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Digital Restoration of Medieval Tapestries

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Abstract

Medieval Burgundian tapestries belong to the most valuable treasures of historical museums, in particular of the Bern Historical Museum. Many of them are well preserved, but much of their color is highly faded. Thus their today's appearance is very different from the original one. This paper deals with the digital restoration of the appearance of such tapestries. Two methods are developed and examined, one using the back side of the tapestry, the other one using color clustering. Our main criteria are a convincing approximation of the expected appearance and - due to the large size of many of the tapestries - a high degree of automation.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Image processing and computer vision]: Restoration of tapestries, registration, color clustering

1. Introduction

The present paper deals with a rather special but important part of Cultural Heritage, namely the famous Burgundian tapestries dating from the epoch 1440-1515. These wall tapestries are valuable because of their historical, artistical and manufactural significance. Many of them are very big, e.g. 10m in width and 5m in height. Our work has been performed in collaboration with the Bern Historical Museum which owns a large collection of about a dozen of such tapestries.

The Burgundian tapestries in the Bern Historical Museum are well preserved, but their colors are often highly faded. This reduces their artistical quality, in particular their plastical appearance, and makes it difficult to judge them in an objective way. In the past, these tapestries have been restored "classically" several times: a number of patches have been applied, and - worse - some of the weaving has been redone. These restorations are certainly not as doubtful as in many other cases, but they too have modified the originals in an irreversible way. Therefore, there was enough motivation to make digital "copies" of some of these tapestries and to try to recover their original appearance by means of these copies. Although nobody will ever know exactly how the original tapestries looked like, there exists enough knowledge to judge reconstructions reasonably well. Beside obtaining a good appearance of the digital reconstructions, a high degree of automation is attempted because of the large size of many of the tapestries.

In this paper we develop and discuss two restoration methods, one using the back side of the tapestry, the other applying color clustering. Both use standard techniques from image processing but have to adapt them to the given special application. With both methods we get promising results, but the frequent classical repairs as well as "noise" due to the weaving process set limits to the degree of automation we can achieve. Our paper is organized as follows: after a short discussion of related work and an introduction to Burgundian tapestries, we present our two approaches in detail and indicate their advantages and limits. Then we try a short direct comparison of the two methods and end our paper by giving some conclusions and an outlook to possible further work.

2. Related work

Digital preservation and reconstruction is a wide field and includes manuscripts, newspapers, books, photographs, films, paintings and sculptures. But to our knowledge there exists no work dealing specifically with the reconstruction or preservation of tapestries.

2.1. Photographs

To reconstruct faded or discolored photos one can use techniques included in most image processing software packages: correction of tone, color, contrast and saturation, copying of texture, or noise and blur filters. Small errors in a homogeneous environment can often be removed by a simple interpolation of the adjacent pixels. But if larger parts of the motif are missing this technique does not succeed. Sapiro and Bertalmio developed a solution to this problem, i.e. digital inpainting attempts to replicate the techniques used by "classical" restorators [BSCB00]. Further work analyzes inpainting with automatic error recognition, global inpainting and acceleration algorithms. A summary of the state-of-the-art can be found in [Pra04].

2.2. Film

Unlike with photographs, the frames before and after a certain frame of a movie can be used to reconstruct this frame. Reconstruction of films is a large subject which cannot be discussed here. Useful information can be found e.g. in [Kok98]. The possibility to compare successive frames is important for us because, like the frames in a film, the front and back side of a tapestry can be compared.

2.3. Textiles

Adabala et al. [AMT03, AMTF03] developed a technique to render textiles with complex weaving patterns. The micro- and millistructure of textiles and single threads, respectively, and the complex refraction of light are considered. To represent a weaving pattern, three images are used. The first is a greyscale image showing the portion of warp threads at a certain place. The two others are color images which indicate the color pattern of the front and back side of the fabric. Thereby the number of different colored threads is unlimited. Further information for the modelling of textiles can be found e.g. in [GRS96, XCL*01].

2.4. Color transfer between images

Besides the techniques for digital restoration mentioned above, also color transfer between images is a relevant topic with respect to our problem. Reinhard et al. [RAGS01] perform a statistical analysis to determine the color characteristics to be transformed from one image to the other. Chang et al. [CSUN05] determine color characteristics by a classification of pixel values according to color categories which are defined by considering properties of human color perception.

