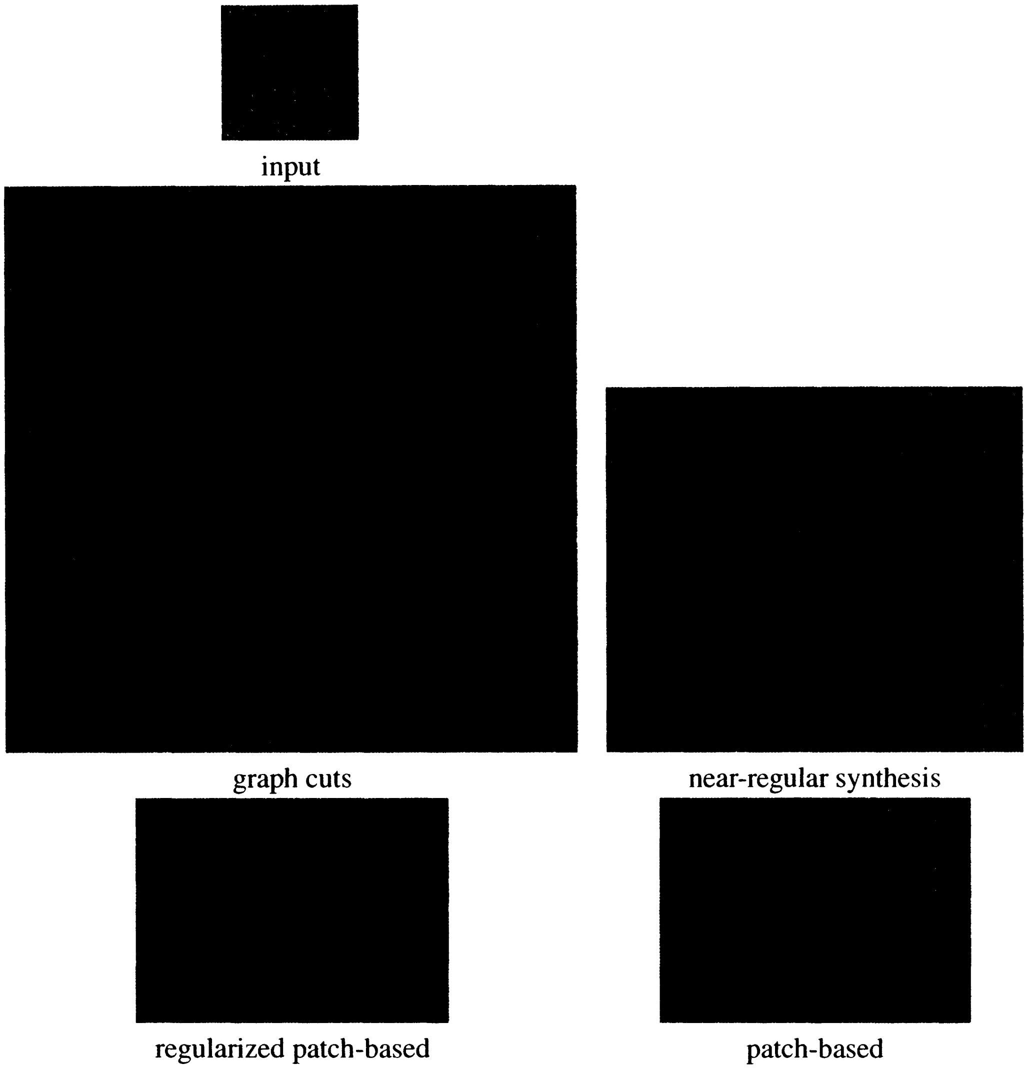


Figure 21: Synthesis results of a fabric texture.

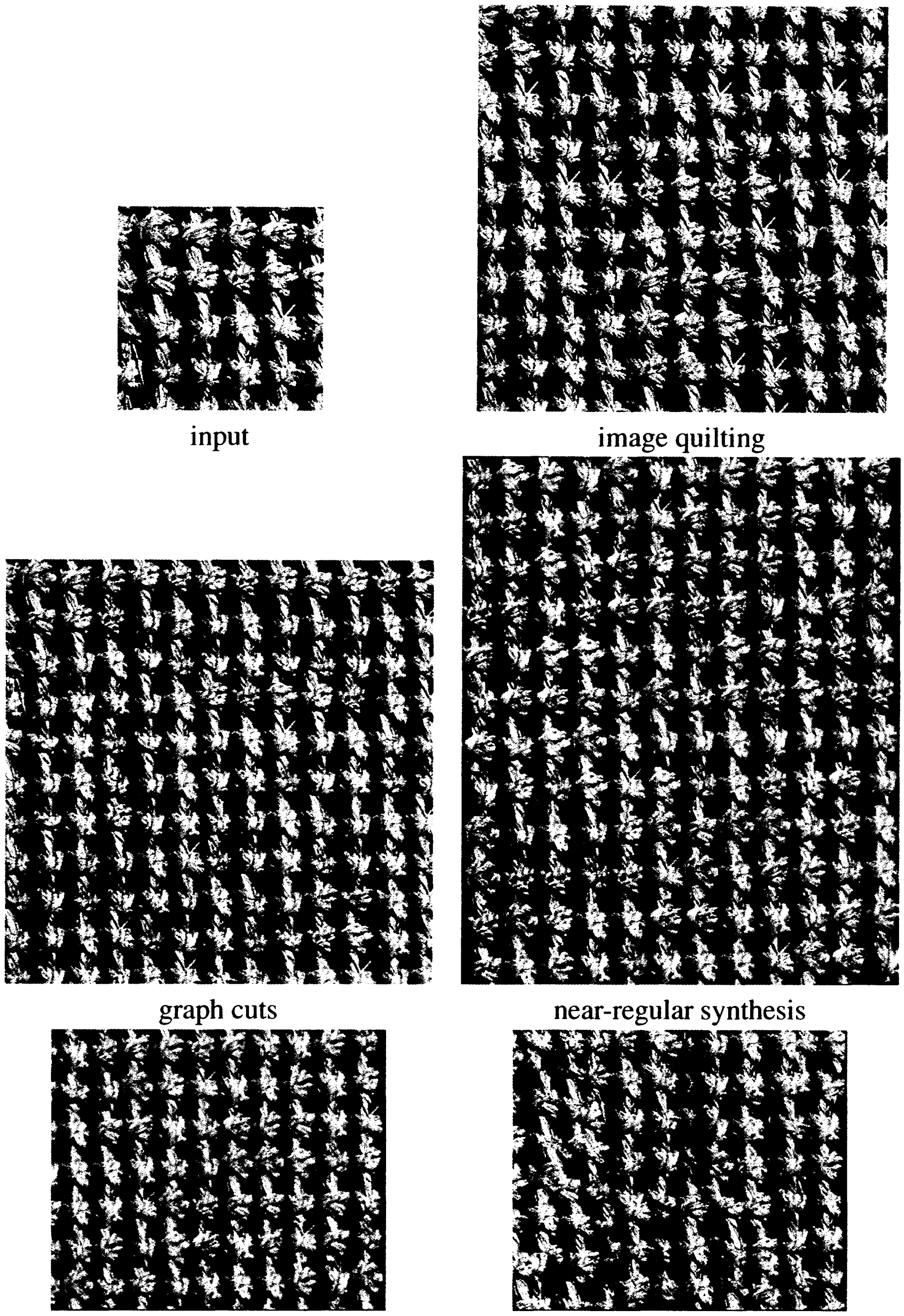


Figure 22: Synthesis results of a knot mat texture. Global regularity is not preserved in the patch-based result.

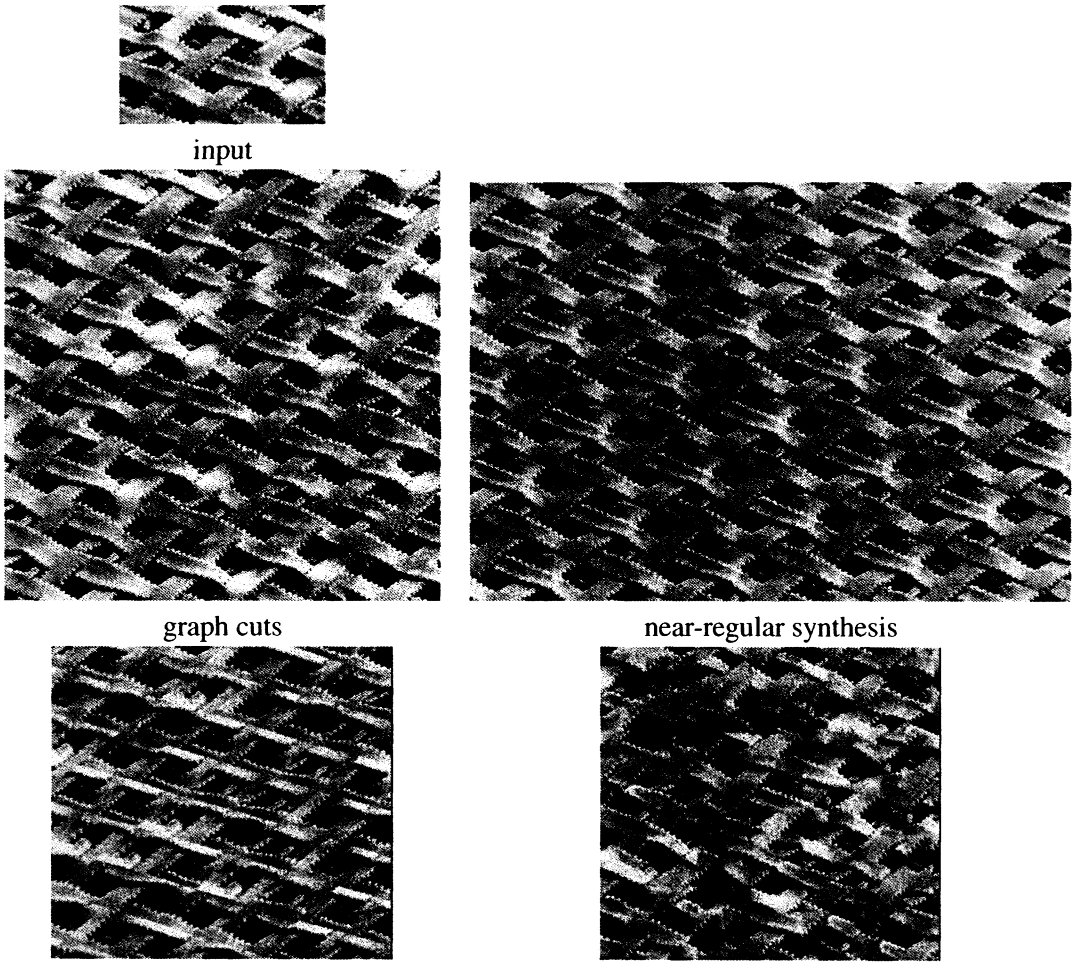


Figure 23: Synthesis results of a fabric texture. Near-regular synthesis result almost preserves the interwoven structure except there are some artifact edges in the intersections.

