Fragment-Segmentierung bei der virtuelle Rekonstruktion von Fresken

Fragment segmentation in the virtual recomposition of frescos

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Zusammenfassung: Der Vortrag behandelt die Objektsegmentierung, ein Thema, das im Zusammenhang steht mit der Entwicklung eines digitalen Systems zur computergestützten Rekonstruktion von zerbrochenen Fresken. Diese innovative Methode der Rekonstruktion wird gerade an einem Fresko (Darstellung von S. Matteo) von Cimabue in der Oberkirche San Francesco in Assisi erprobt. Das Fresko hatte eine Größe von 35 m² und ist während des Erdbebens 1997 in mehr als 120.000 Einzelteile zerbrochen. Das Projekt steht in enger Kooperation mit dem Zentralinstitut für Restaurierung, das für die gesamte Restaurierung der Kirche San Francesco verantwortlich ist. Die Restauratoren sind sehr an dieser innovativen Arbeitsmethode interessiert und haben bereits auf mehrere Verbesserungen, die das System für ihre Arbeit bringt, hingewiesen.

Abstract: The paper addresses the fragment segmentation, a topic involved in the on-going development of a digital system for the virtual aided recomposition of fragmented frescos. This innovative approach to reconstruction is currently being proved on a fresco representing S. Matthew, made by Cimabue for the Upper Church of S. Francis in Assisi: it had an extension of 35 squared meters and broke, during the earthquake in 1997, into more than 120.000 pieces. This project is going on in close cooperation with the Central Institute for Restoration that is in charge of the whole restoration of the S. Francis church. The restorers are very interested in this strongly innovative approach to their work and have already pointed out several improvements that the system can bring into their work.

INTRODUCTION

Aim of this paper is to describe the fragment segmentation, a topic involved in the on-going development of a digital system for the virtual aided recomposition of fragmented frescos. This innovative technique is currently being proved on a fresco representing S. Matthew, painted by Cimabue for the Upper Church of S. Francis in Assisi, shown in fig. 1. The fresco, having an extension of 35 squared meters, has been broken into more than 120.000 pieces by the earthquake in September 1997.

The particular technique used by Cimabue (that makes the pictorial film very sensitive to the long physical manipulation required by the traditional recomposition) and the huge number of fragments (more than twice the ones of the larger manually recomposed fresco that has been placed back in the church last summer) have suggested the application of digital tools to this challenging problem. Unlike puzzles, the fragments do not cover the whole fresco and could partially belong to a neighbor fresco broken during the same event; moreover their contours do not always match exactly.

The developed system is based on a tight cooperation between the automatic algorithms and the operators charged of the recomposition process [1]. It substitutes the physical lab, close to the S. Francis church in Assisi, with a geographically distributed digital laboratory: a network of suitably designed stations connected with a server (located in our Institute) that allow several operators to cooperate in the recomposition using digital images of fragments instead of physical objects.

The designed system transposes the traditional recomposition process in a digital way, by offering, to operators with high skills and specific preparation but not necessarily familiar with digital systems, the central and critical role of managing and applying new tools and flexible algorithms of image analysis to increase the efficiency and efficacy of their work [2].

The working modality implied by the digital system is very similar to the traditional one. The multi-monitor graphical station, reported in fig. 2, allows the selection of a part of the image of the whole fresco (visualized in a scaled version on the central monitor) as background for the working area that is shown at full resolution on the left-side monitor. The operator looks for the best place for each fragment by moving it with simultaneous rotations and translations across the region of interest using a special mouse.

