An Innovative Aided Virtual Approach to the Recomposition of Fragments

F. Renna, N. Mosca, G. Carlomagno, G. Attolico, and A. Distante

Abstract—**The recomposition of fragments is a challenging task that must exploit all the available information about fragments and the whole skill of human operators. A new approach to the recomposition of fragmented artworks is presented. It has being developed working on the problem of recomposing the St. Matthew fresco, painted by Cimabue in the Upper Church of St. Francis in Assisi, which broke into more than 140.000 fragments during the earthquake in September 1997. This innovative approach avoids any risk of damages due to the long manipulation of real fragments substituting digital images to physical fragments. The system supports the interaction of the operators with these images through suitably designed tools. Its client-server architecture allows the physical laboratory located in Assisi to be spread on a geographical base: several operators can work in a synchronized and cooperative way on the same project from any location where a properly configured workstation and a low-speed Internet connection are available. The restorers of the Central Institute for Restoration proved the system and showed a strong interest in this new recomposition modality.**

***Index Terms*—Virtual aided recomposition, Internet application, Colour correction.**

I. Introduction

THE recomposition of fragments is a challenging task that must fruitfully use all the available information and the skill of the human operators. Differently from the classic jig-saw problem, fragments normally do not cover the whole surface, do not necessarily match exactly at their borders and can exhibit significant variations in colours and textures even when belonging to neighbouring parts of the artwork at hand. Moreover a documentation about the subject represented in the artwork (pictures, textual descriptions, …) is not always available or do not have a quality sufficient to make it usable for the recomposition.

A new approach to the recomposition problem has been developed working on the St. Matthew fresco [1], painted by Cimabue in the Upper Church of St. Francis in Assisi, which had an extension of about 35 squared meters and broke into more than 140.000 fragments during the earthquake in September 1997 (Fig. 1). In this case, the recomposition work is particularly hard because, immediately after the earthquake, fragments have been moved, mixed and further damaged. As a result, some of them are missing and a part of them is suspected to belong to a neighbouring fresco broken during the same event. Moreover, their pictorial film of the fragments has been further degraded.

Fig. 1. The interior of the Upper Church of St. Francis in Assisi after the earthquake in 1997 [2].

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This innovative approach transposes the traditional recomposition in a digital way: it substitutes digital images to physical fragments and supports the interaction of the operators with these images through suitably designed tools. In fact, the system offers to the 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 efficacy of their work [3]. Moreover, it avoids any risk of damages due to the long manipulation of real fragments, required by the traditional recomposition process.

The system is based on a client-server architecture that allows to work remotely in a virtual laboratory spread geographically instead of requiring the access to the physical laboratory located in Assisi: several operators can work in a synchronized and cooperative way on the same project from any location where a properly configured workstation and a low-speed Internet connection are available. A server, located in our institute in Bari, manages the fragments' database and the synchronization of the process and, due to its great computational power, applies an extendable set of image processing algorithms to extract visual characteristics that describe the pictorial content of the images.

Aside from the support provided by the proprietary software running on the workstation, the server offers a search engine that can be used to retrieve the images of interest by the database using a query-by-example approach: this feature can significantly improve the interaction with huge collection of fragments.

The restorers of the Central Institute for Restoration that proved the system showed a strong interest in this new recomposition modality and suggested several extensions that could further support their work.

The paper describes the system and the tools supporting the task at hand. A special emphasis will be given to the comparison between this new approach and the traditional one, by a careful examination of the possibility offered by the implemented digital methods.

II. The Database Construction

The input data to the system are the digital images of the physical containers holding the real fragments (Fig. 2). In fact, the real fragments have been placed in containers, each containing from few tens to about 300 fragments, and fitted into the foam, to keep them in place and provide an highly contrasted background.

Fragments have been separated from the background in order to create a database of images each containing a single object [4]. An algorithm based on colour analysis has been used to automatically build these images: its application on the image of each container produces a set of digital pictures where fragments appear separately, surrounded by the foam. During this phase each image receives a unique identifier combining the reference to the corresponding physical container and the reference to its location inside the box. These identifiers allow the virtual recomposition to be easily translated in the physical recomposition of the real fragments.