2.5. Importance for the reconstruction of tapestries

A photograph or a film consists of homogeneous material. This means that all points in the picture have the same physical and chemical characteristics, thus the change of colors obeys the same laws in the whole picture. On the other hand tapestries are woven with different materials and dyed with different colors which change differently in the course of time. A global correction of the tone or color, as with the reconstruction of photographs, is not possible. Each color must be corrected individually.

Inpainting: The idea of inpainting is used in our first approach to remove disturbing features on the back side of the tapestry. Since images of the front and back side exist, a comparison of these images is used with our inpainting algorithm.

Modelling the fabric: The technique described in [AMT03, AMTF03] for modelling woven textiles could probably be adapted to the reconstruction of tapestries. The weaving pattern would have to be adapted in such a way that only weft threads are visible, and the color pattern of the front and back side would have to cover the whole tapestry, for in Burgundian tapestries no repeating patterns arise. However we do not model the fabric of the tapestry. The reason is that small irregularities, errors in the fabric and peculiarities of the weaving techniques are very important for the natural appearance of the tapestries which should not be lost during the reconstruction.

Color clustering: The classification of pixel values into clusters is very useful to identify regions of a certain color.

In summary it can be said that many ideas can be taken from related fields e.g. inpainting or the comparison of frames. But they must be adapted to the specific situation with tapestries.

3. Burgundian tapestries

3.1. Fundamentals

Burgundian tapestries enjoyed a high appreciation, and the production of large size tapestries was even more important than that of oil paintings. Often their drafts were drawn by the best artists [Jez01]. Some of these drafts are preserved and can be used to study the original coloring of the tapestries. Another useful possibility is to study the coloring of paintings made by the same artists.

Often the size of a tapestry is enormous; 5 meters in height and 10 meters in width is not unusual. The motifs are very complex and detailed, and different techniques were used to intensify the plastic impression. Thus the figures are mostly enclosed by a dark brown outline. Other lines result because the gaps which arise when leading back the weft thread are set intentionally. In order to make larger parts woven in the same color more vivid, the thread was inserted partially in diagonal or curved form. The high degree of detail makes the restoration more difficult too. None of the important small parts should be lost, and the plastic effects should be preserved.

3.2. Manufacturing the tapestries

The tapestries are hand-woven. The needle leads the weft thread through the warp only as far as necessary, according to the intended picture. The tapestries are dyed with natural colors e.g. archil, indigo or a yellow color called ”luteolin”. These colors are described in [HdG04]. The specific way of manufacturing also affects the restoration. To obtain a good result, all factors constituting the characteristics of a tapestry must be considered. For example, the kind of weaving affects its structure. The structure is important for the appearance of the tapestry and may not be lost during restoration. Also important is the ”noise” on the back side, caused by the weaving technique e.g. loose threads or threads carried along the back side.

3.3. Aging and preservation

The aging process has damaged the fabric: The tapestries are frayed at their borders, they contain holes, and in some parts the weft thread is lost and the warp thread is visible. Furthermore the colors have faded in the course of aging. On the front side the originally intensive colorfulness is often lost. Parts dyed with archil have faded from a dark magenta to a pale beige. Because the silver has oxidized, the silver gimps have become black, and because the lightfastness of ”luteolin” is much smaller than the lightfastness of indigo, originally green parts are bluish now. On the back side the color is normally much better preserved, although fading has occurred here too. Parts dyed with archil can only be identified here. By classical restoration defective parts have been repaired, patches of dyed linen fabric have been stitched on, or parts have been even woven again. During these restorations crosses and ribbons of fabric were attached to the back side to reinforce the tapestry. They have all been taken away today, but their positions on the tapestry are still visible because the color is less faded where they were stitched on [RBSS01]. The fact that the back side is normally less faded forms the basis of our ”back side approach”. Of course the patches and traces of the attached ribbons lead to problems.

Most features of Burgundian tapestries and all problems listed above can be found in the part ”widow” of the famous Trajan tapestry. It contains most colors of the tapestry, and a large part has been dyed with archil. On its back side many traces from classical restorations can be found. Figure 1 shows the front side and Figure 2 the back side of the part ”widow” of the Trajan tapestry.