Digital tools expand the capabilities of the human operator. In fact he is allowed to create and manage several virtual containers, that are the digital counterpart of the boxes used in the real lab to collect logically related fragments. The content of virtual containers is completely under control of the operator that can organize the digital images in any way functional to its work. Moreover, he can also duplicate fragments, display them with half-transparency, change color, brightness and contrast, zooming or increasing the field of view: all operations that are impossible on physical fragments and that allow to execute further useful comparisons between the images of fragments. The located fragments can be seen at different scales, offering an overview of the recomposed fresco that is very hard on a physical surface of 35 squared meters. The holes in the recomposition can be filled in different ways (for checking their visual appearance and meaningfulness) and they can also be deformed in order to study the effect of their placement on a curve surface (similar to the one of the vault in the church). Finally, the system manages and synchronizes the cooperation of several operators that, using different graphical workstations connected over a network with a server, can jointly work on the same fresco.

All this advantages compensate the unavoidable loss of information due to the use of two-dimensional images instead of physical fragments, that can be observed by several points of view, including their reverse side.

A fundamental improvement to the recomposition process is the support that the system gives in retrieving fragments of interest from the database (digital images of every single fragment) using a query-by-example modality that is incremental and iterative. The operator picks-up a set of examples (images of fragments or of details of the reference image) and the system selects in the database the fragments that are more similar to them. If the results are not satisfying, the set can be modified adding, removing or changing the examples and the query can be repeated until operator's needs are fulfilled. This very simple schema is generally used on text in the web search engines. Color and texture are the most important components of similarity evaluation [3,4,5], especially when shapes, due to damages occurred during the fragmentation process, do not necessarily match perfectly.

THE SEGMENTATION APPROACH

The physical fragments have been placed in particular containers, each hosting from few tens to about 300 fragments: they are fitted into a material (foam) that keep them in place and provide an high contrasted background (fig. 3). The input data to the system are the digital images of these containers. Fragments need to be separated from the background in order to create the database of images each containing a single piece. These images have been built by an automatic algorithm based on the analysis of color characteristics: its application on the image of each container produces a set of digital frames where the fragments appear separately, surrounded by the foam. In this phase each image receives a unique identifier that combines the references to the physical container holding the corresponding physical fragment and to its location inside the box. Using these identifiers the result of the virtual recomposition can immediately be translated in the physical recomposition of real fragments. All these images of the fragments have been stored into an properly designed database.

Enabling an effective aided retrieval of fragments from the database using a query-by-example modality requires their reliable separation from the background: in this way the algorithms for the analysis of color and texture can operate only on the pictorial content of the fragments. Moreover, each fragment can be further divided into homogeneous regions: this allows a stronger and more precise characterization that improves the performance of the retrieval phase. This second segmentation can separate the pictorial film from regions belonging to the brick or to the plaster and, similarly important, can divide it into regions with homogeneous contents in terms of color and texture. This paper deals with the segmentation process needed for separating the fragments from the background. Specifically it deals with the fine definition of the fragment mask, that is the exact separation of pixels belonging to the fragment from the ones related to the background.

To reach this result the fast global k-means algorithm has been applied [6]. It is a deterministic effective global clustering algorithm for the minimization of the clustering error that employs the k-means algorithm as a local search procedure. This method incrementally adds a cluster center at a time using a deterministic global search procedure based on the execution of the k-means algorithm on the already found clusters centers augmented with a new element picked up from the available data set. The original code, written for the Matlab environment, has been translated in the C languages to allow the processing of the huge number of images (more than 120.000) in an acceptable time.

In our problem, the data set fed to the clustering algorithm is composed by all the colors present in the image to be analyzed, each described by its three coordinates in the CIE-Lab color space. This method aims to partition the data set in M disjoint subsets such that a suitably defined clustering criterion is optimized: in this case it minimize the clustering error, evaluated as the sum of the squared Euclidean distances between each data point and the centroid (center) of the cluster it belongs to.

The algorithm proceeds in an incremental way: to solve the search for M clusters (this number has to be chosen depending on the application) it sequentially solve all the intermediate problems with 1, 2, ..., M-1 clusters. The basic idea is that an optimal solution for a clustering problem with M clusters can be obtained by several local searches, each made using the k-means algorithm applied to the M-1 cluster centers provided by the optimal solution of the M-1 problem and to a new center initialized at different positions in the data space. The method is effective and avoids the strong dependence of other methods on the initialization or on empirically adjustable parameters.