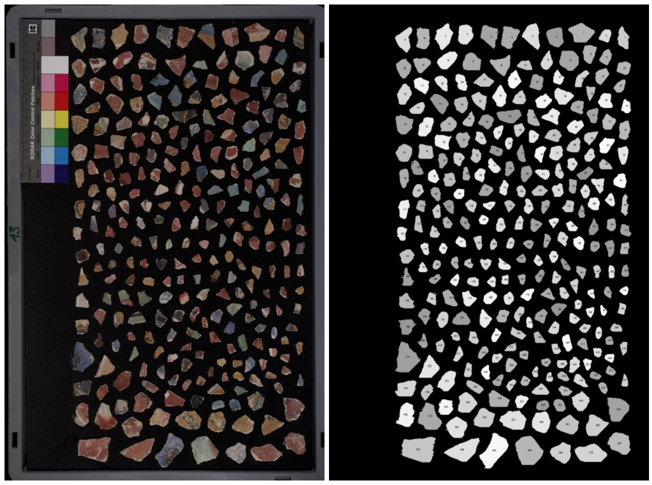

Fig. 2. One of the digital images acquired from the physical containers holding the real fragments (left). The images of single fragments have been extracted and their properties have been stored in a suitably designed object-oriented database. The corresponding map of the container (right) assigns a unique identifier to each fragment: the real objects can be retrieved and the virtual recomposition can guide the real restoration of the fresco.

A suitable separation of fragments from the background has been required to allow users to have a more realistic and effective interaction with virtual fragments while they are recomposing the fresco in the workspace and to enable the analysis of image characteristics can operate only on the useful pictorial content of each fragment. This segmentation step gives rise to a binary mask for each image which is obtained by means an approach based on the fast global k-means algorithm [5].

All the data associated to these images (colour and texture characteristics, dimension, …) are stored into a properly designed object-oriented database.

III. The Virtual Laboratory

The main components of the user interface characterizing the digital system have been inspired by their counterpart in the physical laboratory. In fact, the most important elements in the recomposition process such as the fragments, the table covered by the image of the fresco (if available) at a real-scale size, the boxes used to organize fragments have a digital version in the system (Fig. 3).

In the virtual laboratory, each real fragment is represented by its two-dimensional picture. Unfortunately, some information such as roughness, weight, characteristics of the back of fragments usefully exploited in the real recomposition of the fresco, is missed. A few advantages can compensate for this loss: fragments can be manipulated without damaging their sensitive pictorial film; fragments can have multiple instances, therefore they can be classified in several boxes (each referring to a different property such as colour, texture, dimension,

Fig. 3. The workstation for the virtual aided recomposition. From the left: the working area on which the images of fragments are moved while searching for their place; a scaled version of the whole fresco used for selecting the area of interest; one of the virtual containers used to organize fragments. A special mouse allows to rotate and translate simultaneously the fragments images on the working area.

graphical elements in the pictorial area,…) and used by multiple restorers at the same time, increasing the efficiency of the work; using image processing techniques several characteristics (colour, contrast, lightness, scale,…) can be manipulated to enhance the perception of visual details.

The virtual counterpart of the physical table is the workspace where the restorers can bring fragments and move them around to find their correct place. Restorers can use a 3D mouse [6] to simultaneously translate and rotate the selected fragment in this area. This special mouse allows to access the main functionalities without changing the input device during the fragment manipulation: to hold or release a fragment, block/unblock it, enable and tweak fragment transparency, show or hide its identifier, and so on.

The image of the fresco, if available, can be superimposed to the workspace to reproduce the condition of the physical laboratory where the restorers usually recompose a fresco placing fragments on the corresponding areas of a 1:1 reference image.

Operators often work with more containers, used to classify fragments based on their pictorial contents (Fig. 4). In the same way, several windows, whose number depends on the operator's needs, display the virtual containers, one for each window. Fragments' digital images are arranged in a grid and displayed at their full resolution, giving full access to their pictorial content, or scaled to be all visible at the same time. A container can be filled by the operator or it can be created as a result of an operation of the system (normally a query to the database). The fragments in each virtual container can be dynamically sorted on the basis of different criteria (names, width, height, global dimension, similarity to examples if retrieved from the database). The operator can move fragments, from containers to the working area or between containers, using the drag-and-drop technique commonly used in Microsoft Windows.

