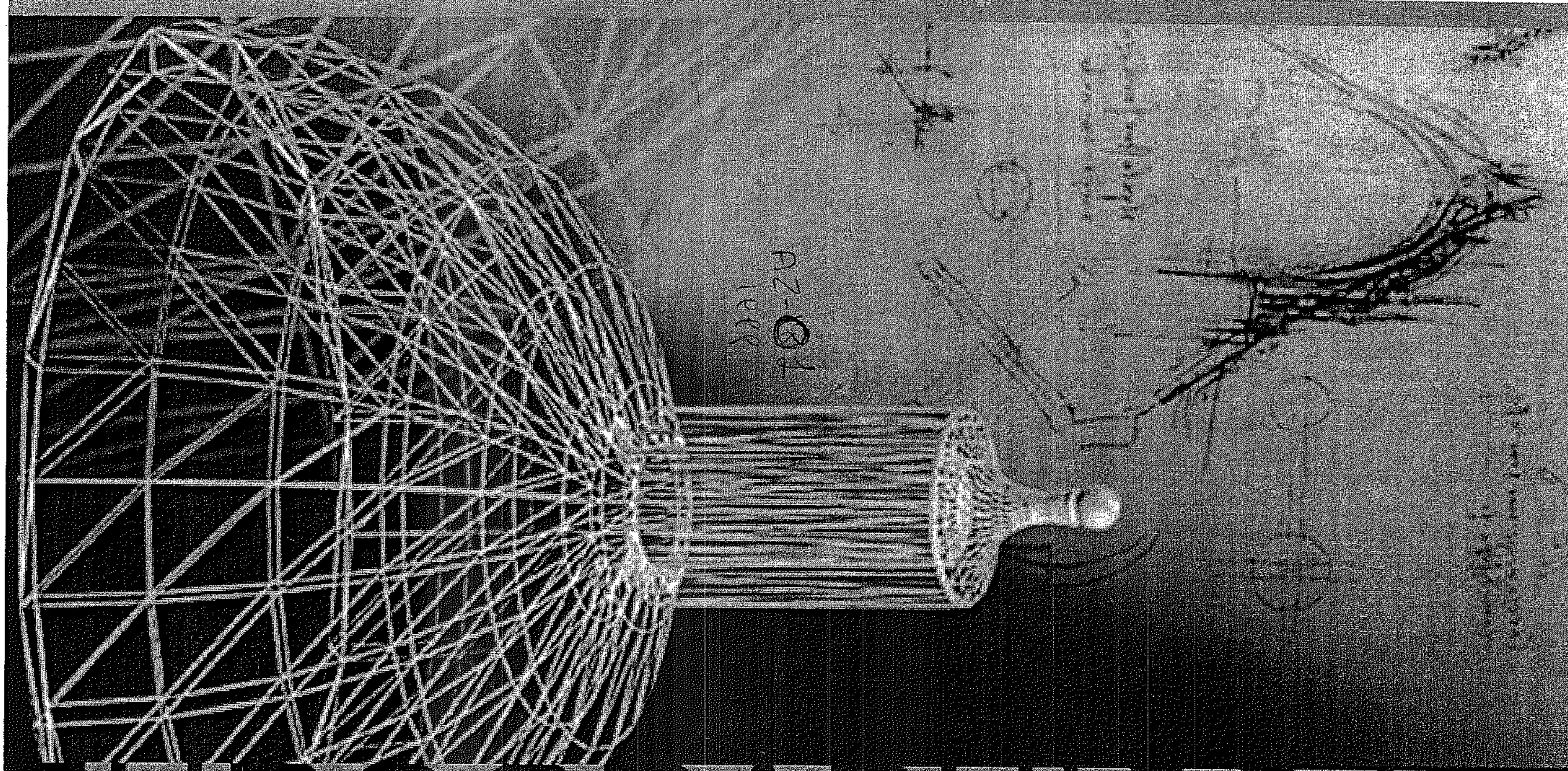

EUROGRAPHICS '99

Tutorial T5

Integrated Environments for Cultural Heritage Knowledge

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Abstract

Restoration and conservation actions on buildings of historic importance are generally performed relying on wide and heterogeneous information describing their degradation status. The high quality of this information is most important for designing appropriate action strategies. Typically, this is a hard task for Cultural Heritage experts not provided with computer science background and computational tools easy to understand and use. A deep knowledge of the buildings' conservation status requires preprocessing of the acquired data, while dedicated procedures generate new data for further processing, integrating for instance techniques for image analysis and synthesis. Appropriate fusion of data and efficient ways of information presentation to the user can highlight significant conceptual links. This Tutorial course presents an overview of some fundamental methodologies that must be developed in such integrated environments, and discuss a case study where different computing methodologies are deployed.

1 Introduction

The buildings of historic importance are, generally, described by means of a heterogeneous documentation ranging from the information on the territory where they are located to their conservation state, from the way of documenting and treatment to different possibility of access and fruition. The "high quality" of this information is very important in order to design appropriate proposals for restoration and conservation actions. Typically, this is a hard job for Cultural Heritage experts not provided with computer science background and computational tools easy to understand and use.