The global k-means would require the k-means algorithm to be executed for each element of the CIE-Lab data set. The computational load can be reduced, without significantly affecting the quality of the solution, using the fast global k-means. This method does not execute the k-means with M clusters until convergence for each possible initialization. Instead, an upper bound of the expected error is computed for each possible intialization: $E_n \leq E-b_n$ where E is the error in the M-1 clustering problem and b_n measures the guaranteed reduction in the error measure obtained by inserting a new cluster center at position x_n. The k-means is executed only for the initial value associated with the lower upper bound.

The global k-means algorithm has been used to divide the whole image into M=10 regions (clusters) having the similar color characteristics. This number of clusters offers a sufficient number of representatives to both foreground and background colors. Finding a threshold value on the CIE-Lab colors for separating foreground and background on a huge number of images can be very hard (if possible). It is much easier to fix a threshold that separates the clusters related to the background from the ones belonging to the fragments: the same threshold has been able to work on quite all the images allowing a fully satisfactory binary image to be obtained.

As shown in fig. 4 (second column), the segmentation based on thresholding the result of clustering is effective but still originates a large number of artifacts: regions with different size (from small dots to significant blobs) that are misclassified due to their color values. Two post-processing phases have been applied to correct this problem.

A filtering step, based on the recursive application of a median filter, removes the smaller areas assigning them to the correct class (fig. 4, third column). A window of size 3 has been used: it corrects most of the misclassified regions without affecting the fine details of the fragment shape. This filter is recursively applied until its application does not introduce any further modification in the image.

The median filtering cannot remove larger regions that can be still assigned to the wrong class. A blob detection algorithm, based on a region growing schema, has been used for identifying these areas, that are sensibly smaller than the fragments, and for changing their value (from foreground to background or vice versa). The result of this blob removal algorithm is shown in fig. 4 (fourth column).

These three steps have been applied to the whole collection of images without any further human intervention. The result has been a collection of masks that, for each image of the fragments, identify the pixels that belong to the object of interest and must be considered by the image processing and analysis tools.

CONCLUSIONS

This project is going on in close cooperation with the Central Institute for Restoration, that is in charge of the whole restoration of the S. Francis church in Assisi. The project is a big challenge: the available data do not provide the best base for this work. The available images of the whole fresco are quite different from the digital images of fragments for both geometrical resolution and colorimetric characteristics. Any effort is being made for reducing this gap that strongly reduces the expected performance of the system. The restorers, that are working in Rome using a station connected to our server in Bari, are anyway very interested in this strongly innovative approach to their work and have already pointed out several improvements that the system brings into their work. They are working on the virtual recomposition of the S. Matthew's fresco and providing new stimuli about further functionalities and visual characteristics that can be fruitfully introduced in the system as well as further support to its fine tuning and to the evaluation of its performance. Up to now restorers have correctly identified several fragments on the fresco's recomposition. Fig. 5 reports some of the identified fragments on a working-area (that is a small area of the fresco, represented at full resolution and that can be completely displayed on the monitor). However, the identified fragments have confirmed the expected differences between colorimetric characteristics of the acquired fragments and the best color image available of the whole fresco. In the next months restorers are expected to provide others very interesting hints arising from the extensive application of the system to the real recomposition of the S. Matthew fresco.