The digital environment allows several features impossible in reality. The visual characteristics of the reference image (colour, brightness and contrast) can be changed dynamically, if needed. If a reference image is available, a fragment can be shown in half-transparency to better appreciate its position with respect to the reference image, while the restorer is looking for its correct placement. The already placed fragments can be shown or removed to improve the visual perception of the workspace. The display scale can be increased to enhance visual details or decreased to evaluate larger parts of the fresco. Moreover the recomposed fresco can be viewed from different distances: this is very hard to obtain on a physical surface of 35 squared meters.

A miniature image, showing the whole fresco at low resolution, enables an easy navigation through the picture by selecting the region of interest that is then displayed at full resolution in the working area (the mechanism is very similar to the navigator window featured in Photoshop).

The identifiers of the fragments placed on the working area provide the information required to pick-up the real objects: this can be useful to evaluate further properties that are not available in the two-dimensional images and during the physical recomposition of the fresco.

The system offers a fundamental improvement to the whole process by supporting the retrieval of fragments of interest from the database using a query-by-example modality that is incremental and iterative. A set of images, fragments or details of the image of the whole fresco, are used as examples to query the database. The system returns the fragments most similar to the examples on the basis of the selected characteristics. The set can be modified by adding, removing or changing the examples and the query can be repeated until the operator's needs are fulfilled.

The similarity evaluation mechanism has a modular structure that allows to easy change or add further characteristics useful to compare fragments. In fact, the system can be updated with image processing algorithms that measure the desired properties, which must be evaluated off-line for each fragment of the whole collection and on-line for details

Fig. 4. A restorer organizes fragments into containers on the basis of their pictorial content. She is aided in her work by some pictures of the areas that need to be recomposed.

Fig. 5. The first column shows some of the fragments that have been correctly located, using the system, on the reference image without colour correction. Starting from these correspondences it has been possible to determine the colour corrections that have produced the corresponding images in the second column. Although displayed, the fragments are almost unnoticeable, due to the effectiveness of colour correction.

extracted from the reference image. This is particularly important because the restorers often become aware of relevant new data that can be useful for their work only during the use of the system.

One of the facilities offered by the system is the colour correction of the reference image [7]. This is particularly important for the recomposition of the St. Matthew fresco. In fact, the colours of the only available reference image, a picture taken several years before the earthquake under unknown illumination conditions, are very different from those of the fragments. Moreover, due to different deteriorations occurred across the 35 squared meters of the fresco, colours have changed differently in each of its regions. Therefore, several different transformations are needed to correct the whole reference image.

The application of the colour correction makes meaningful the query results obtained by querying the database using details extracted from the reference image. Moreover, a suitable colour correction can simplify the work of restorers when, to correctly place the fragments returned from the system onto the working area, they compare the fragment image with the reference image (Fig. 5).

An automatic tool has been designed to avoid any direct involvement of restorers in the evaluation of the colour correction matrix. The system uses a small set of fragments whose position can be recognized in the whole fresco and it is possible to refine the results as soon as new fragments are correctly placed. To compute this matrix, an over-determined set of linear equations (coming from pairs of corresponding colours) is solved in the least-squares sense using an algorithm based on the singular value decomposition technique [8].

IV. The Client-Server Architecture

The physical lab, actually situated close to the St. Francis church in Assisi, is substituted by a geographically distributed digital laboratory (Fig. 6). A network of suitably designed workstations connected with a server, located in our Institute, allows several operators to cooperate in the recomposition of fragments.