A deep knowledge of the conservation state must include the pre-processing of the acquired data and new data must be obtained by using dedicated procedures, for instance integrating techniques for image analysis and synthesis. Appropriate data fusion and efficient ways of information presentation can reveal highly significant conceptual links.

The Tutorial presents an overview of some fundamental methodologies that must be developed in integrated environments where have to be dealt with the previous mentioned problems in the field of Cultural Heritage. Not thinking to be exhaustive, such proposal derives from some Italian experiences carried out in research projects by multidisciplinary groups in the last five years.

In order to give a contribution to the study of problems characterised by a lot of different data types it is necessary to use of environments where different Computing Methodologies are available. Then, even if in this Tutorial a particular stress will be put on Computer Graphics, also the description of some Image Processing and

Computer Vision methodologies will be included. In fact, the image becomes a powerful knowledge tool if analysis, coding and representation techniques of pictorial information are integrated.

Proposed solutions to specific problems could be effectively usable from Cultural Heritage experts if the Computing Environment can be moreover extended by means of other Information Technology field methodologies. Among them are those concerning Data and Information Systems, for which a brief description, very close to the specific problems, will also be included in the Tutorial topics. In particular we will refer to appropriate G.I.S. techniques, to user-interface aspects and to special purpose versus general-purpose interactive systems.

A general introduction will start the Tutorial considering "from the user's point of view" the questions arising in some typical problems of the study of the conservation state of historical building, giving also a brief overview of the specific data types. In order to better understand the computer assistance we are now proposing, a very traditional approach, named "naked-eye analysis", is also mentioned.

In the field of Computer Graphics some methodologies will be presented in order to:

- simulate restoration and degradation events by means of bitmap operations used in picture/image generation area;
- reconstruct single component surface, also during a degradation event, at different scale levels using computational geometry and object modelling techniques;
- simulate realistic representation both of the single component and the entire building.

Image Processing and Computer Vision methodologies will be considered in order to characterise, starting from the images, degraded and not degraded regions and different materials structure. Apart from traditional approaches to image coding, a new approach for coding of the extracted information will also be dealt with, in relation to which the simulated scenarios can be very much increased as regards their realistic and dynamic functionality.

These tutorial notes, following this Introduction by Laura Moltedo, are organised as follows:

- Chapter 2: Recovery of the architectural heritage and information systems, by Paolo Salonia
- Chapter 3: Multi-view surface reconstruction, by Federico Pedersini, Augusto Sarti, Stefano Tubaro

- Chapter 4: Methods and techniques for image characterisation, by Ovidio Salvetti
- Chapter 5: Experiences on characterisation and recognition, by Barbara Caputo, Antonella Troncone, Domenico Vitulano
- Chapter 6: Virtual reality and photorealistic representation of ancient monuments, by Maurizio Rossi.

2 Recovery of the architectural heritage and information systems

2.1 Introduction: Heritage Safeguard and required actions

The study outlined here is part of the process of recovery and defines a specific methodology aimed to organise the knowledge and the cataloguing of monuments to be preserved. For this purpose some functions specific to the Geographic Information Systems field have been applied to the architectonic scale. An Information System has been designed for development in ArcCAD environments.

The finally acknowledged value of Cultural Heritage makes it mandatory to investigate appropriate procedures for studying and analysing the individual artifacts to be conserved. A correct management of the various aspects of the knowledge of the architectural heritage and the evaluation of its state of conservation are required for designing, implementing and verifying a recovery plan. Such knowledge can only be achieved by mapping the specificity of the monument, following its exact geometrical restitution, with other information. This information concerns historic-architectonic analysis, survey of the structure, building techniques and state of conservation of the composing materials.

Such a rationalisation of the whole recovery process strongly demands sinergies between humanist and scientific culture.

Infact, both the complexity and the systemic structure of the phenomena underlying historic buildings (geometry, materials, pathologies, history, successive stratifications) demand a wide range of tools and methods for exploring information coming from different domains of interest. The integration of several data sets and the formulation of evaluation syntheses are also required.

It must be stressed that, recently, the conservation of existing buildings is considered as a process:

2.2 The proposed methodology

In order to achieve such a result, it is necessary to identify the various paths of knowledge, the related databases deriving from them and the relationships used to define the state of conservation of the historic building. Thus, we need to define different procedures for the acquiring and recording of data describing geometry, structure, material composition and historical and architectonic features. The analysis of the pathology of decay and how it was formed (whether endogenous or exogneous) as a function of material components' typology and environmental factors, have also to be defined.

Such an organisation represents a typical Information Technology application, mainly concerning the innovation of conventional geometric survey methods and the definition and management of data archives. For the purpose of giving a significant contribution in this field a National Research Project was undertaken. The Project is aimed to design a modular information system able to manage both the various levels of knowledge required for the recovery of the historic buildings and the structural organisation of different kinds of information, by means of the integration of alphanumeric databases and geometric and iconographic data archives. The innovative aspect of the research consists in transferring the specific functions of Geographical Information System (GIS) to the architectonic scale of the individual building in the canonical forms of its graphic representation (plan views, elevations and sections), just like any other geographic area. A first prototype model was implemented after a detailed analysis of the requirements it had to satisfy from the point of view of both its functionality in information technology terms (organisation and management of different kinds of information) and the architectonic domain (definition of the data structure and the various methods of acquiring descriptive and geometric data).