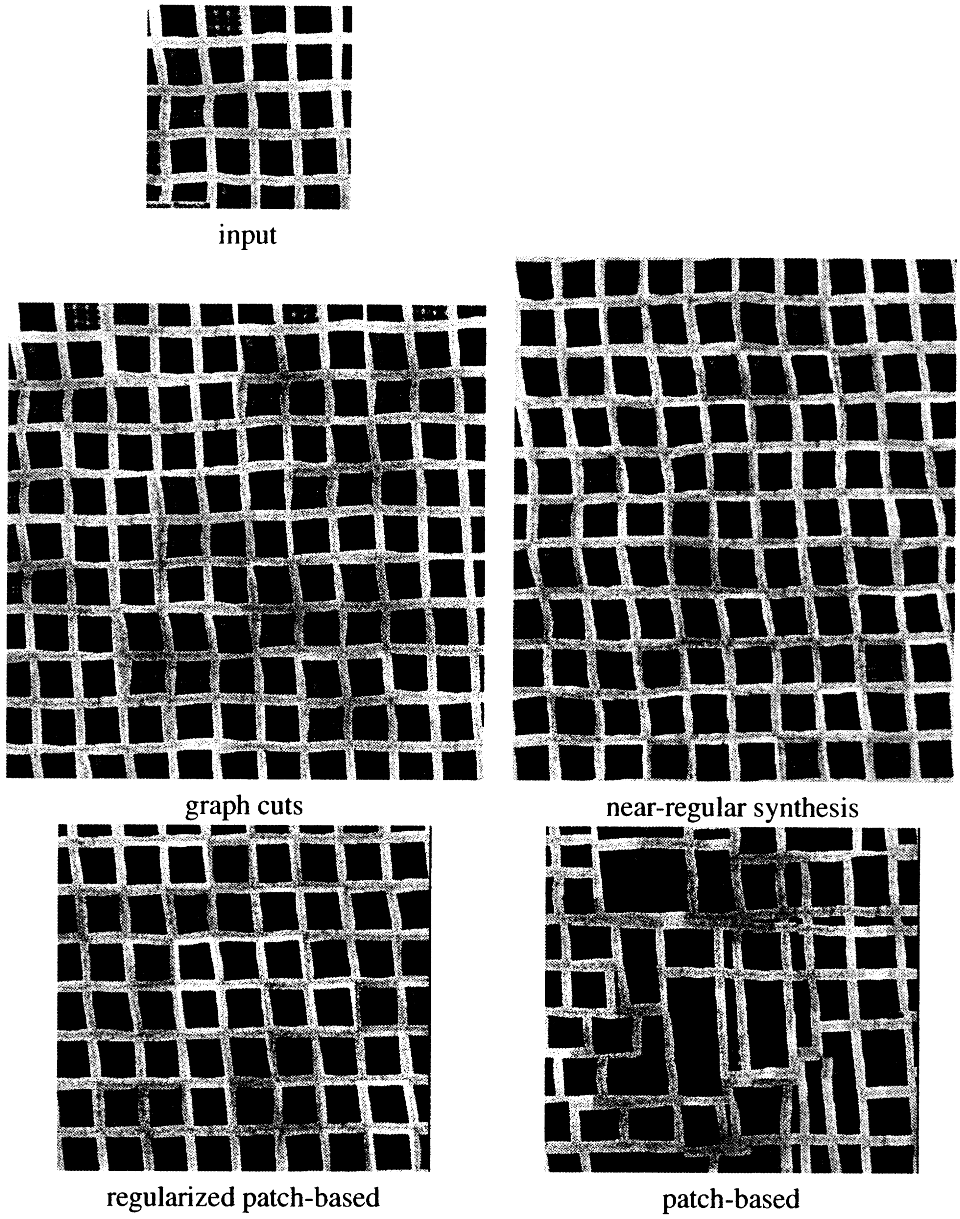
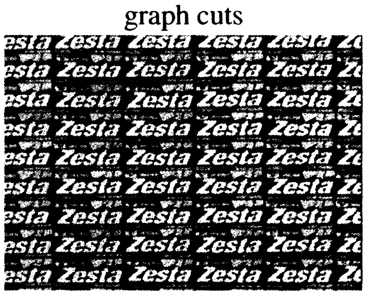


Figure 24: Synthesis results of a fabric texture. Global regularity is preserved in graph cuts, near-regular synthesis, and regularized patch-based results.

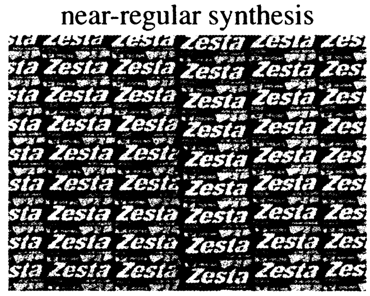
input

graph cuts

near-regular synthesis



regularized patch-based



patch-based

Figure 25: Synthesis results of a toothpaste texture.

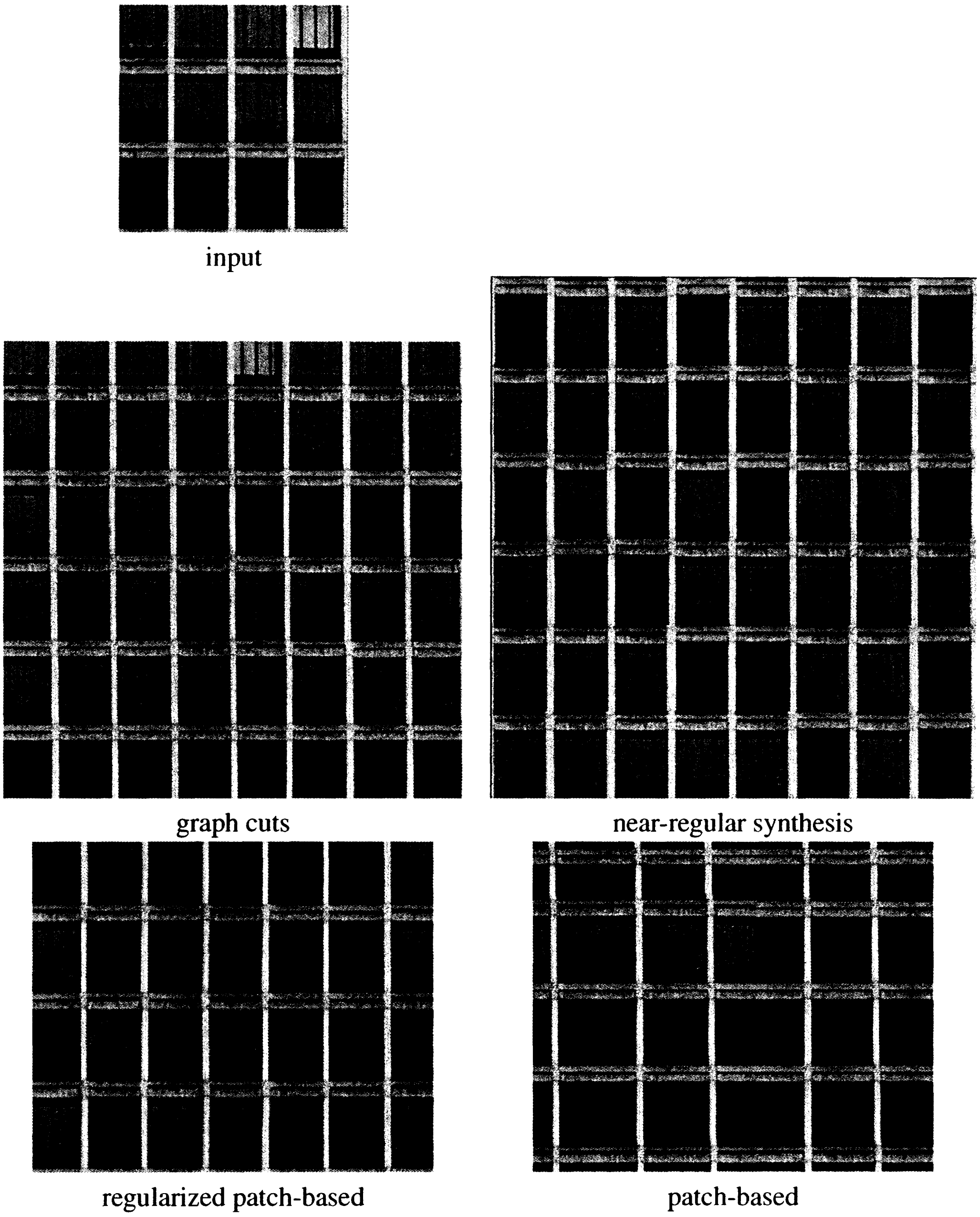
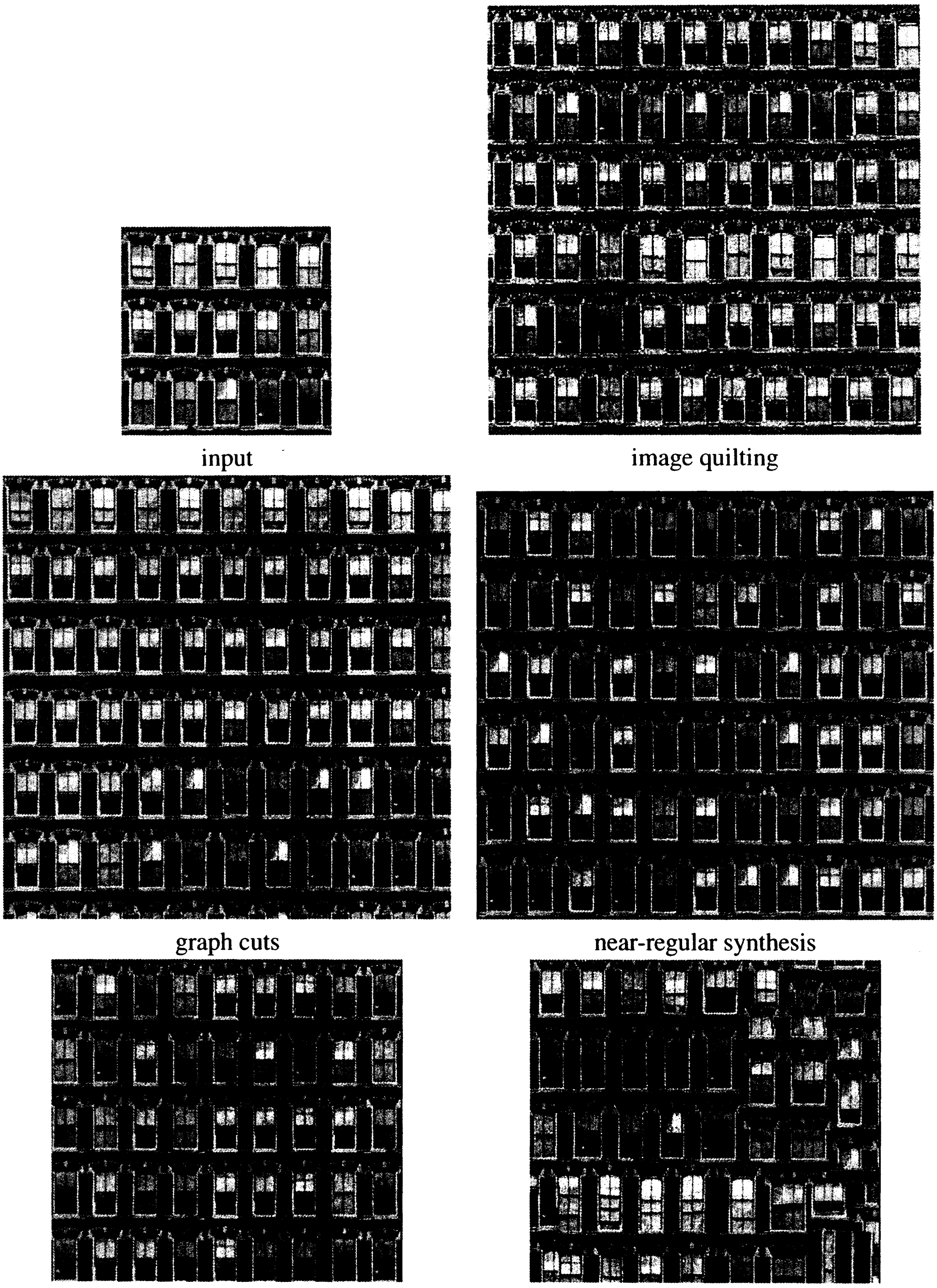


Figure 26: Synthesis results of a window texture. The size of windows is varied in the patch-based result.



input — image quilting — graph cuts — near-regular synthesis — regularized patch-based — patch-based

Figure 27: Synthesis results of a window texture. Global regularity is violated in patch-based approach.