Figure 1: *The front side of the part ”widow”*

Figure 2: *The back side of the part ”widow”*

4. Digital restoration

We present two methods to restore the ”original” colors of a Burgundian tapestry. Both are applied to a high-quality digital photograph of the tapestry in its today’s state. Our first approach makes use of the photographed back side of the tapestry, our second approach works mainly with color clustering.

4.1. Preprocessing

With both methods, the pixels on the front side must be compared to the corresponding pixels on the back side. To do this, the image of the back side must be ”laid” as accurately as possible onto the image of the front side. Thus a registration of the images must be made. To match the two images, matching points are defined by hand in both of them and then the transformation matrix is calculated using a least-square estimate.

4.2. Back side approach

As the back side of a tapestry hanging at the wall is less exposed to light than the front side, its colors are normally much less faded. Therefore replacing each front side pixel by the corresponding back side pixel should give a good approximation to the tapestry's original appearance. The idea is straightforward, but its implementation is complicated by a number of difficulties: unfortunately, there are normally many disturbing features on the back side, especially patches sewn on and loose threads hanging down (Figure 3). Our approach intends to restrict the restoration to the removal of such features. To do this, the colors of the matching pixels of the front side are applied, or the restoration of the color is determined by means of a simple inpainting algorithm.

Figure 3: *Disturbing features on the back side of the tapestry*

The restoration of the image of the back side is performed in three steps. The first step consists in the registration between the front side and the back side image. In the second step, disturbing features on the back side are marked. Finally, the marked pixels are replaced by the matching pixels of the front side, or the marked parts are filled by inpainting. Figure 4 illustrates this back side approach.

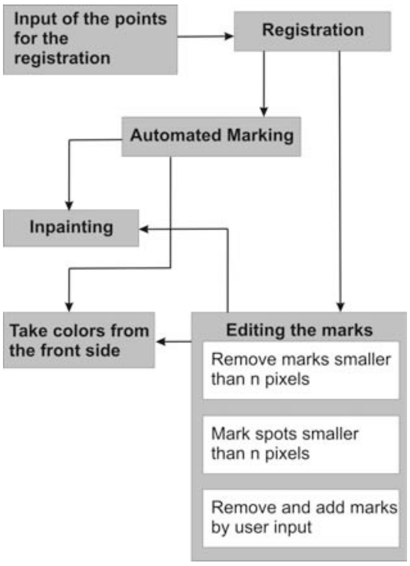

Figure 4: *The back side approach*

Marking the disturbing features: Their pixels can either marked by hand or automatically: If there is a patch or a loose thread on the back side, the difference between the color of the pixel on the front side and that of the matching pixel on the back side is normally much bigger than it would be if the color were simply more faded on the front side than on the back side. Therefore the difference between the colors of two matching pixels can be used to mark the disturbing features on the back side. If the distance is bigger than a chosen value, the pixel will be marked. The calculation of the distance can be done in the RGB or HSI color space. Marked areas smaller than n connected pixels can be deleted automatically, and unmarked spots of less than n connected pixels can be marked. The appropriate value for n depends on the resolution and size of the image.

Inpainting: Each spot of marked connected pixels on the back side is filled pixel by pixel, beginning at the border of the spot. For each pixel p_{b1} on the back side the new color is calculated in four steps:

- The color of the matching pixel p_{f1} on the front side is read.
- This color is compared with the color of the pixels in the neighbourhood of the pixel p_{f1}. Only pixels not marked or already recolored are used for this comparison.
- The pixel whose color has the smallest distance d to the color of p_{f1} becomes the pixel p_{f2}. The distance between the two colors is saved.
- The color of the corresponding pixel p_{b2} on the back side is read. The distance d is subtracted from it. The result is the new color of pixel p_{b1}.

Figure 5 illustrates this inpainting.