2.3 The information system

The Information System has been designed as an auxiliary tool for the organisation, representation and utilization of knowledge concerning the management and recovery of historic buildings. The System in question is interactive in the sense that the user is also allowed to manipulate data in various ways for interpretative, evaluative and predictive purposes. It also represents a modular tool, consisting of modular subsystems, each of them providing a specific level of knowledge corresponding to successive levels of detail. In order to create a tool that could be used for performing different functions (from cataloguing to planning strategies and recovery projects), three different levels of detail were envisaged, each provided with a definite homogeneity of scale, ensuring the typological congruity of the results, aimed at specific user categories:

- overall documentation for cataloguing purposes;
- basic documentation for the planning of action strategies;
- detailed documentation for the design of specific recovery action.

Apart from modularity, other basic characteristics are the flexibility, to allow application to different historical, geographical and cultural contexts and also the intercommunicability with other systems. This will have to evolve towards an integrated support environment for the recovery of the architectonic heritage.

However, the fundamental characteristic of the system is represented by its capacity to interconnect alphanumeric and geometric data by means of relational geometric characterisation of the information. For each knowledge domain, the latter is graphically projected on the building's geometry and represented on separate layers, each of them containing homogeneous information. Each layer is mapped with tables, databases and text pages in which the descriptive data referring to the image it contains are organized and they can be consulted simply by clicking on the part of interest. The possibility of having several superimposed layers (each therefore with its own associated information baggage) allows several different forms of knowledge synthesis to be formulated and, then, different phenomenologies to be interpreted. The choice of GIS approach has made it possible to link the descriptive data to the graphic data, localising the information in the geometrically exact point (or area) with respect to the reciprocal topological relationships between the various parts of the building. The fundamental structure on which the entire methodological approach is based is the extension of the georelational model to normal Autocad procedures and to the most common types of relational databases. It follows that every database of objects and graphical entities typical of Autocad, thus, takes on the topological/vectorial modalities of GIS. Both the geometric and geographic units characterising the objects to be managed are treated, in their form and position, in accordance with topological/vectorial methods combined with descriptive data (attributes), graphic input (DXF created in CAD environments) and iconographic input acquired by means of scanners (raster BMP, TIFF). The alphanumeric data are structured into attribute tables, each field being flagged with the same identification code as the topological element to which the descriptive data is referred to. GIS functions also regulate all the selection and query operations, which are based on geometric or topological criteria, as well as on logic-arithmetic expressions.

Overlay operations (topological cross referencing) allow the intersection between the different databases to be achieved by superimposing the various graphic-rendered topics and the relative tables of attributes. At the same time the analysis of the different coverages (information layers) is ensured by combining together elements having different common attributes. Consultation is achieved by acting inside specific view areas where logical queries interactively address the databases, by clicking either on the elements defined within the alphanumeric fields of the tables or on the geometric elements themselves. Clicking on multiple windows allows the user to interactively create representative priorities of the topics included in the project(see Fig.1).

It is obvious that such a system will be mainly considered as a tool for the analysis of the information, in order to obtain additional information from the input data processing. Some functions are: calculation of the surface area affected by the same type of decay, number of elements characterised by the same component material and quantification of architectonic objects included in a given urban sector with reference to the same typological family according to selectable parameters (such as historical period, construction typology, presence of given pathologies, statistics, etc.). At the same time the System is also able to manage both input and output information representation by means of the display of graphic and inconographic data. Such data are suitably thematised on the basis of the descriptive data visualized in the same screen display as database tables.

The system guarantees the homogeneity of the classification by setting procedures to compare new data with inventories of possible cases, wherever the pursued aims are the uniformity of the collected data and the utilisation of unified and standardized lexicons to identify various typologies (architectonic, structural, constructive, material, decay). To this purpose typological data archives were devised in the form of vocabularies for each of the fields into which the descriptive data records are structured. Such vocabularies can be open or closed, according to whether they refer to situations having a wide range of possible variants of the basic type. The exact identification of the individual cases recorded and their correct attribution are carried out by using the vocabularies themselves. The latter ones, which are subject to continual updating over time and merging with local lexicons, represent a valid support during both the information input stage (they help 'to define') and the consultation and analysis (they help 'to interpret'). User friendly interfaces provided with buttons permit the access to a set of software tools for the acquisition and processing of different kinds of data before being introduced into the system itself. In conclusion the interface facilitates the various operations of consultation and analysis to a large number of possible user types, which, according to different methods and purposes, are allowed extensive facilities for navigation inside the system as a whole.

2.4 The study case of the Roman Theatre

The system proposed above is currently being further tested and developed in an application, selected in cooperation with Istituto Centrale del Restauro (Ministero Beni e Attivita' Culturali), that is the Roman Theatre in Aosta, a monument dating back to the Augustan age, recognized as a rare example of Roman covered theatre architecture. In elevation it consists of the remains of the facade, some 22 metres high, which is architecturally composed of a series of arches and of three superimposed orders of windows, alternating with buttresses. The masonry is of the rustic type, consisting of pudding-stone and travertine ashlars. This Tutorial briefly outlines the more significant achievements of research activities coordinated by Istituto per le Tecnologie Applicate ai Beni Culturali (ITABC - CNR, Rome) within the framework of the C.N.R. Strategic Project "Conoscenza per immagini: un'applicazione ai beni culturali" (Knowledge through Images: an application to Cultural Heritage).