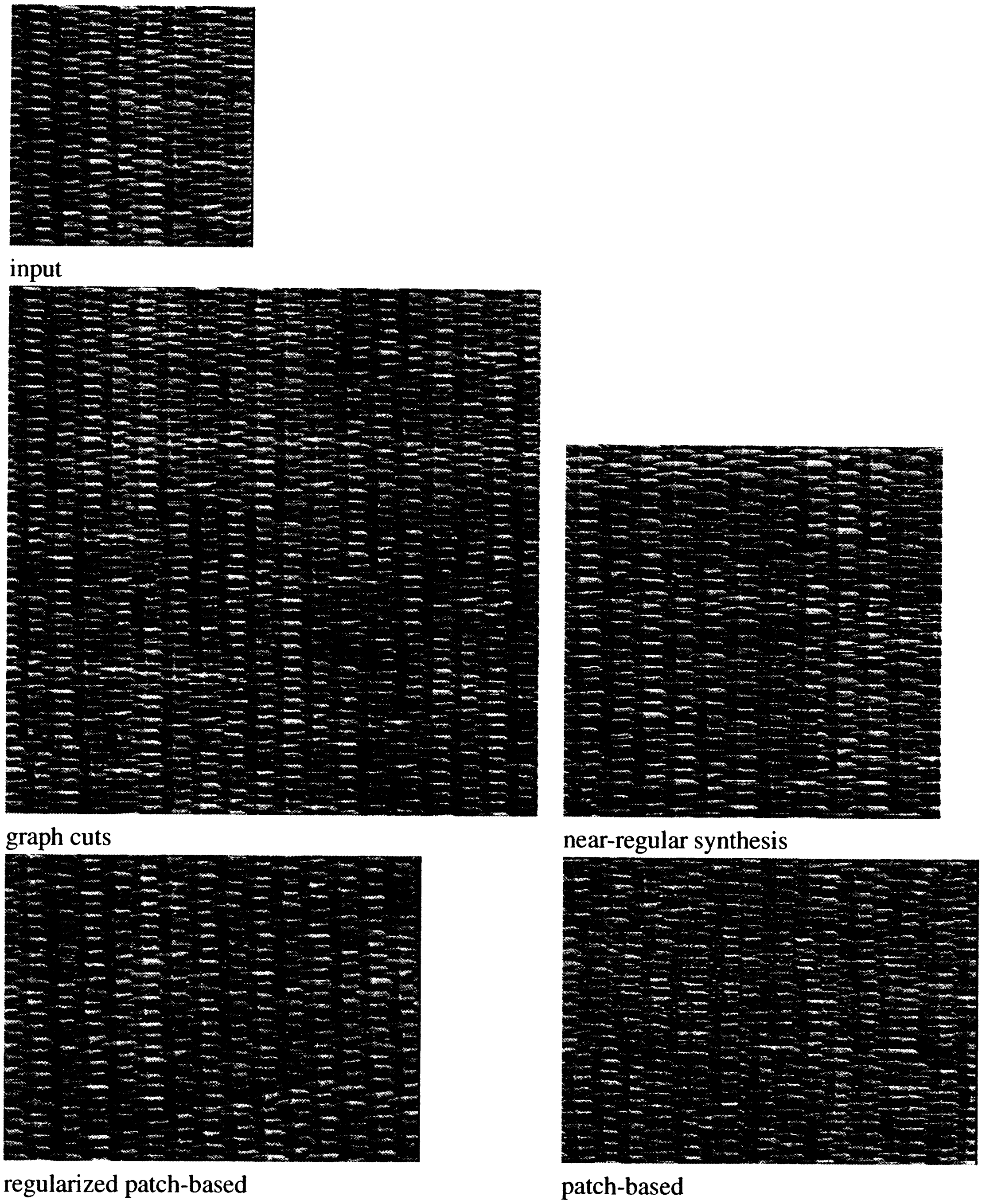


Figure 28: Synthesis results of a fabric texture. In the graph cuts result and patch-based result, there are some vertical straws are disconnected.

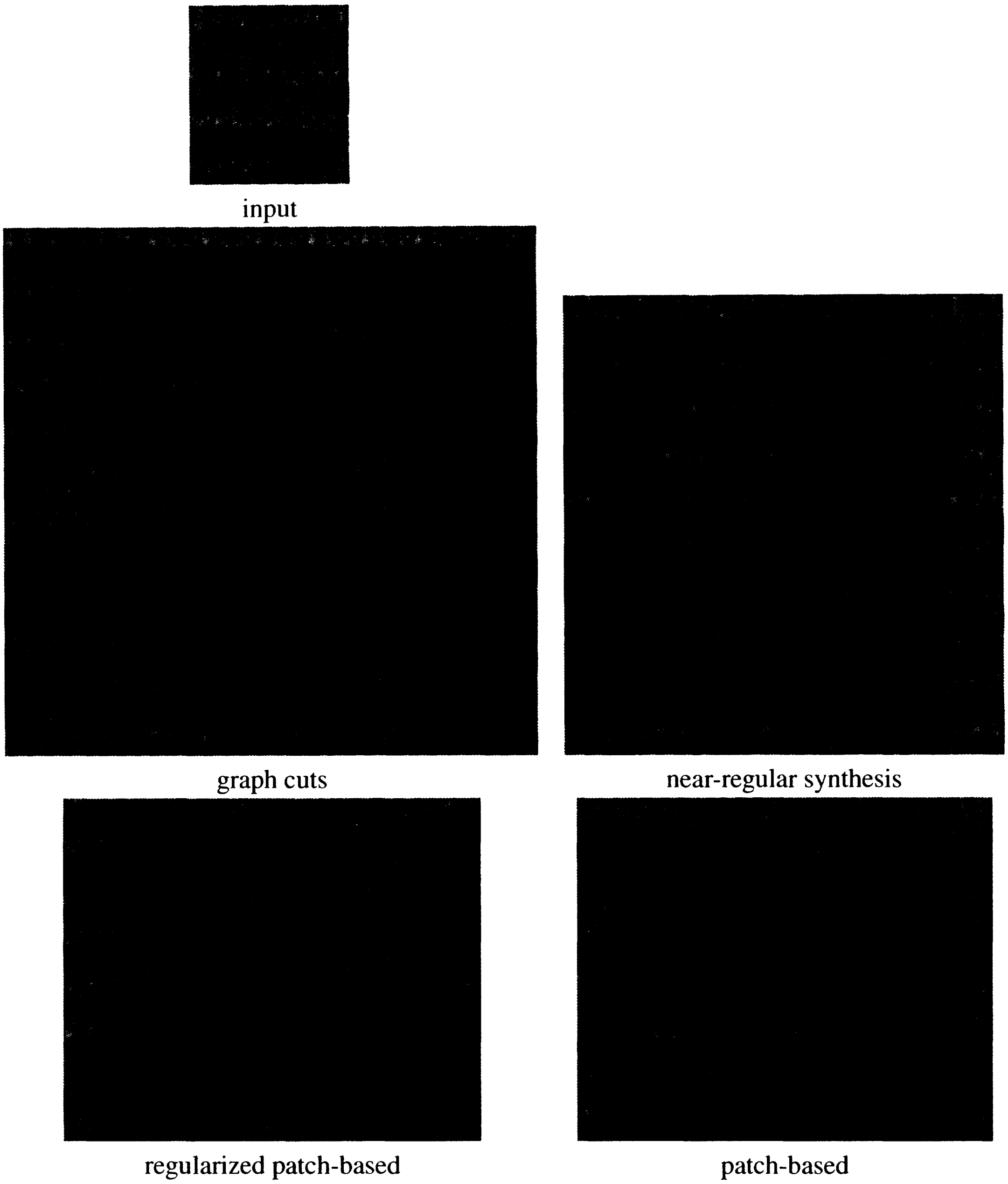
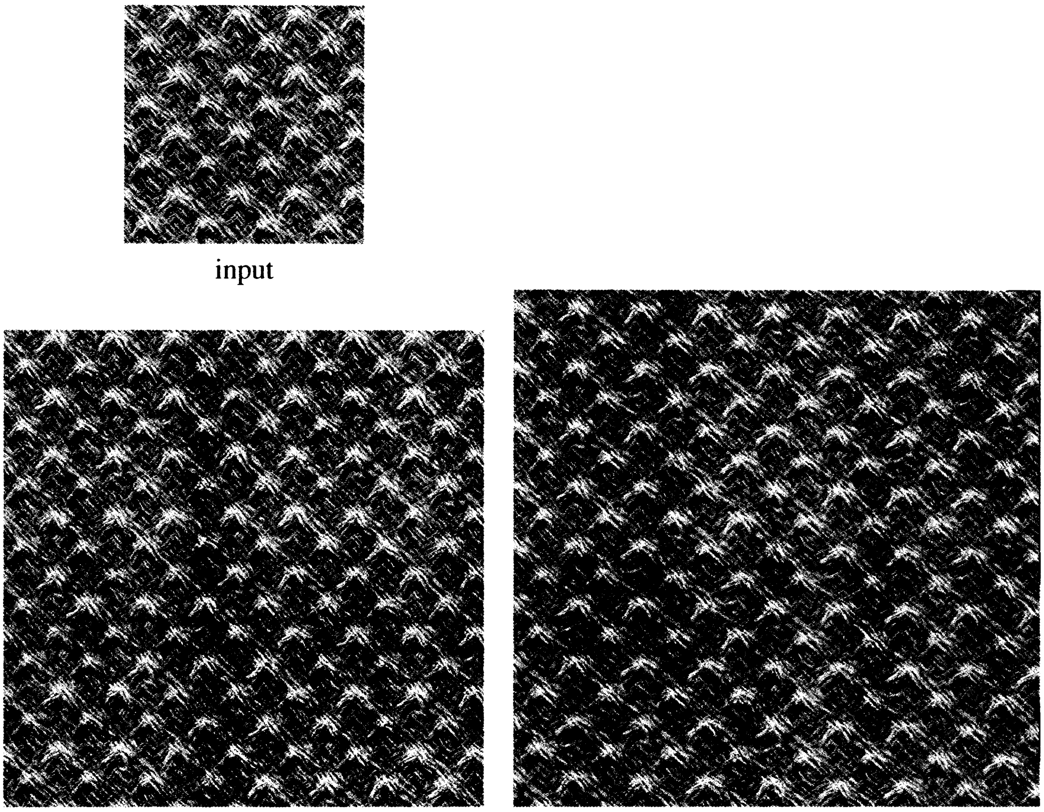


Figure 29: Synthesis results of a basket texture. Note that the orientation of texture in the regularized patch-based result is not correctly synthesized.