FIGURES

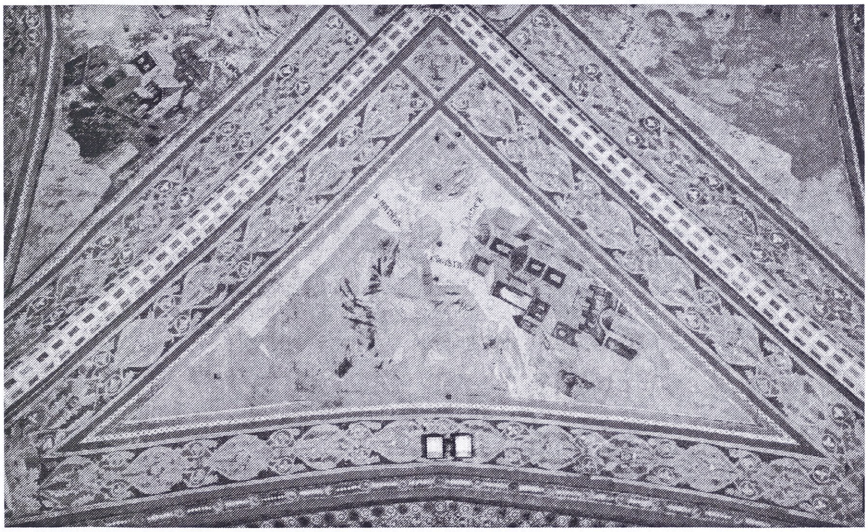

Fig. 1: The S. Matthew fresco, painted by Cimabue for the Upper Church of S. Francis in Assisi. The fresco, having an extension of 35 squared meters, has been broken into more than 120.000 pieces by the earthquake in September 1997.

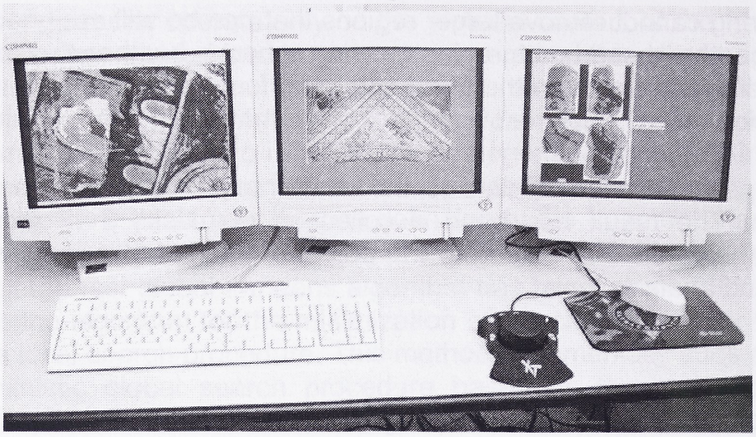

Fig. 2: The workstation for the virtual aided recomposition. The left-side monitor is the work-area for positioning the fragments. On the other ones a scaled version of the whole fresco and several logical containers used for organizing the fragments.

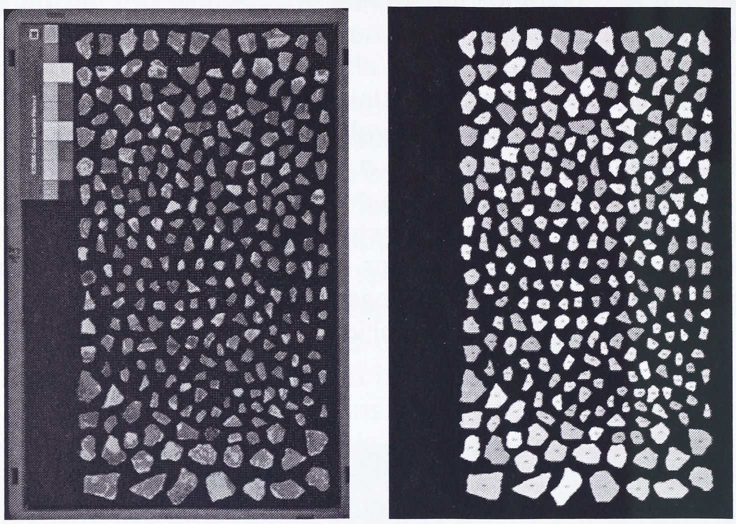

Fig. 3 : The image on the left shows an example of the digital images acquired from the physical containers holding the real fragments. These images, several hundreds, are the input data for the system. During the segmentation phase the images of single fragments are extracted and stored in the suitably designed database. During this step a map of each image (on the right) is created. It allows a unique identifier to be assigned to each fragment: this identifier will be used in the final real restoration for retrieving the real objects corresponding to the components of the virtually recomposed fresco.