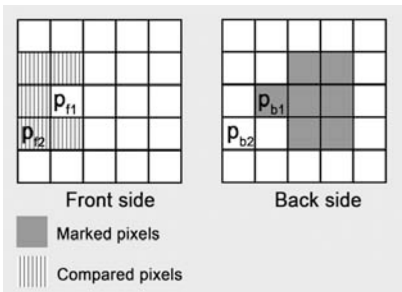

Figure 5: *Corresponding pixels during the inpainting process*

4.3. Color clustering approach

A human observer can easily describe the colors appearing in a certain part of the tapestry. For example he perceives the colors black, blue, beige and yellow. An experienced observer can also estimate the original appearance of these colors. He may judge e.g. that a beige region was originally purple. Color clustering allows us to find all pixels corresponding to this beige region. They do not all have exactly the same beige, of course, therefore an average beige is determined and then converted to a suitable purple. Now, if we would just recolor all beige pixels with this purple, the structure of the tapestry would get lost. Therefore we calculate the distance between the color of the corresponding pixel on the front side and the color of the cluster and subtract this distance from the new color. Unfortunately, a faded color cannot be replaced by the same new color in every part of the tapestry. An example can be found in the part "widow" of the Trajan tapestry: the horse and the skirt of the widow have the same color. But on the back side can be seen that the skirt originally was purple, while the horse was beige. These parts cannot be separated by a clustering of the front side colors. If all beige colors were converted to the same color, the result would be false. Either the horse would be purple or the skirt would stay beige. Because the color of one cluster cannot be converted to the same color everywhere in the image, in general, a segmentation of the image is necessary. Thus the clustering method consists of four steps. In the first step, the image of the front side is segmented. Then the colors of each segment are clustered separately. In the third step, the colors of each cluster are transformed into the new colors. Finally all segments are assembled to the restored image. Figure 6 illustrates the clustering approach. In the following, the four steps will be explained in detail.

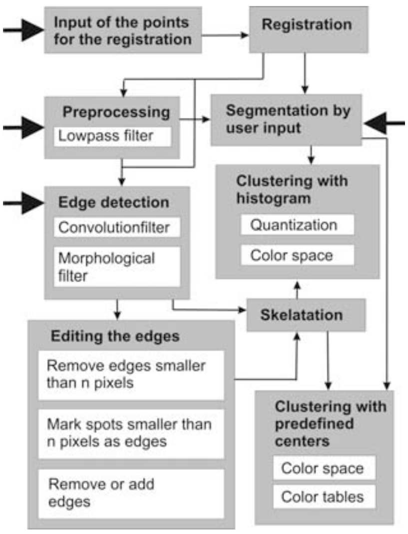

Figure 6: *The clustering approach*

Segmentation: The simplest way to divide an image into segments is to define the outline of the segments by marking points with the mouse. The advantage is that the segments result in accordance with the requirements. The disadvantage is the lack of automation. Our automatic segmentation tries to find segments by finding edges in the image. We choose this procedure because of its relative simplicity and because all relevant segments are separated by clear-cut edges or whole outlines. It is performed by the following steps:

- Conversion to a greyscale image
- Edge detection
- Thresholding to convert the image to a binary image
- Skeletonizing
- Identification of the segments

For edge detection we use several convolution and morphological filters. The skeletonization is done using the "two pass algorithm" of Zhang and Suen [Lyo99], and segments are identified by a simple flodfill algorithm. Because too many segments can cause problems, we try to determine only the important ones. That is, lines caused by the structure of the tapestry should not be marked as edges, and all segments should have a certain size. For this reason a preprocessing with a lowpass filter is done before edge detection. A second method to reduce the number of segments and to get larger segments consists in marking all spots smaller than n pixels as edges, after edge detection and before skeletonizing. Figure 7 shows an example.

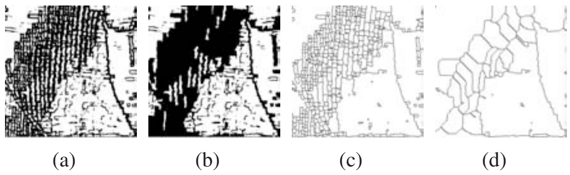

Figure 7: *Edges before and after marking small spots (a,b), and the resulting skeletons (c,d)*

Color clustering: The clustering of the colors can be done either with predefined cluster centers or automatically. If we use predefined cluster centers, we define their colors for all clusters we need. Furthermore we define a new color for each cluster. For each pixel the cluster with the smallest distance between the color of the pixel and the color of the cluster center is found and the pixel's color is changed to the new color. Clustering with predefined cluster centers can only be used in case of a small number of segments because one has to define interactively the cluster centers for each segment. Automatic clustering is done using a color histogram. The number of clusters and the colors of the cluster centers are not known in advance. Automatic clustering is done by the following steps:

- A histogram of the colors occurring in the image is created.
- For each cell in the histogram a pointer to the biggest neighbour is saved.
- Now the histogram contains chains of cells, each one pointing to a local maximum. Each of these chains represents a cluster [SKPB00].