2.4.1 Data structure

The preliminary operations involved the organisation of various data, both already existing and subsequently acquired, according to type and format enabling the planning of the photogrammetric survey activities and the setting up of additional information. The main typological families into which the various data sets were structured may be summarised as follows:

- general geometric data referring to the Theatre, deriving from a topographical survey and subsequent CAD rendering of the entire facade (taken by Studio Professionale Di Grazia - Rome, see Fig.2);
- detailed geometric-architectonic data and photographic records referring to a 6mx6m sector of the Theatre and 11 ashlars included in the photogrammetric survey (taken by FO.A.R.T. - Parma, see Fig.3);
- 2D and 3D geometric reconstruction models of the surfaces of the ashlars obtained from multitelecamera sequences (taken by the Department of Electronics and Information (DEI) of Milan Polytechnic);
- chromatically corrected colour images of pudding-stone and travertine ashlars (acquired and corrected by the Department of Electronic Engineering (DIE) - Florence);
- data on the physical-chemical characteristics of the materials, obtained from spectrometric and colorimetric analysis of pudding-stone and travertine ashlars and referring to the chemical composition and the reflectance curves (performed by the Department of Organic, Metallorganic and Analytical Chemistry (DCOMA) of the University of Milan);
- macroscopic survey data concerning the state of conservation, the spatial arrangement of the various lithotypes and the surface characteristics, obtained

by visual inspection of each ashlar by the experts of the Superintendency of Cultural and Environmental Heritage of the Valle d'Aosta Region.

2.4.2 Storage of data and their representation and management in a GIS environment

One of the first operations was to define an alphanumeric data base, in harmony with the NORMAL recommendations (CNR/Istituto Centrale del Restauro Commission), including the data referring to the classification of individual ashlars. Such a classification derives from an optometric examination and refers to the typology of the component materials, their texture, the various degradation pathologies (chemical, physical, biological and structural), as well as to the evaluation of the state of conservation.

Lastly, the Information System, including GIS techniques and above described, was tested at the architectonic level using the photogrammetrically surveyed sector of the facade, in order to obtain a strong integration between the descriptive data and the geometric data which was not merely visual. The geometric basis of the monument surveyed was used as a topographic reference of spatial and topological relations among the descriptive data. The whole information set, georeferenced on the configured GIS coverage (ArcInfo - ESRI), can be consulted (ArcView - ESRI) at each single level for several of them by means of overlay operations (see Fig.4-5).

2.5 Towards the automation of naked eye analysis

Naked eye analysis (visual or direct inspection) forms the basis of the process of assessment of a historic architectonic monument, that we have described above. It allows information to be obtained concerning: the environment and the building's relationship with other buildings and/or monuments, its significant dimensions, architectonic typology, the typology of its main structures, the component materials, effects of structural, chemical-physical-biological and typo-morphological degradation. In order to guarantee an enhanced interpretation of the degradation processes, a series of experiments were performed to identify methods that would render more objective the conventional expert's interpretations during the visual inspection phase. These experiments have been carried out by means of image and data processing using appropriate AVS (Advanced Visual System) networks. It is to be outlined that such experiments represent the first stages of a broader perspective aimed at the automation of the visual inspection process.

2.6 Conclusion and perspective

In collaboration with ESRI ITALIA, a first prototype model developed in ArcView (GIS) environment has been proposed for analysing, querying and consulting data in the field of the recovery of Architectural Heritage. Overall, the system structured in this way is easy to use and represents an effective support and guiding tool for different organisations, in particular the Superintendencies which have a wide range of responsibilities as regards the management and reutilization of the historic building heritage (ranging from cataloguing to the preparation of strategies and the planning of specific action).

In such a context, it was thus deemed of interest to investigate possible ways and means of enhancing the prototype produced which, in any case, in order to be validated, requires further testing also using different study cases. Future plans involve the specialisation of several modules of the system in order to obtain a better definition of priority knowledge pathways associated with several specific phenomena typical of buildings of historical interest. In the medium term we essentially aim to integrate the module for the typological and historical-chronological survey with the one concerned with the various states of alteration and respective pathologies, in order to achieve a systematic evaluation of the state of conservation.

A subsequent development of the research will consist in the completion of the whole logic process by means of the implementation of modules where the criteria for the evaluation of the state of conservation will be transferred. Together with them, the data required for the definition of the recovery action, the criteria and the tools for planning the action itself, the descriptive data concerning the subsequent stages and the criteria for the evaluation of the action taken will be included.

The final aim is that of configuring a comprehensive modular tool to perform functions related to knowledge, design and continuous monitoring, at different levels of detail, at the same time guaranteeing several different navigation itineraries, all tuned for a wide range of possible users. In the long term, the research will generally tend towards the definition of procedures for the design of tools to be used for the recovery and management of the historic buildings as a methodologically correct practice aimed at attaining a true geographic and environmental upgrading.