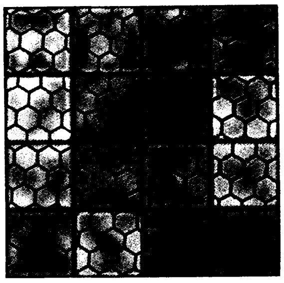


input

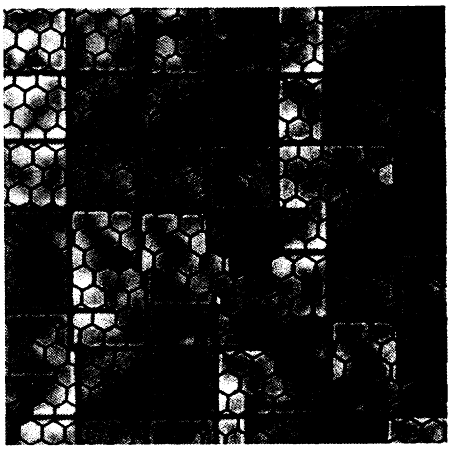
graph cuts

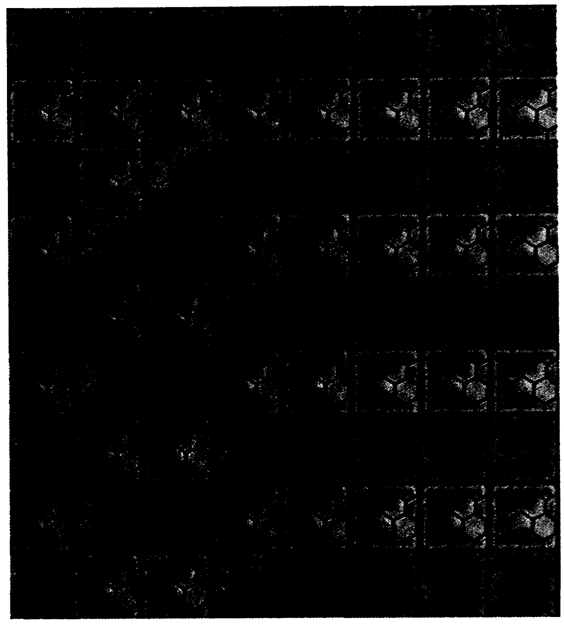
near-regular synthesis

Figure 30: Synthesis results of a fabric texture.



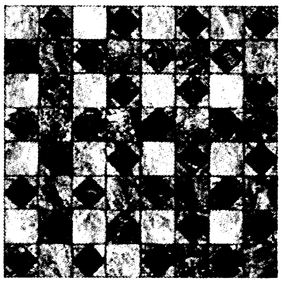
input



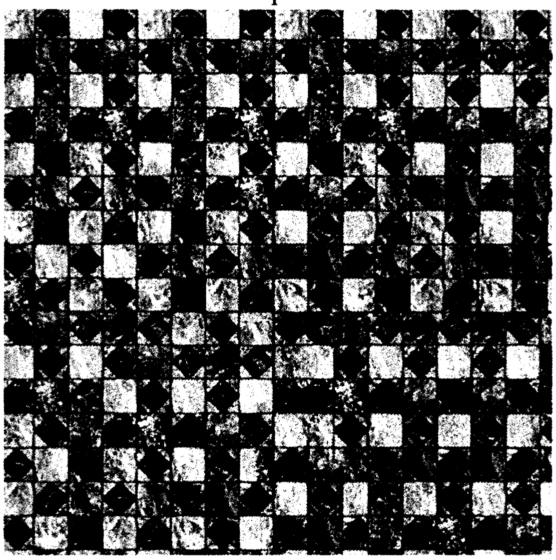


graph cuts near-regular synthesis

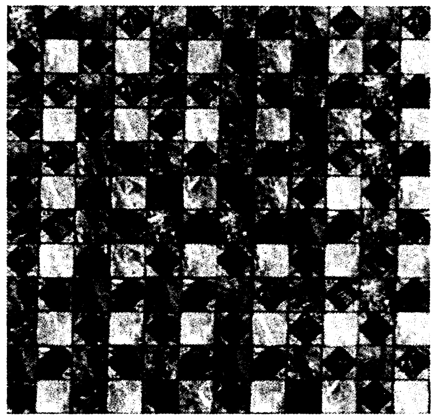
Figure 31: Near-regular texture synthesis result preserves the regularity of the squares, but the hexagon net structure is not maintained. We consider both algorithms failed in this texture.



input



graph cuts



near-regular synthesis

Figure 32: Synthesis results of a mosaic texture. The regularity of the squares is not preserved in the graph cuts result.

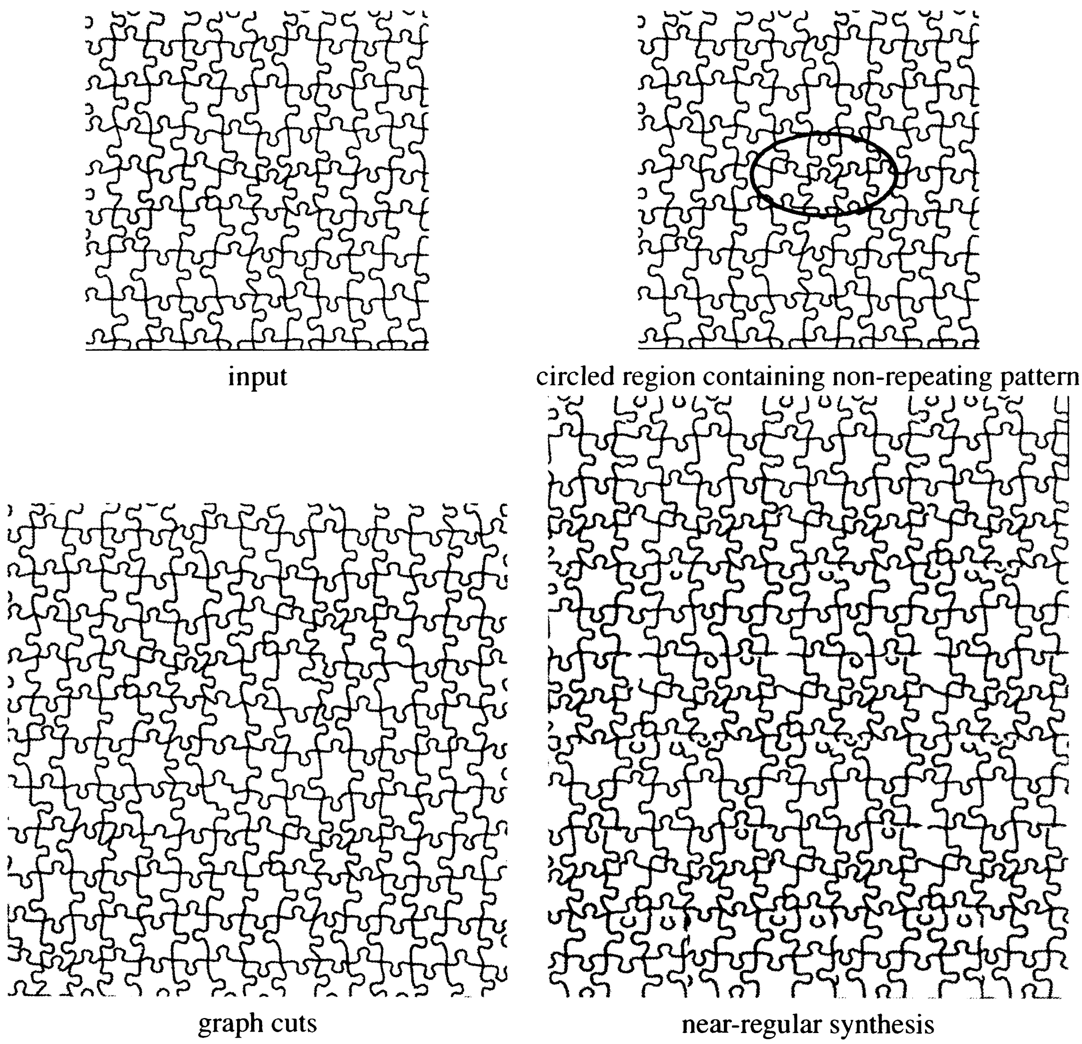


Figure 33: Synthesis results of a jigsaw puzzle texture. The global regularity of this texture is not easy to observed. Near-regular texture synthesis can not preserve the regularity of this texture. The upper-right image shows that the input texture does not contain a complete tile as the pattern in the circled region only appears once in the texture.