Figure 8 shows the automatic clustering in case of a greyscale image. Colored images need a three dimensional histogram. The number of clusters is influenced by the quantization of the colors. Clustering can be done in the RGB or HSI color space and with different levels of quantization. There are three possibilities to determine the new colors of the clusters:

1. Only the colors on the front side are clustered. The new colors are defined by the user.
2. The colors on the front and on the back side are clustered. The matching of a clusters on the front side to a cluster on the back side is done by the user.
3. Again, the colors on the front and on the back side are clustered. Those clusters are matched that share the largest number of pixels.

Transforming the colors: Before transforming the color of a pixel, the distance between this color and the color of the cluster center is saved. After performing the transformation this distance is added again. Doing this, the structure of the tapestry is preserved. Without considering this distance the tapestry looks flat because all pixels of a cluster get the same color.

5. Results

We have implemented both approaches and performed a number of tests using the part ”widow” of the Trajan tapestry. The size of the corresponding digital images of the front and back side is 5780 (height) x 4521 (width) pixels (Figures 1 and 2). The tests used different parts of this image and different resolutions.

5.1. Back side approach

The main advantage of this approach is its simplicity. As the new color is taken from the back side, no further knowledge about the colors is needed. Furthermore no segmentation is necessary. A single color area is automatically refreshed in different colors if appropriate. Problems arise because some patches and threads on the back side are not marked because the difference between the color of the patch or thread, respectively, and the corresponding color on the front side is too small. Especially threads are often not marked because they typically hang over parts of the same color. Another problem arises because the registration of the two images is not perfect. Wherever false pixels match, the color difference is big, and thus the pixels are marked. These marks are wrong. Moreover parts dyed with archil are marked too, because the color is very much faded and thus the color distance is big. These marks are wrong too. The burls on the front and on the back side of a woven fabric do not lie at the same position, in general. Therefore the front side and the reflected back side of a tapestry never look the same. This leads to wrong marks and to a bad reconstruction of the structure of the tapestry after inpainting. The result of inpainting is good in case of images with a perfect registration and no difference in structure.

A better registration should enhance the results of the back side approach. Another possibility might be to process the pixels in correlation with their neighbourhood. If all these problems could be solved, the problem of correctness would still remain. The color on the back side is faded too. Thus the result is only an approximation to the original appearance.

Our conclusion is that a faded tapestry can successfully be restored by means of our first approach if on its back side the number of patches and loose threads is small, the patches themselves are small, and the colors are not much faded. A high degree of automation and a fast restoration may then be expected.

5.2. Color clustering approach

The best results for the task of segmentation can be achieved by edge detection with a morphological filter after a preprocessing with a lowpass filter. In addition, after edge detection edges smaller than a certain number of pixels should be removed and spots smaller than a certain number of pixels should be marked as edges. The optimal number of pixels depends on the resolution and on the size of the image.

The main advantage of the color clustering approach is its flexibility. The new colors of the tapestry may be defined arbitrarily. Furthermore the degree of automation is relatively high. If the reconstruction is done by automatic segmentation and by automatic clustering, using the matching of the front side and back side colors, it is possible to reconstruct a significant part of a tapestry in a reasonable time. Unfortunately, it is not yet possible to have the advantage of flexibility and that of automation at the same time because the assignment of arbitrary colors to the pixels of the front side clusters cannot yet be done automatically. Another advantage is the good preservation of the tapestry's structure due to considering the distance between the color of a pixel and the color of the cluster center it belongs to.

One of the disadvantages of the method is the dependency of the result on the quality of segmentation. As the new color is automatically extracted from the back side image, the occurrence of too many segments in a part where the back side contains patches is problematic. The reason is that the color of the patch is taken as the new color. The quality of the clustering influences also the result. Colors located almost in the middle between two cluster centers are problematic because they are assigned only to one cluster and normally have a relatively big distance to the center of this cluster. After converting these colors to the new color and adding the color distances, undesired colors can result. This happens mostly if a color is modified very much. After adding the distance, it may result that the value of a color component has to be clipped. Thus the automatic matching of the clusters of the front and back side is better if the clusters contain many pixels. The clustering using predefined cluster centers is not very useful. The main problem is to determine the colors of