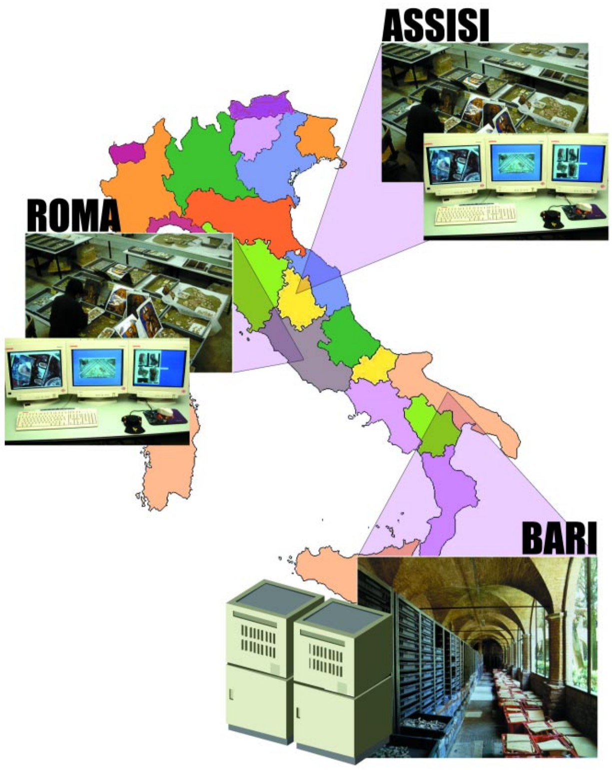

Fig. 6. The geographically distributed virtual laboratory for the aided recomposition of fragmented frescos: the picture emphasizes how the physical laboratory has been moved onto a digital and distributed architecture.

The system is designed around a client-server architecture. The client application runs on a workstation with a Windows 2000 environment and acts as a link between operators needs and the recomposition system. The server application runs on a multi-processor Digital Alpha with a Unix environment: it manages the database, executes the processing required to extract meta-data from the huge amount of fragments and to execute queries on the basis of the examples provided by the users (Fig. 7).

The client part handles the interaction with the restorers: it is responsible for the presentation layer as well as for handling user requests.

Clients are equipped with a suitable mouse that can handle up to six degrees of freedom and has a wide collection of programmable buttons. This peripheral, commonly used in CAD applications due to its properties, allows to concentrate in one place the most common operations involving virtual fragments manipulation, without requiring frequent switching to other input devices.

The workstation is also configured to support multiple monitors to show the different components required by the recomposition process. Two graphics cards are installed on the workstation: an OpenGL compliant accelerated graphics card (to manage high speed rendering of fragments on the workspace) and a second PCI graphics card that can connect up to four monitors (to expose a suitable virtual space to work with).

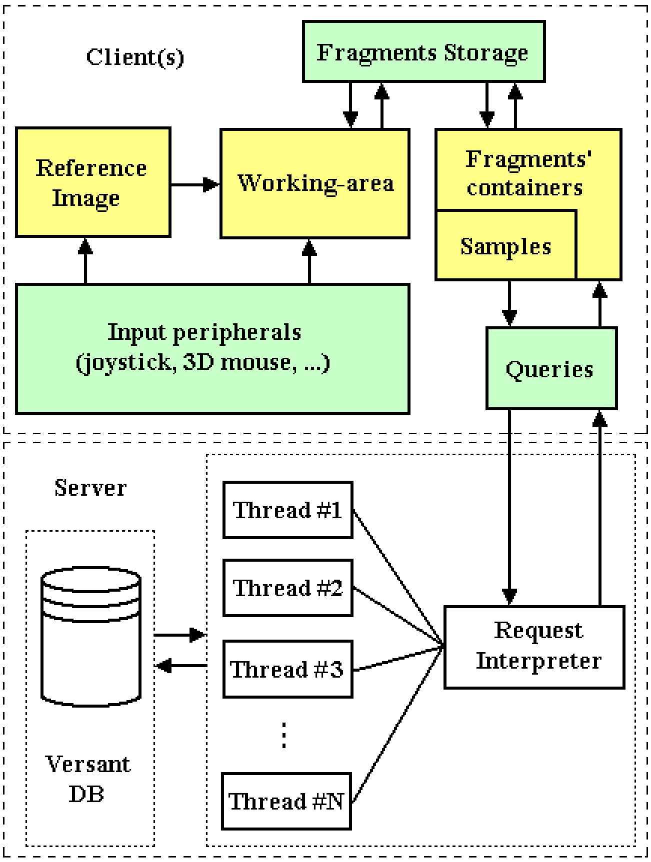

Fig. 7. Primary software modules of the developed system and their interactions. On the client there are modules either (yellow) to handle the visually represented reference image, the working area, and the containers hosting the fragments either (green) to grab user actions from the input peripherals, retrieve fragment's images, and execute queries. On the server-side, the main thread of the services manager accepts client requests and spans threads to accomplish them. Data of interest are retrieved by a database.