3 Multi-View Surface Reconstruction

3.1 Introduction

In the past two decades, a number of 3D object reconstruction methods based on the analysis of camera images, have been proposed for applications of 3D modeling in multi-media applications. There is a considerable number of applications, however, in which the accuracy of the 3D reconstruction plays a crucial role. Close-range digital photogrammetry applications, for example, can be fruitfully employed for the evaluation and planning of preservation and restoration of 3D works of art; or for industrial/architectural metrological applications. Such methods, in fact, require effective techniques for accurate, quantitative, reproducible and repeatable 3D reconstruction. One successful approach to the accurate 3D modeling objects of modest size (from 10cm to 1-2m) is based on laser scanners [55]. Although there are several types of laser scanners, they all measure 3D data through geometric triangulation. In one common type of laser scanners, for example, a laser generator projects a light stripe onto a 3D object, which is imaged by a video camera from an angled viewpoint. The image reveals the contour of the object where the laser light intersects the object surface. This contour is captured and processed in order to obtain 3D information about it. This solution, unfortunately, is characterized by a cost that rapidly increases with the size of the object to be reconstructed, as both laser head and sensor need be mounted on a mechanical support with a high-precision positional feedback. Furthermore, such devices are usually quite difficult to transport and handle. One way to overcome this problem is to adopt an image-based approach.

In general, the 3D reconstruction methods based on feature matching can be classified into two categories:

- *uncalibrated reconstruction*: a series of uncalibrated views are taken in sequence or at random, and then processed all together (*global approach*) or in subgroups (*local approach*) in order to jointly estimate camera viewpoints and 3D scene structure. In the global approach, one or more cameras are employed for acquiring a number of images of the object from a variety of viewpoints. The pose of the cameras and the 3D coordinates of the features are found through a joint analysis of feature correspondences between all available views. In the local approach a video sequence of the object is acquired in such a way to "cover" all portions of the object. Then the views are partitioned and processed in small (usually two or three) groups of images, using projective constraints and invariants.

- *calibrated reconstruction*: a set of cameras is mounted on a rigid support and calibrated, so that all camera parameters are known beforehand. If the 3D scene is imaged using many synchronized cameras positioned all around the scene (*global approach*), then a reconstruction of a dynamical scene is possible [56, 57]. When the scene is static, however, the complexity of the acquisition system can be greatly reduced. In this case, in fact, it is sufficient to acquire a series of multi-ocular views, each of which will originate a partial 3D reconstruction of the object (*local approach*). Indeed, the resulting 3D data will have to be fused together into a global full-3D model using rigidity constraints [58, 59] to determine position and orientation of the camera system for each acquisition (egomotion).

In general, a global approach is what estimates the 3D object structure with the best accuracy. In particular, in the uncalibrated case, a global approach would be characterized by a very heavy computational complexity and would produce a sparse set of 3D features that could not easily be interpolated into a global surface unless some a-priori information on the object were available. Partitioning the views into "good" subsets for a local uncalibrated approach is a way to overcome this difficulty. The accuracy of a local uncalibrated approach, however, is limited by the fact that camera motion and 3D scene structure are estimated from natural image features, whose localization accuracy and whose distribution in the volume to be reconstructed are not optimal. Furthermore, consecutive views in a video sequence are likely to be "aligned" with each other and, therefore, they are not optimally positioned for feature matching purposes. The local uncalibrated approach, however, is quite promising for its flexibility and cost.

As far as calibrated reconstruction is concerned, the global solution is interesting for applications of full-3D reconstruction of dynamical scenes, but it suffers from problems of cost, portability and flexibility. Our interest in the local calibrated approach, on the other hand, is justified by the following facts:

1. the multi-camera acquisition system induces a "natural" partition of the views; if the cameras are well-positioned on the rigid frame (e.g. three cameras at the vertices of a regular triangle), such partitioning will be optimal;

2. the acquisition system can be quite easily calibrated using targets that can be accurately localized and positioned in the scene to be reconstructed; furthermore, the calibration can be made adaptive in order to compensate for the drift of the parameters throughout the acquisition process;

3. the accuracy of a partial reconstruction resulting from the analysis of a well-calibrated triplet of views is comparable to that of a global calibrated reconstruction;

4. a partial reconstruction (3D patch) is topologically easier to deal with than the whole surface;

5. 3D patches can be fused into a global surface reconstruction through a "patchworking" process.

In this tutorial we present a summary of the results of our research activity on local calibrated reconstruction, conducted within projects related to the areas of cultural heritage and multi-media applications. We will also briefly discuss our approach to local uncalibrated reconstruction.

3.2 Local approach to calibrated modeling

Our local calibrated approach to 3D object modeling is based on the acquisition of a number of multiviews, each of which will generate a surface patch (partial reconstruction) through a multi-resolution area matching approach. The 3D patches will then be registered in the object space through a process of optimal 3D data (curves and points) fusion, in order to obtain a global 3D model.

All calibrated 3D reconstruction methods are critically dependent on the accuracy with which the camera parameters, i.e. the geometrical, optical and electric characteristics of the camera system (camera position and orientation, focal length, pixel size, location of the optical center, nonlinear distortion coefficients, etc.) are known. Before discussing our 3D modeling process we will thus briefly describe our calibration strategy.