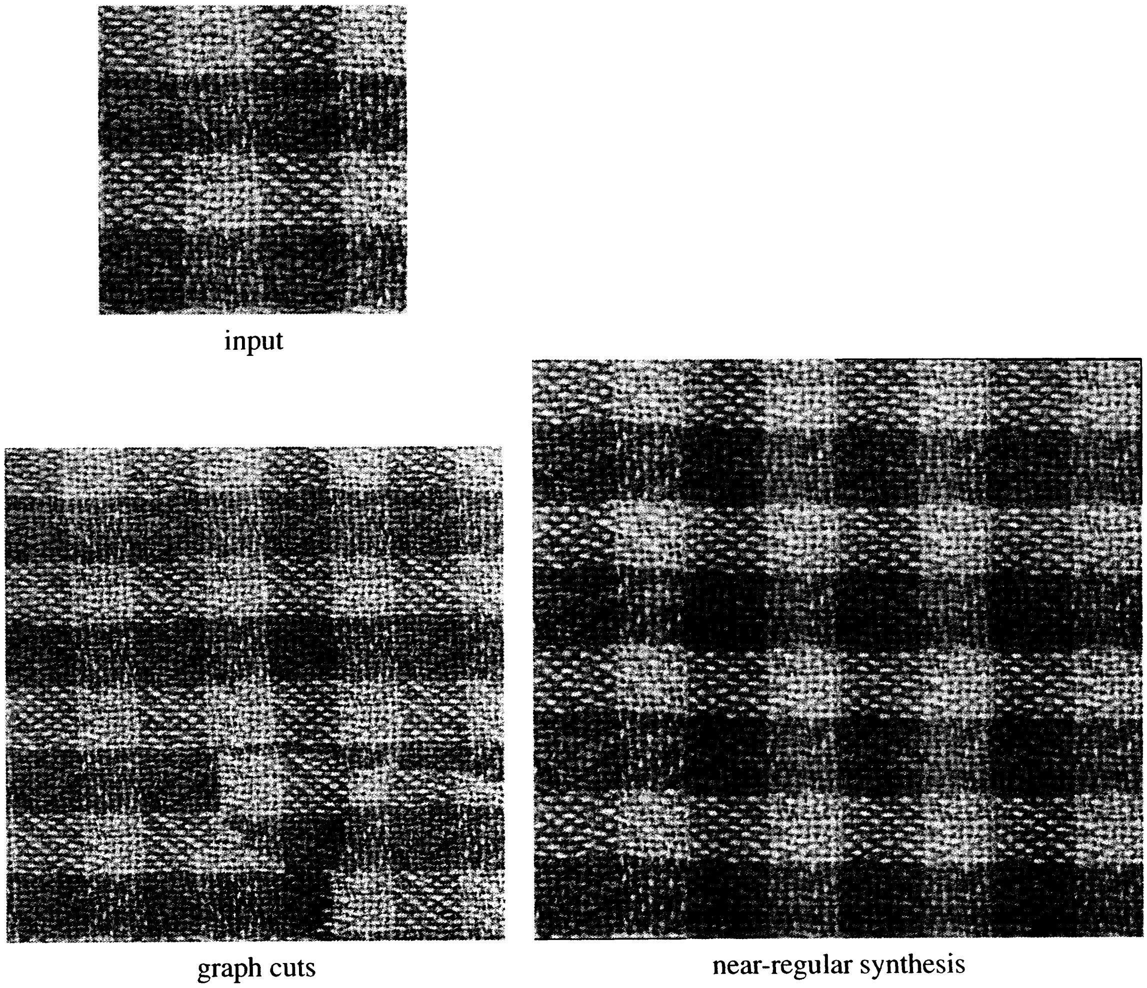
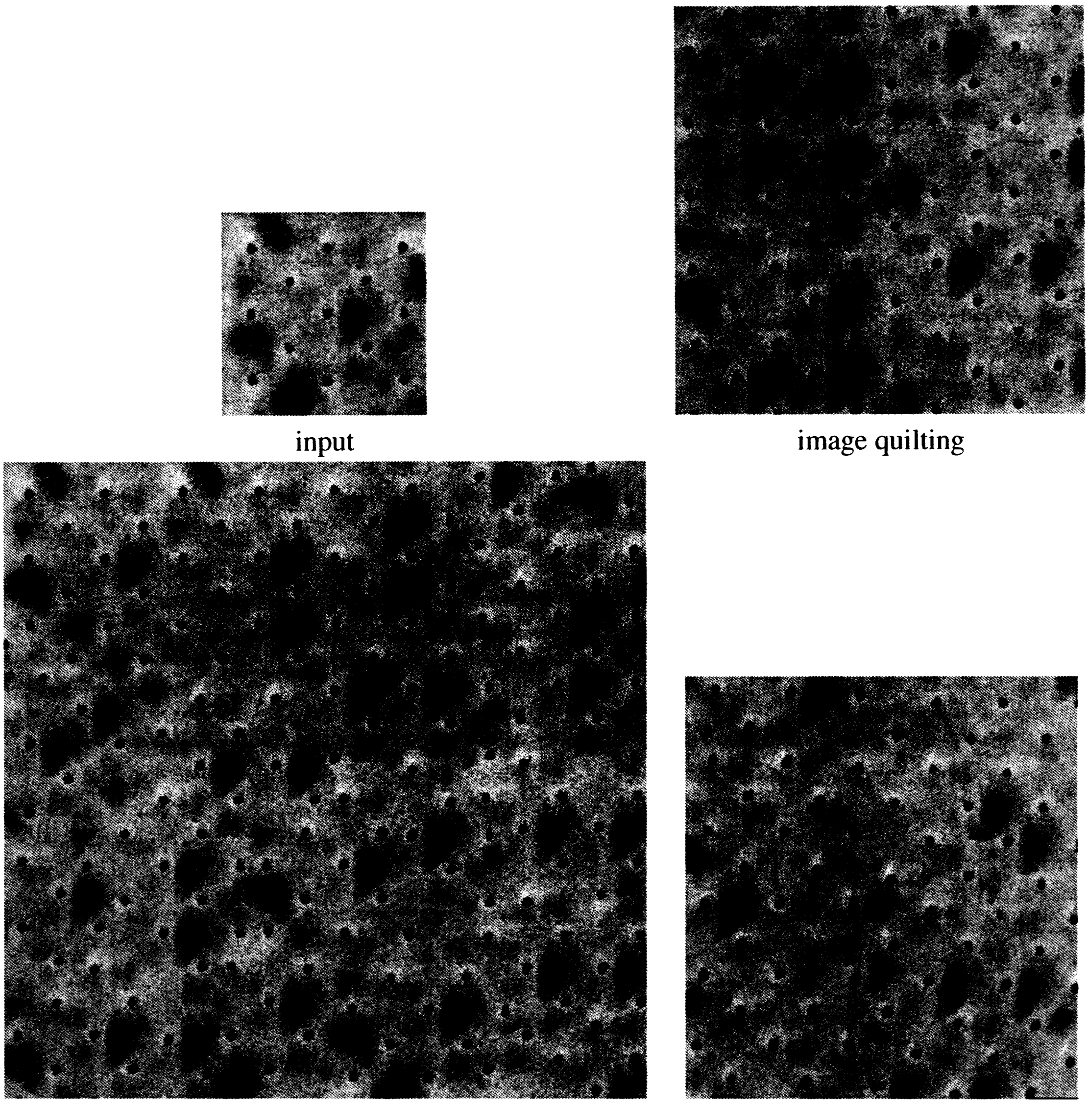


Figure 34: Synthesis results of a fabric texture. Global regularity is not preserved in the graph cuts result.



input | image quilting | graph cuts | near-regular synthesis

Figure 35: Synthesis results of a biscuit texture. There are some misplaced small holes in the image quilting and the graph cuts results.

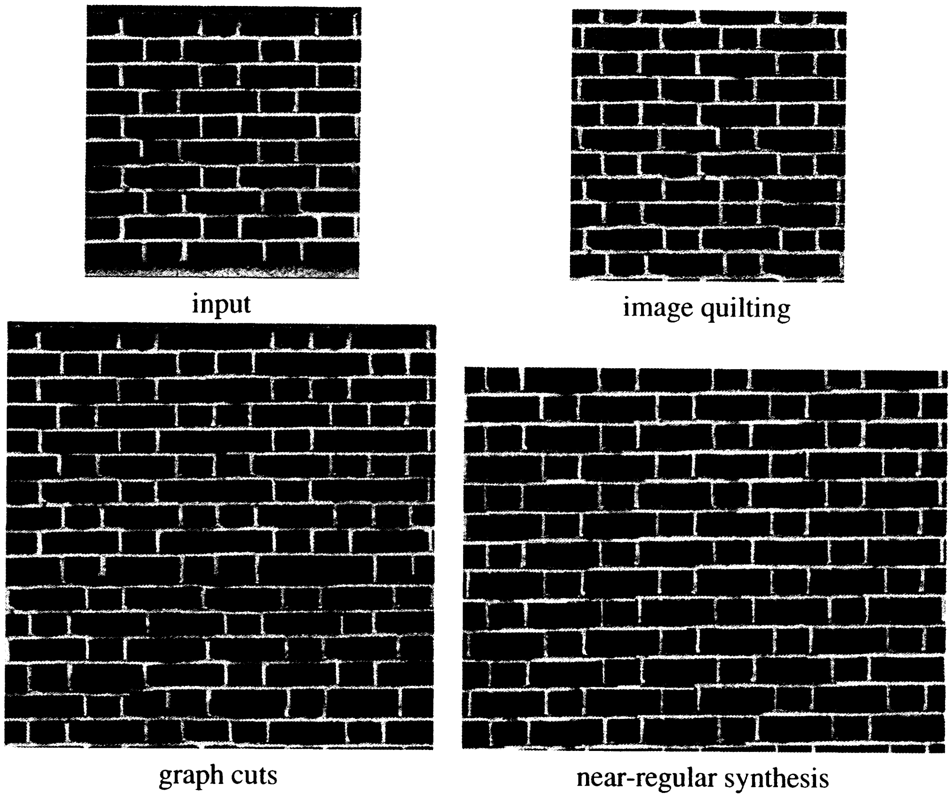


Figure 36: Synthesis results of a brick wall texture. The regularity of the grout structure is not maintained in the image quilting and graph cuts results.

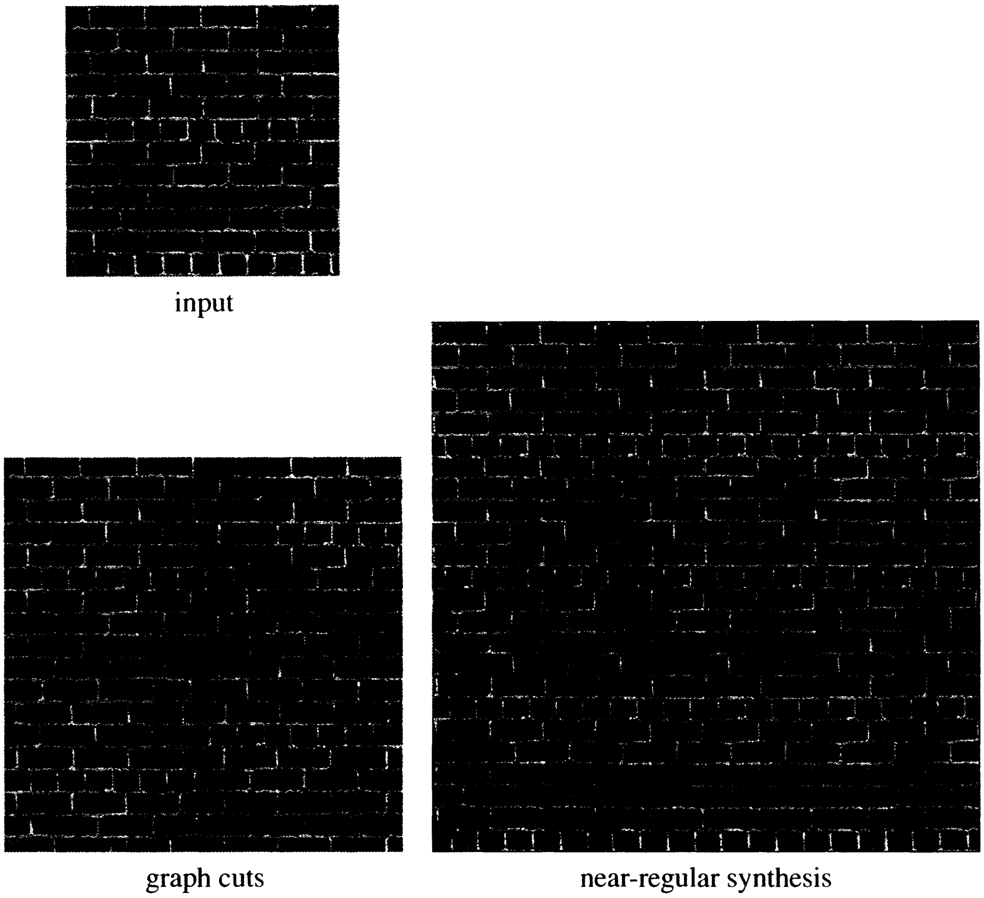
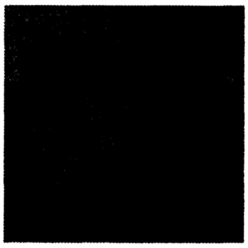
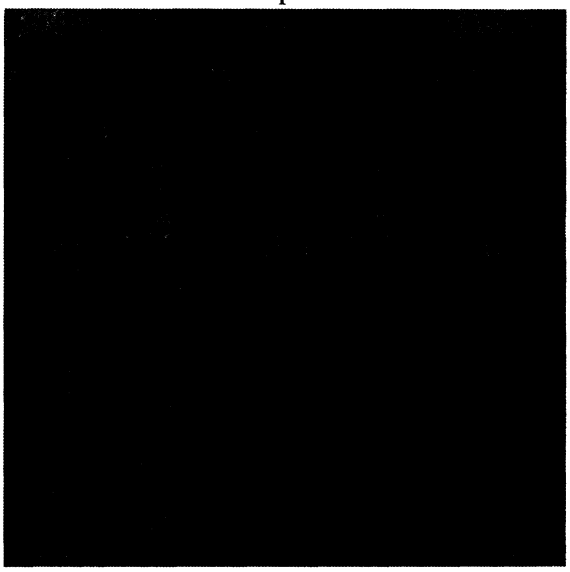