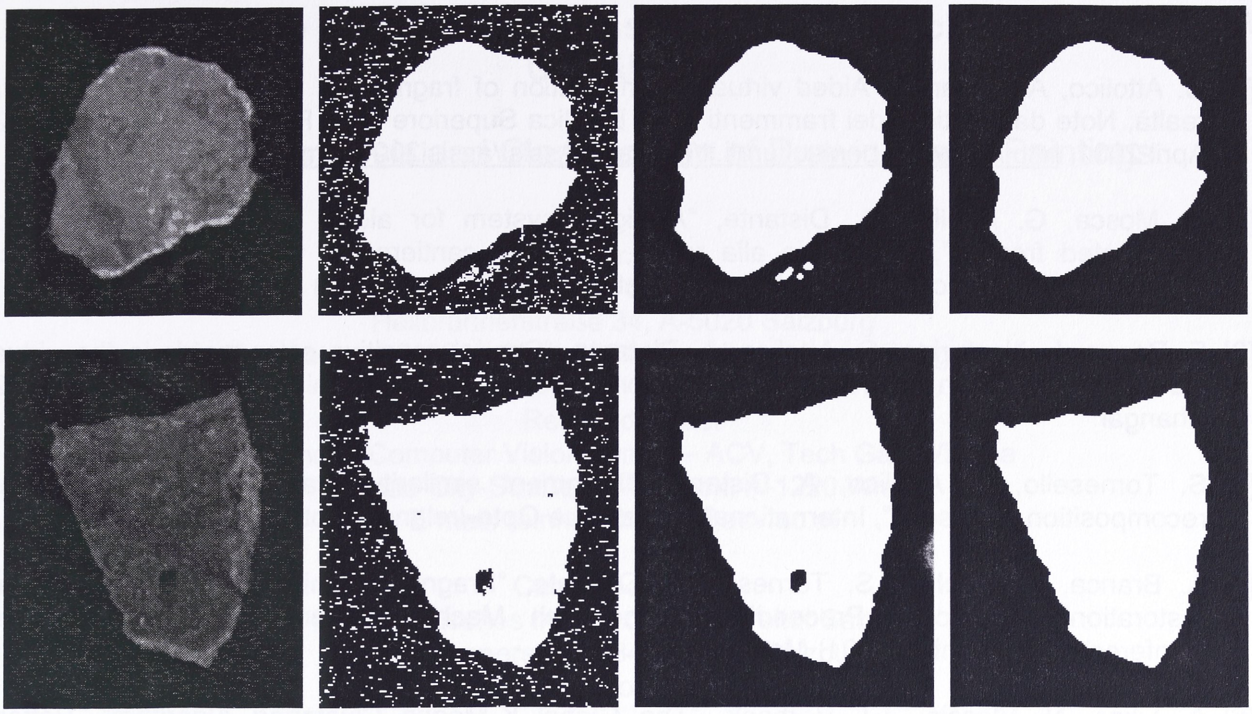

Fig. 4 : The first column shows a couple of fragments. The second one presents the results of thresholding the clustering results: There are several artifacts (a large number of spots and a few larger regions misclassified). The first post-processing step, based on a median filtering, removes the small spots (third column). The blobs removal algorithm correct the classification of regions too large to be coped with by the median filter but still sensibly smaller than the fragment size. The final result is shown in the fourth column.

Fig. 5 : Example of the first results obtained by applying the system to the virtual aided recomposition of the S.Matthew fresco.

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