3.2.1 Calibration

In the past few years several approaches to the calibration problem have been proposed. Such methods apply to electronic cameras the same techniques that were traditionally used for the calibration of photogrammetric cameras [60, 61]. The camera characteristics are, in fact, computed through a proper processing of the image of a test object (calibration target-frame) placed in the scene. The accuracy of the camera model can be arbitrarily improved by employing an adequate number of parameters therefore, when the goal is that of improving the calibration accuracy as much as possible, the pattern's accuracy becomes the major bottleneck. For this reason, we developed an advanced photogrammetric method that jointly estimate the camera parameters and the geometry of the calibration target-set in a more accurate fashion [62, 63].

This method is based on a multi-camera, multi-view calibration approach, and performs an accurate estimation of the parameters of the multi-camera system from the analysis of several views of a simpler calibration target-frame, such as a marked planar surface (e.g. a printed sheet of paper glued on a glass surface, as shown in Figure 6) or some other even simpler structure (a bar of fixed length). In fact, not only is this technique able to estimate the camera parameters, but it can also determine the 3D position of the targets on the calibration frame, which can be just roughly known or, in some situations, not known at all. As an example of application, Figure 7 shows the *a-posteriori* corrections on the nominal coordinates of a set of circles laser-printed on a sheet of A4 paper (glued to a flat surface), as estimated through self-calibration. The orientation of the (magnified) correction vectors denotes the deformation of the sheet of paper due to the action of the dragging mechanism of the laser printer.

Finally, we developed method for making the calibration robust against the inevitable parameter drift that takes place during the acquisition process. Such method detects and tracks some "safe" features that are naturally present in the scene, and use their image coordinates for making the calibration process adaptive [64].

3.2.2 Local reconstruction

Typical stereometric methods for 3D data extraction from multiple views are based on the detection, matching and backprojection onto the object space of viewer-invariant features such as corner points and sharp edges [65]. Such methods, unfortunately, are unable to produce dense clouds of 3D data, therefore it is usually quite difficult to interpolate them into a global surface that resembles that of the imaged object. Another approach to stereometric reconstruction that produces dense depth maps is stereopsis, which consists of the matching of the luminance profiles of small image areas of the available views [66]. The 3D coordinates of the surface patch that originated the corresponding luminance profiles are determined through geometric triangulation, while the matching process is performed by maximizing a similarity function between the luminance profiles. A generalized version of this approach has been proposed in the literature [67, 68], which is able to perform area matching while accounting for geometric and radiometric distortions of the luminance profiles. The object, in fact, is modeled as a bundle of tangent planes, whose position and orientation in the 3D space is determined in such a way to maximize the similarity (correlation) between the luminance profiles projected onto them from the available views. Such solutions, however, need an initial approximation of the object surface to begin with, in order to prevent the algorithm from encountering relative minima.

The 3D modeling approach that we developed, on the contrary, is able to effectively and efficiently perform an accurate area matching from scratch (modeling bootstrap) without producing outliers. In order to do so, we adopt a multi-resolution strategy for shaping the surface. At each resolution level, we determine the surface shape that maximizes the correlation between the original image and the luminance profile of the other views, as transferred through the 3D surface model.

The object surface is modeled as a hierarchical radial basis function (RBF) network [70], i.e. as an array of gaussian functions scattered on regular grids of progressively increasing density.

In order to model the surface at the lowest levels of resolution (low-density RBF) we perform a global optimization of all surface parameters, using the above luminance correlation as a goal function. The grid doubles its density at each step, by alternating rectangular and hexagonal geometries. As the density of the RBF increases, however, the number of parameters to be optimized soon becomes excessive for a global optimization. When this happens, the algorithm switches to a local mode, and determines a cloud of points, each of which corresponds to a small surface patch locally modeled as an RBF, which is "trained" through an area matching process.

The estimated local RBFs are then fused into a single (higher resolution) RBF network, by interpolating the resulting cloud of points through a multi-resolution approach, once again, based on hierarchical RBF networks [70]. The elimination of the outliers is performed right before every intermediate re-interpolation step, by thresholding the value that the goal function takes on the points of the estimated cloud (see Figures 8-10)

3.2.3 Patchworking

Stereo matching methods can usually provide a reconstruction of just a portion of the scene surfaces, while it would be desirable to reconstruct the surfaces of the whole scene. As a matter of fact, automatic 3D reconstruction systems based on stereo-matching can only reconstruct the visible portion of surface. Such systems, in fact, typically provide a description of just the front side of the imaged scene or, when the surface is too large to fit simultaneously in all views, of just a limited portion of it. In conclusion, in order to obtain a complete scene reconstruction through stereometry, it is necessary to observe the scene from several significant viewpoints and put together the final reconstruction like a patchwork of partial reconstructions. In order to be able to merge 3D data coming from different reconstructions, we need to accurately estimate the rigid motion that the acquisition system undergoes between two partial reconstructions. When doing so from the available images, this operation usually requires a certain amount of computational effort. When the object to be reconstructed is relatively small, however, it is usually simpler to mount the acquisition system on a mechanical support with positional feedback or, conversely, to place the object on a rotating support. This a-priori solution of the ego-motion problem, however, usually becomes quite expensive and not very flexible, especially when the size of the object is significant.