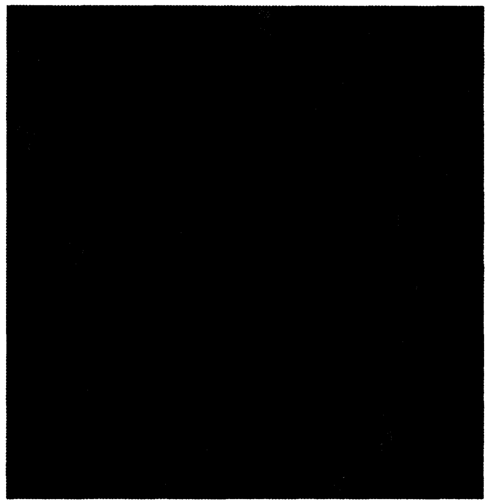
Figure 37: Synthesis results of a brick wall texture. The regularity of the input texture is that there is a row consisting of smaller bricks in every six rows. The graph cuts result does not keep this regularity.



input

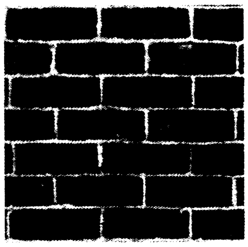


graph cuts

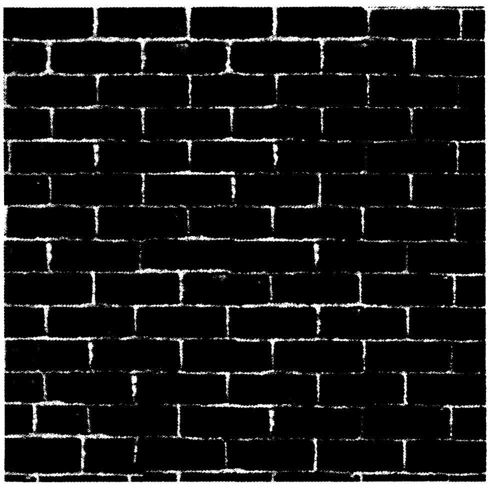


near-regular synthesis

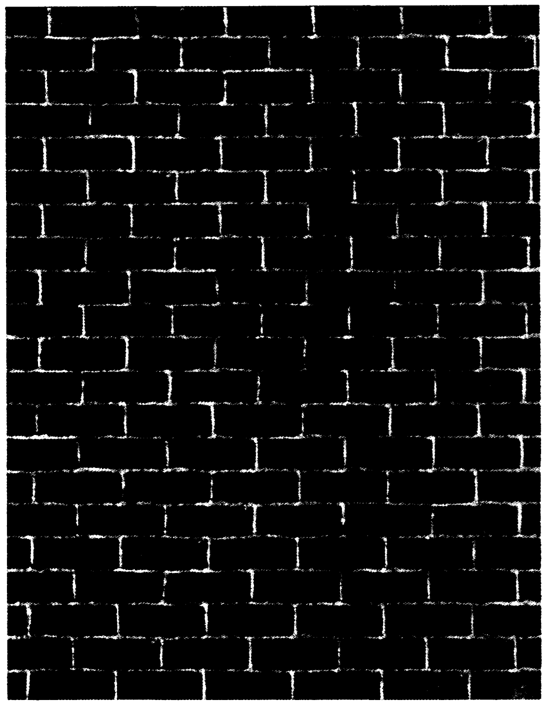
Figure 38: Synthesis results of a brick wall texture. In the graph cuts result, the size of some bricks in the 5th and 6th row is 50% larger than the others.



input



graph cuts



near-regular synthesis

Figure 39: Synthesis results of a brick wall texture. Global regularity is preserved in both results.

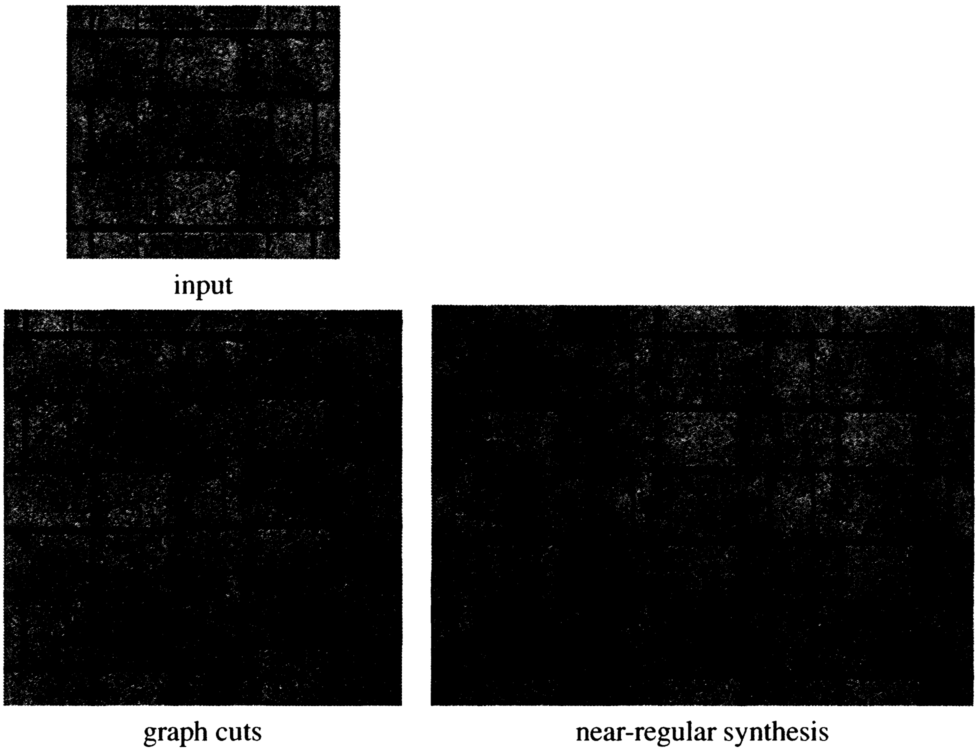


Figure 40: Synthesis results of a brick wall texture. The graph cuts result does not preserve the global regularity.

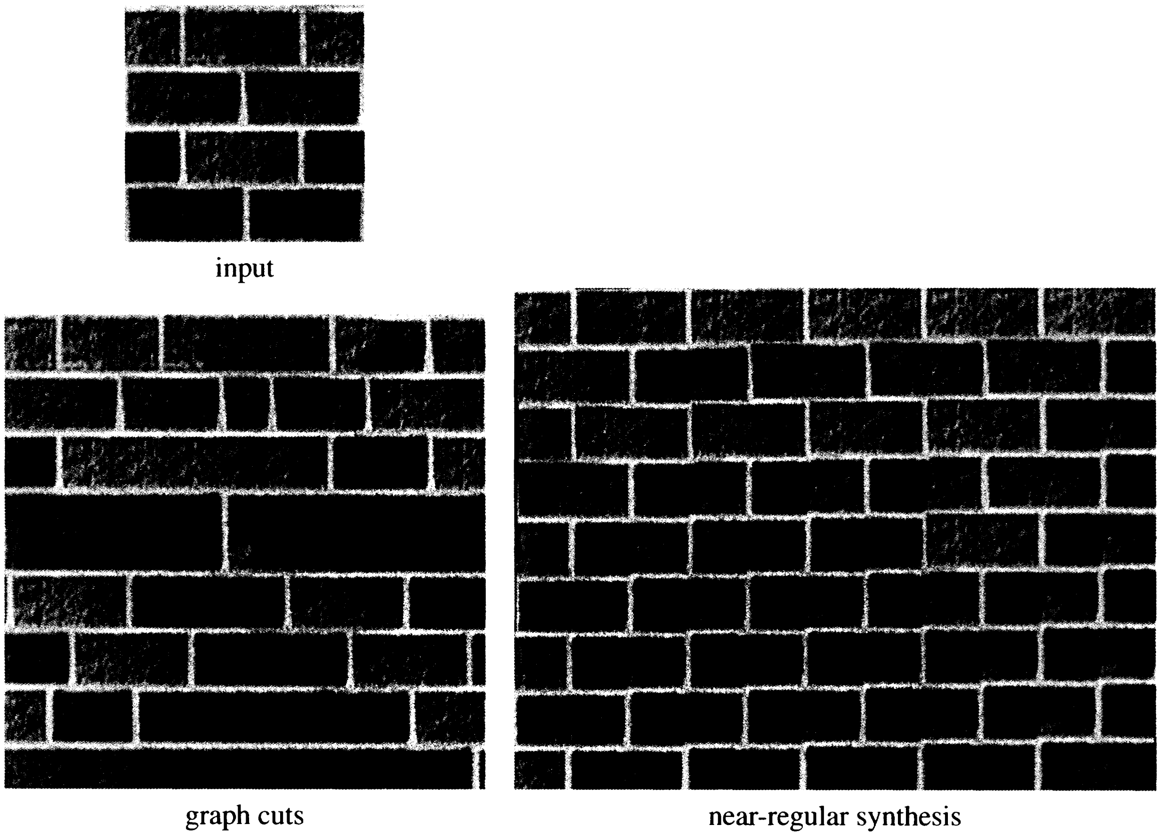
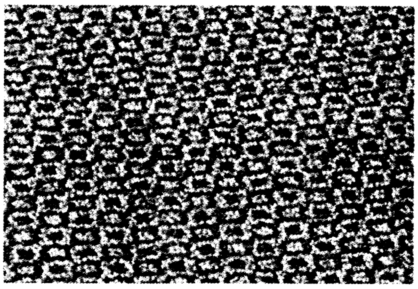
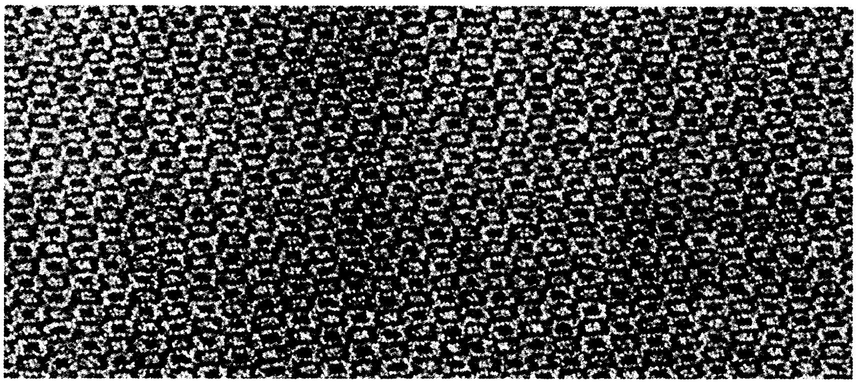