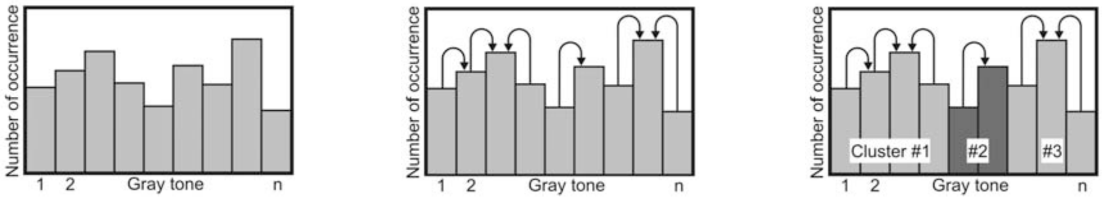

Figure 8: *Clustering in case of a grayscale image*

the cluster centers. A color may seem to be a good representative for a group of colors to the human eye, but proved not suitable to calculate the clusters. Clustering using a histogram is much more practicable. The clusters correspond to the color groups that are identifiable by eye. An important parameter is the value of quantization. If it is too small, fairly different colors are combined into one cluster. If it is too big, too many clusters arise, causing problems when the clusters of the front side are combined automatically with the clusters of the back side. Suitable is a value between 15 and 30 for each color component. If there are only few segments, it is possible to refresh the colors by user-defined colors. When defining the new colors, it is necessary to make sure that the new colors aesthetically fit. Moreover defining the colors is time-consuming. To reconstruct an image with many segments, only the automatic matching of the colors of the front and back side can be used, of course.

An enhancement of our approach could be achieved by an automatic matching of user-defined colors to the colors of the front side. For example, a matching of these colors could be done by analyzing the colors found on the back side. A better matching of the colors of the front and back side could enhance this approach and reduce the errors. For instance, not only the number of shared pixels but also the size of the clusters could be considered. An enhancement of the registration as well as a better automatic segmentation could also improve the result. With a fuzzy clustering as described in [CSUN05], the number of undesired colors could probably be reduced.

Our second approach, if using nonautomatic segmentation and automated clustering leads to satisfactory results. If the colors of the back side are used for the reconstruction, the necessary time and user effort are acceptable, and a first impression of the original appearance can well be gained.

5.3. Comparison of the two approaches

To compare the two methods with each other, we applied them to the part ”widow” of the Trajan tapestry and judged the results visually. In practically all aspects the color clustering approach proves to be better than the back side approach. In most cases the result of the reconstruction looks better and contains less faults. The color clustering approach is more flexible and thus a result close to the assumed original appearance can be achieved more easily. Also an adaption to other applications, like the digital restoration of paintings, is only possible with this approach, because of the dependency of the back side approach on the existence of a back side. Only with respect to automation the two methods prove equal. Figure 9 shows the result of a reconstruction using the back side approach. The disturbing features on the back side were marked by hand and filled by inpainting. Figure 10 shows the corresponding result using the color clustering approach. The segments were created by user interaction and the clustering was done in RGB color space using a quantization value of 25 and automatic color matching.

6. Final remarks

Fortunately, quite a few Burgundian tapestries have survived until today. There are many good reasons to provide digital photographs of high quality of them, an important one is that such digital copies make experimentation possible - without damaging the precious originals. The present paper deals with such an experimentation by proposing two methods for reconstructing the original appearance of such tapestries.

The back side approach is more straightforward but normally less useful than the color clustering approach. Burgundian tapestries make image processing difficult: the normally very complex scene, the irregular structure of the woven fabric, as well as the patches and hanging loose threads on the back side are the reasons that user interaction cannot be completely avoided. Our methods cannot be expected to be perfect, but they are more than a first step, and experimenting with them offers much valuable insight.

It is rather well-known how colors were manufactured in the Middle Ages [HdG04, Sch02]. Using this knowledge could enhance our two methods. Discussing further the results with professional restorers could give ideas for improvements. A completely different approach would consist in building 3D models of Burgundian tapestries, as it has already been done successfully with other kinds of textiles [AMT03, AMTF03]. Adapting our methods to other kinds of tapestries, e.g. modern carpets, seems promising too.

7. Acknowledgement

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Figure 9: *A reconstruction using the back side approach*

Figure 10: *A reconstruction using the color clustering approach*

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