One solution to the problem of camera motion estimation consists of the mutual 3D registration of the surfaces that constitute the partial reconstruction, using, for example, the Iterative Closest Point (ICP) algorithm [69]. In alternative, one can perform detection and tracking of some image features throughout the acquisition process, and use the location of such features for estimating the camera motion. This last approach becomes particularly interesting when the features to be extracted are part of the scene to be reconstructed rather than being artificially added to it. Adding special markers to the imaged scene is, in fact, common practice in photogrammetry but, besides making the egomotion retrieval more invasive, it requires a certain expertise and slows down the acquisition process [58]. Scene features that can be quite safely detected and are commonly present in natural scenes are luminance edges. These features are more likely to be naturally present in the scene and rather easy to detect, which makes them good candidate features for egomotion estimation. Our method for estimating the egomotion of a multi-camera system is based on the analysis of 3D contours in the imaged scene [59]. Being the method based on a calibrated multi-ocular camera system, the estimation is performed entirely in the 3D space.

In fact, all edges of each one of the multi-views are previously localized, matched and back-projected onto the object space [65]. Roughly speaking, the method searches for the rigid motion that best merges the sets of 3D edges that are extracted from each one of the multiple views. The fusion of partial reconstructions into a global 3D model can be performed by estimating the rigid motion of the camera system between acquisitions, and by referring all 3D data to a common global frame. We perform this operation by looking for the rigid camera motion that best merges the 3D contours that are in common between partial reconstructions. The egomotion estimation method that we developed and implemented for accurate patchworking purposes is organized in two mains steps.

After having partitioned the available 3D contours in lines and curves, we first perform a rough egomotion estimation from straight contours; then we refine the egomotion using curved contours. Both steps include contour matching followed by a motion estimation process that minimizes the distance between homologous 3D contours. Notice, however, that the egomotion refinement starts from a first approximation of the egomotion, therefore the matching process is, in this case, much simpler (see Figure 11).

3.3 Local approach to uncalibrated modeling

Our approach to uncalibrated 3D modeling from multiple views is a mixture between classical uncalibrated reconstruction methods and stereometric techniques. As a first step, we analyze the available views with the goal of computing a first estimate of the position and the orientation of all viewpoints. In order to do so, we perform a simultaneous estimation of camera motion and 3D coordinates of some significant viewer-invariant scene features (e.g. luminance corners [71, 72]). The second step consists of densifying the 3D data determined in the previous step and, at the same time, refining the camera motion estimate by exploiting the available viewpoint geometry and stereometric methods based on image features such as points and edges.

3.3.1 Tacking the viewpoint geometry

This first step of the reconstruction procedure consists of "peeling the layers" off a stratified model of vision, from projective to affine to Euclidean. In fact, the first operation that we perform is projective calibration, which consists of determining a projection matrix for each one of the available views, exploiting a number of image correspondences [73, 74]. Given two views and the fundamental matrix that expresses the projective relationship between them (which can be quite easily determined from a number of point correspondences), there are a variety of methods that allow us to determine the projection matrices (see, for example, [73, 74]). Such methods usually exploit the fact that the projection matrices can be determined up to a similarity transformation so that the projection matrix of the first view can be simply chosen in canonical form.

This choice results in a simplification of the procedure for determining the other projection matrix. When more than two views are available, the determination of the projection matrix can be made more robust by adopting multilinear constraints. For example, one constraint that is often exploited when using three views is the trifocal tensor [75], which determines the position of a primitive in one image, given the position in other two.

Once the projection matrices are available for all the views, we determine the intrinsic and extrinsic matrices of camera parameters that generated them. The literature is rich with methods for determining such matrices using additional geometric constraints. Such solutions usually applying constraints to the intrinsic camera parameters through the absolute conic [77, 78], which is a set of points of imaginary projective coordinates $[x, y, z, t]^T$ that lie on the plane at infinity ($t = 0$) and satisfy the equation $x^2 + y^2 + z^2 = 0$.

One remarkable property of the absolute conic is that of being invariant under scaled Euclidean transformations. Its projection onto the image planes is thus invariant under rigid displacements of the camera (if the intrinsic parameters remain unchanged). This property leads to the so-called Kruppa constraint, which can be used for recovering the Euclidean geometry.

Once the intrinsic camera parameters are known, the epipolar constraint between two views can now be explicitly written in terms of the essential matrix (instead of the fundamental matrix), which only contains extrinsic camera parameters. From the essential matrix it is possible to algebraically determine rotation and translation (up to a scale factor) through a process based on singular value decomposition [74].

The scale factor of the translation can finally be (at least approximately) determined by exploiting some a-priori knowledge on the actual distance between any two scene points.

3.3.2 Refining the geometry

The epipolar geometry estimated above, allows us to determine a number of additional correspondences between a variety of image features. For example, we can perform edge matching along the available epipolar lines. As far as area matching is concerned, the sole epipolar geometry does not allow us to account for the geometric distortion of the luminance profiles as they need be transferred through the Euclidean model of the surface. However, if we could trust the Euclidean geometry estimated in the first step of the procedure, we could still adopt an area matching approach such as the one illustrated before.