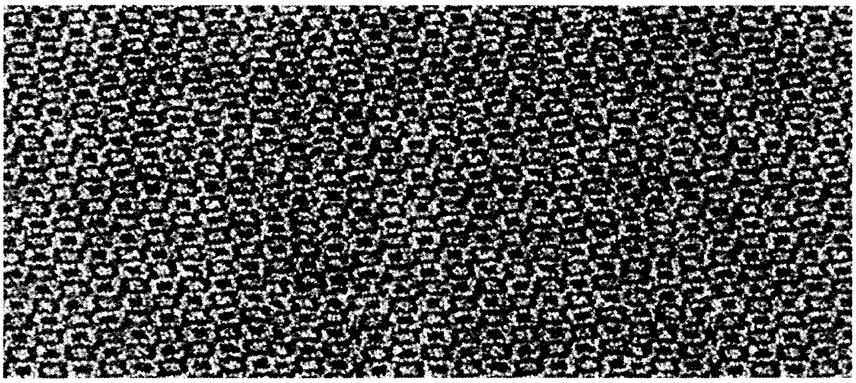
Figure 41: Synthesis results of a brick wall texture. The grout structure is not preserved in the graph cuts result.



input



graph cuts



near-regular synthesis

Figure 42: Synthesis results of a carpet texture.

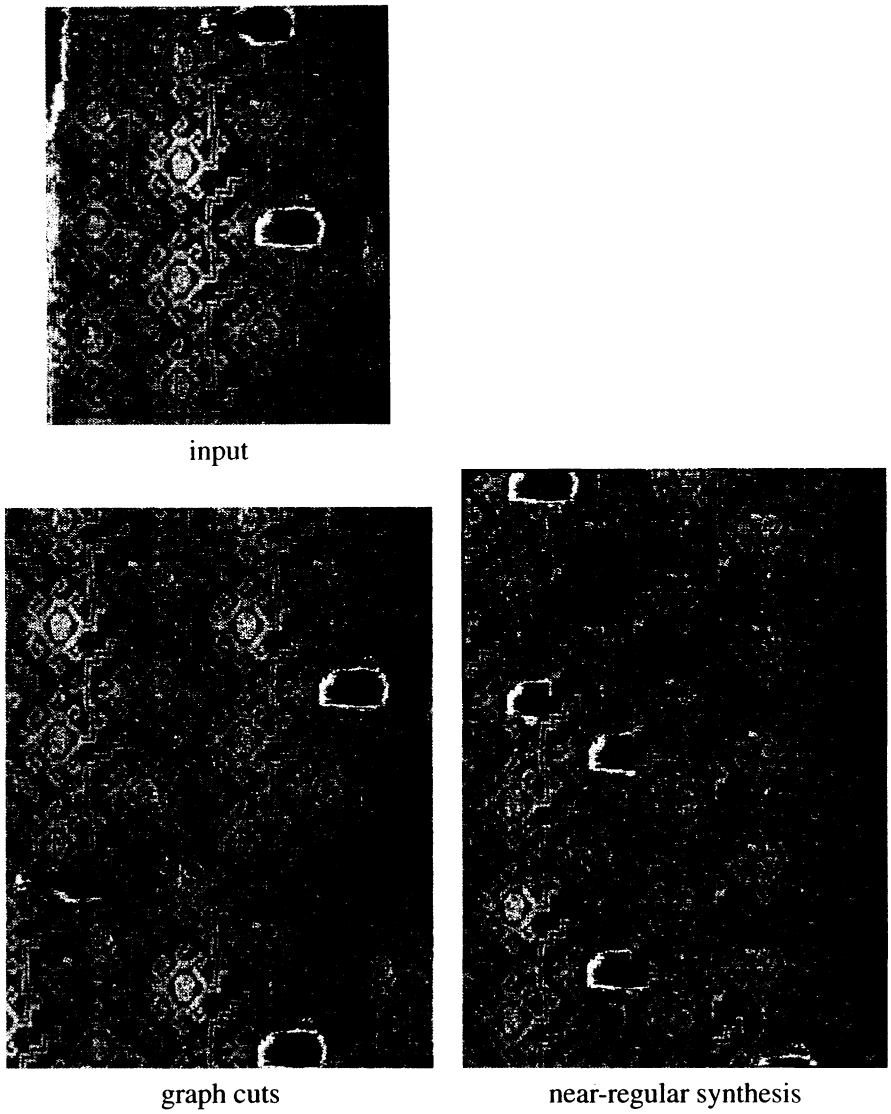


Figure 43: Synthesis results of a rug texture. Global regularity is not preserved in the bottom portion of the graph cuts result.

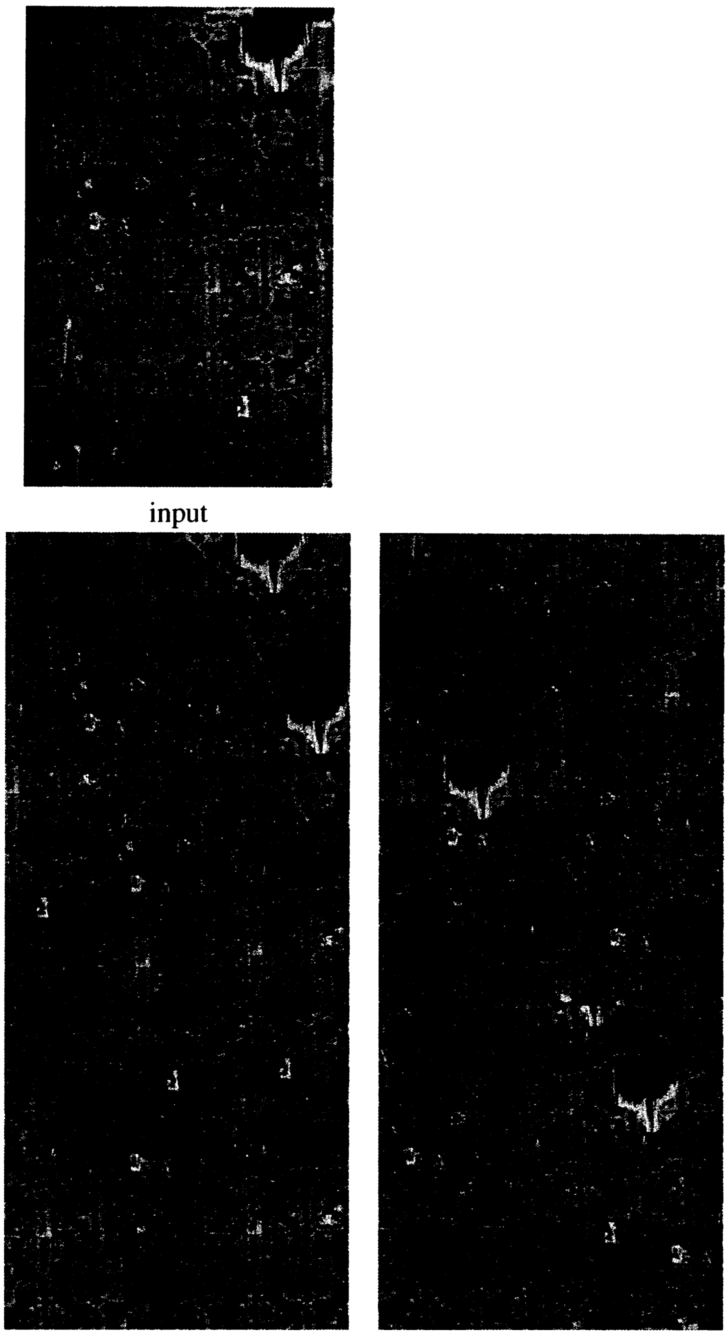
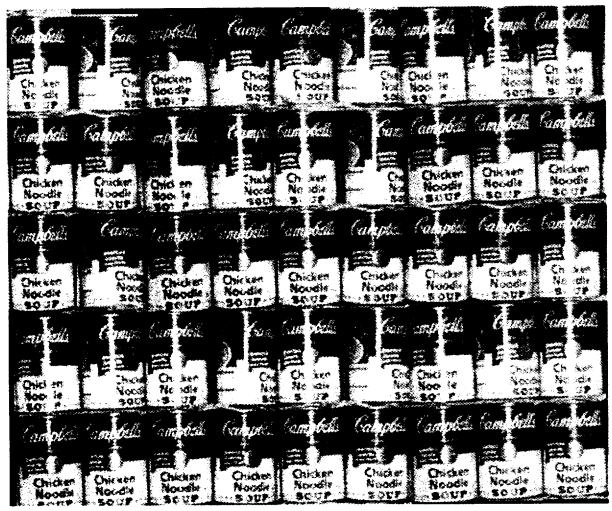


Figure 44: Synthesis results of a rug texture. Vertical patterns are not aligned at the middle part of the graph cuts result.

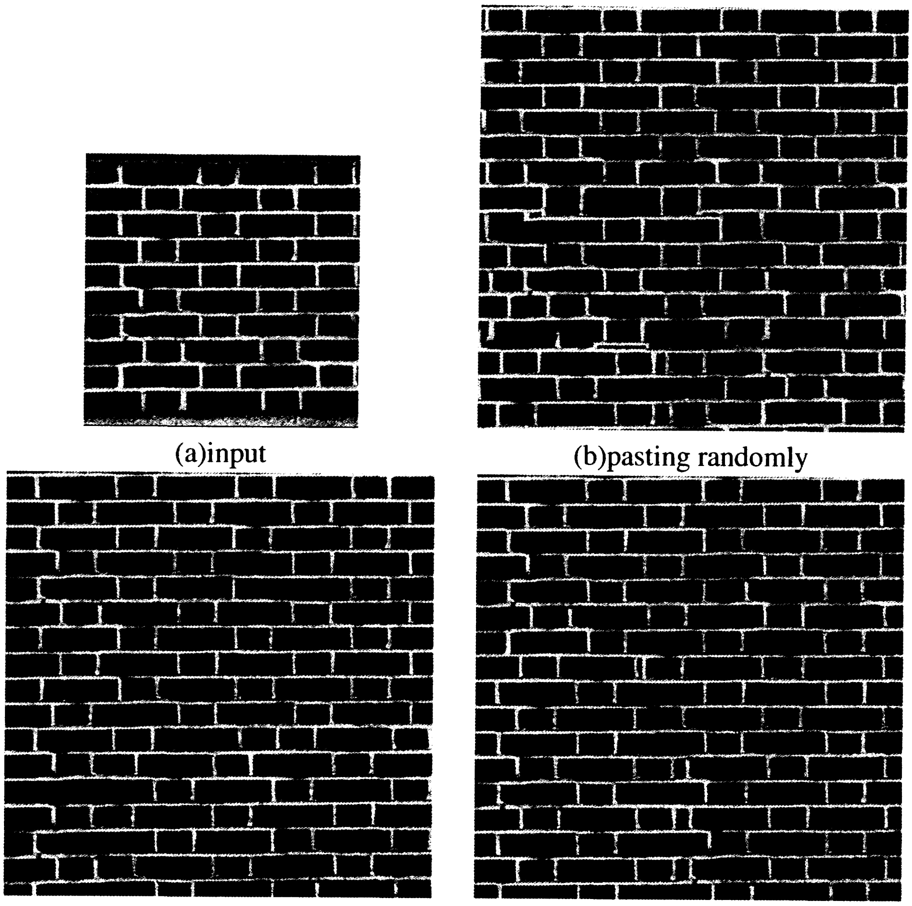
input

graph cuts



near-regular synthesis

Figure 45: Synthesis results of a texture of cans. Some cans in the 5th and 6th rows of the graph cuts result are not synthesized correctly (bottom-right area).