The workstation is equipped with 512 MB of core memory and with a significant amount of disk memory: in fact, all the images of fragments are locally stored to reduce the bandwidth of the connection between clients and server. The computational power of the workstation is quite low: the processing is mostly done by the OpenGL accelerated card or by the application running on the server [9].

Some extensions of the OpenGL Imaging subset are used to control the brightness and contrast of the reference image for a better perception of differences between fragments and reference image.

Server's tasks are mainly related to the evaluation of fragment similarities and to the management of centrally located data (the database of metadata describing the pictorial content of fragments, the data that need to be shared between restorers such as common sets of fragments, already placed fragments, …). The information used for similarity evaluation includes colour histograms, texture-related representations and fragment's dimension.

The application on the server is not directly visible by the restorers: some requests asynchronously activate specific functions (especially those that are computationally demanding) on the server. Restorers can locally accomplish other tasks while waiting for the answer of their requests. It's necessary to note that fragments' digital images are stored on the server as well as on each client. This choice was made to reduce the data exchange required between client machines and the server and therefore speed up some common system operations. Communications between clients and server are in fact kept at a minimum, use TCP/IP packets and are based on a custom protocol. Requests and answers are coded in TCP packets whose exchange is carried through sockets and, optionally, encrypted and compressed using a universal Secure Socket Layer wrapper installed on either clients and server. Syntactic data regarding fragments are actually stored and retrieved using a commercial object-oriented database [10] whose choice was suggested by the need of storing and retrieving with the maximum flexibility the quite complex data structures representing the information extracted from each fragment.

V. Restorers' Comments

Restorers are very interested in this strongly innovative approach to the recomposition of fragments, a problem that occurs frequently and always presents different and difficult challenges. They have pointed out as in several cases a picture of the whole artwork before fragmentation is not available.

Moreover sometimes they lack even any information about the subject represented in the object that needs to be recomposed.

During the early phase of test of the system on the St. Matthew's fresco, at the beginning of its development, they have been able to place more than 400 fragments as a valuable by-product result. The following experiments, done on several measures of colour and texture, have further extended this result: at the moment more that 2.000 fragments have been recognized and placed on the fresco.

They have pointed out several improvements that the system can bring into their work. It allows an integrated and quick access to the huge amount of available information. Moreover measures provided by image processing algorithms provide objective data on the base of which to compare a set of fragments with the whole database: in this way the operator can achieve in a very short time homogeneous groups of fragments to work on.

Several facilities can make easier to find the right location for a fragment. In fact, the system offers a chance of looking at the same time at the reference image, its zoomed parts and the fragments, allowing immediate evaluations even when the fresco is very large. Moreover, the system allows an easy exploitation of partial pictures of details of the fresco that can be available. In the case of the St. Matthew's fresco some high-resolution grey-level images of few details are available: the restorers can use the low-resolution colour image to identify the area of interest for a specific fragment and look on the high-resolution grey-level image for fine graphical signs that can help in recognizing the final position. In addition, to work in a two-dimensional world, aside from the loss of information content, allows the operator to be more concentrated as well as to fully exploit the rendering of the recomposed parts, as a whole in the plane or on the true curved geometry of the final destination.

The on-going activities continuously provide new stimuli about further functionalities and visual characteristics that can be fruitfully introduced in the system.

VI. Conclusions and Future Works

An innovative system for the virtual aided recomposition of fragments has been described. It transposes the traditional recomposition process in a digital way: this makes the training shorter and easier and allows the knowledge and skills of operators to be fully exploited and integrated with the powerful capabilities of the digital system. A content-based image retrieval engine, specifically tuned to the visual characteristics of interest, supports the restorers in managing the huge amount of fragments in an efficient and effective way. The system is based on a client-server architecture that spreads the physical laboratory for traditional recomposition used in the past over a geographical network.

Several enhancements are still possible. Naturally some future works involve the design and implementation of others similarity measures that can be computed on the basis of other features that can be extracted from the fragments and not used yet. It is also possible to further speed up similarity measures in order to allow a more responsive tuning of the queries done.

Another area of major interest is related to the restorers' cooperation during the recomposition phase: a set of functions can be further integrated to share opinions during the recomposition process and, eventually, to discuss and resolve ambiguity cases when the same fragment is being placed by more than one restorer in different places, due for example to the difficult reading of the unique available colour reference image (that is often blurry with respect to the fragments).

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