(a)input (b)pasting randomly

(c)pasting at local minima (d)pasting at local minima and maxima

Figure 46: This figure shows the results by different settings of the patch placement in the graph cuts approach. In synthesis process, an error map is computed using seam cost around each pixel and then the location around which we want to paste. The new patch is picked by sampling from this error map. The results shown are obtained respectively by (b)picking the location to patch randomly, (c)computing a local minima for these error values and picking a location from one of these, (d)computing both local minima and maxima and picking a location from one of these. The synthesis result of the same texture by the near-regular synthesis approach is shown in Figure 36.

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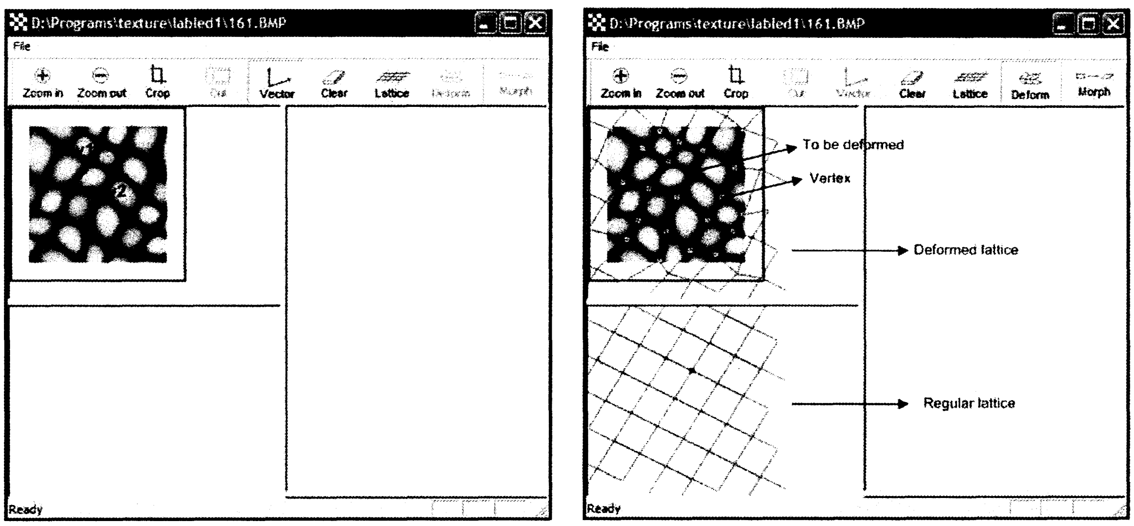
A Regularized patch-based approach

In near-regular texture synthesis, it is desired to extract the "texton", which is the basic element in the texture image. We consider the near-regular texture as an array of arbitrarily deformed textons. We build a regular lattice and warp the original deformed textons to the regular shapes. Then we can synthesize the regular texture. Finally, we compute a deformation field and warp the regular texture to the nearly one.

The whole system includes two parts. One is for analysis and the other is for synthesis. The analysis process is semi-automatic. We design an interface for users to select textons, build and deform the regular lattice. Then we can automatically synthesize the regular texture by using the patch based method, and the deformed near-regular texture by warping. Figure 47 illustrates how to select a texton, which corresponds to quadrilateral or hexagon. We use two vectors to specify the quadrilateral. Then we can automatically build a regular lattice.



(a) (b)

Figure 47: This figure illustrates how to select a texton, which corresponds to quadrilateral or hexagon. (a) The user draws two vectors to specify the quadrilateral. (b) a regular lattice is then automatically constructed based on the two vectors.

In order to get the regular textons, we need to compute the warp field between the deformed lattice and regular lattice, which are showed in Figure 47(b). In our method, we manually deform the lattice to match the deformed textons, and then we use the vertices in the deformed lattice and regular lattice as correspondence. We use the multilevel free-form deformations (MFFD)[8] to calculate a warp field based on the correspondence between the regular and deformed lattice.

We modify the patch-based approach to synthesize the regular texture based on the regular textons. Figure 48 illustrates the synthesized regular texture. The regularized patch-based approach is very similar to the original patch-based method but two differences. One is in the generating order. In the standard method, the synthesis follows the scan-line. Here we follow the order of regular lattice generation. The earlier the vertices of a texton are found, the earlier the texton is "patch-pasted". The other difference is about the patch. In the standard method, the patch is searched in the whole image. Here the patch can only be selected from the set of textons in the warped image. Figure 48 shows a generated large regular texture based on the patch-based method.

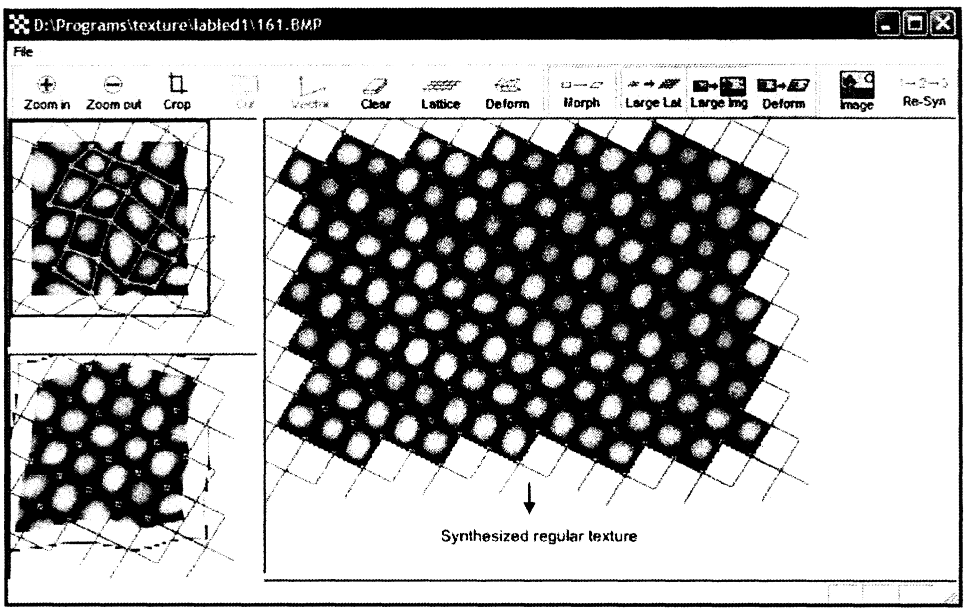


Figure 48: After a texture is regularized, the patch-based approach is used to synthesis this texture. The right window shows the result.

In order to generate the near-regular texture (deformed texture), we need to compute the deformation field. Inspired by the theory of Markov Random Field, for quadrilateral texton, each vertex in the deformed lattice is affected by its eight neighbors. For example, in Figure49, the yellow knot represents the vertex M, and eight orange knots represent the neighbors of M. Each neighbor can be discriminated by its relative position to the center vertex, such as left-top, top, right-top, right, right-bottom, bottom, and left-bottom. We can build a distance density map $p_i(x - x_0, y - y_0)$ for each neighbor. For each center vertex $M(x_0, y_0)$, if its neighbor $N_i(x, y)$ exists,

$$p_i(x - x_0, y - y_0) = \frac{1}{Z}\exp\left(-\frac{dist(M(x_0, y_0), N_i(x, y))}{2\sigma^2}\right) \quad (1)$$

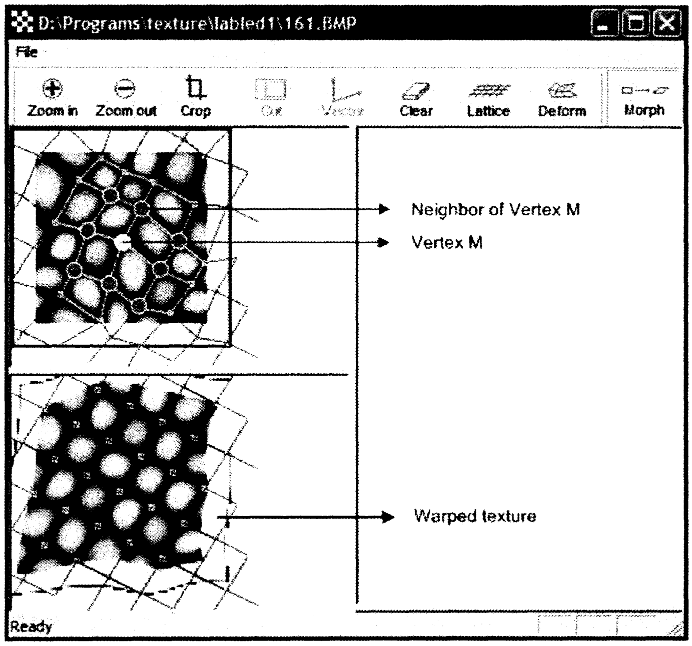


Figure 49:

Then we can generate a deformation field as follows.

1. Initialize the deformed lattice by randomly moving each vertex in the regular lattice within a small window.

2. Deform the lattice iteratively:
   In each round, given a vertex $M(x_0, y_0)$ and a small window $[x_0-\sigma_x, x_0+\sigma_x, y_0-\sigma_y, y_0-\sigma_y]$, its neighbors are $N_i(x_i, y_i), i = 1, 2, ..., 8.$ we can compute the likelihood as follows:

$$p(x0 + dx, y0 + dy) = \prod_i p_i(x_i - (x0 + dx), y_i - (y0 + dy)) \tag{2}$$

   where $dx \in (-\sigma_x, \sigma_x)$ and $dy \in (-\sigma_y, \sigma_y)$ are the displacement of the vertex.
   The optimal position of M can be obtained by

$$(dx^*, dy^*) = arg \max_{dx,dy} p(x0 + dx, y0 + dy) \tag{3}$$

   The method is sensitive to the parameters such as σ_x and σ_y. In other words, the parameters are relative to the size of textons

After we get the regular and deformed lattice, we can warp the synthesized regular texture in the same way mentioned before.