One way to improve the accuracy of the available estimate of the Euclidean geometry is to extract a large number of additional points from luminance edges and use the available epipolar geometry in order to simplify the point matching process between the available views.

Now that we have a much larger number of matched points, re-running the self-calibration procedure described in the previous section results in a considerable refinement of the Euclidean geometry, without impacting too much on the computational complexity, as the uncalibrated matching process is, in fact, skipped (see Figure 12 - 13).

3.4 Conclusions

In this tutorial we presented our approach to accurate 3D scene reconstruction using local strategy based on both calibrated and uncalibrated image acquisitions. In particular, we briefly illustrated a general and robust approach to the problem of close-range partial 3D reconstruction of objects from multi-resolution stereo-correspondences, and we presented a method for performing an accurate patchworking of the partial reconstructions, through 3D feature matching. Finally, we showed how similar strategies can be incorporated with uncalibrated strategies in order to make the reconstruction more flexible. The methods that we propose offer good characteristics of non-invasivity, flexibility and accuracy that make them suitable for a variety of application that range from the preservation and restoration of the Cultural Heritage to industrial metrology and architectural modeling.

4 Methods and techniques for image characterisation

4.1 Introduction

This contribution examines how information systems can assist experts to analyse the state of conservation of buildings of historic importance. The main focus is on image characterisation and recognition, which are fundamental for defining a database on the state of conservation. In particular, an overview of available methods is presented for characterising the structure of materials and recognising the various degrees of degradation. Applications are included for processing stone images.

4.2 State of the art

Current methods for documenting and managing the Cultural Heritage are based on providing tools for data archiving, accessing and querying. Much work is being carried out in many countries in defining appropriate databases, as testified by the contributions at recent conferences [12], [13].

A common approach is to consider heterogeneous and often multimedia data, hence not only alphanumeric data but also images, videos and graphic information. The main characteristics a database should implement are appropriateness and efficiency; appropriateness to fulfil objectivity and conformity to a standardised lexicon and efficiency by allowing easy and perceptive user-interfaces.

At a first level, computer assistance supplies functions for archiving and accessing multimedia databases. In this area many European Research Projects are still supported by EC programs, such as ACTS, ESPRIT 3-4, IMPACT2, INFO2000, TELEMATICS2C and RACE1-2.

At further levels, computing techniques should be provided in order to guarantee that data are made independent from the acquisition techniques, and are as objective as possible. Very often the information acquired should be properly pre-processed before being included in a database, and new data should be obtained using dedicated computing procedures, for instance by applying image analysis and synthesis techniques. In many cases, appropriate fusion of some data might contribute greatly to deep a specific knowledge of the state of conservation.

In this regard, the RAPHAEL EC program recently launched actions in the field of the Cultural Heritage conservation where research projects, including a wide spectrum of information technology techniques, are required.

Bearing in mind, for instance, the documentation of the state of conservation of buildings of historic importance, a computer aided approach is a step forward from the traditional "naked-eye" analysis. This activity consists of an accurate observation followed by a description of the building that the expert complies looking at the monument and using words from a standardised lexicon. By direct visual analysis, information can be obtained, for instance, on significant dimensions, architectonic typology, typology of the main structures, materials, and the effects of structural, physical-chemical-biological and typo-morphological degradation.

This work focuses on image characterisation and recognition, both of which are fundamental for defining a database on the state of conservation of a building. In particular, methods are presented for characterising the structure of the materials and recognising the various degrees of degradation.

Also some examples and results are presented on images acquired from lapideous material from the Roman Theatre in Aosta.

In particular, in the second part of this contribution, a brief overview of computer support for Cultural Heritage conservation and restoration is also provided, followed by a description of the framework and the general aims of the research carried out.

4.3 Computer aided conservation

The analysis and recognition of morphological characteristics of stone images is carried out in [19] by means of characteristic points, lines and regions. Characteristic points are recognised such as minimum, maximum and sella points, characteristic lines identify surface discontinuities and characteristic regions are zones where the surface has a uniform behaviour, for instance the same curvature or a uniform slope. On the basis of a photogrammetric survey, cavities and fissures represented in the stone image can be recognised visually.

A morphological approach [20] is also used in a structural texture analysis of carbonate rock weathered surface [21]. This approach is based on a granulometric and covariance analysis of grey tone functions of texturally representative areas of images.

Modelling techniques that evaluate the behaviour of materials that are subject to downgrading or depreciation due to natural and/or artificial agents have been proposed by [22]. In this approach, texture-based image interpretation and generation are implemented.

A study has been carried out to show how representations of a monument's geometry together with the morphology and distribution of damage, the component materials and their physical characteristics and environmental factors can be used to facilitate the understanding of the degradation process of the monument itself [23]. In this case the representations where the geometry has been reconstructed by means of photogrammetric data have been mapped to information extracted from a "naked-eye" analysis.

A computer assisted procedure is used in order to evaluate the type and the extent of existing damage to historical buildings [24]. The geometry restored by a photogrammetric survey is mapped with information such as the absolute and relative extent of damage obtained by means of appropriate image analysis procedures. Such data are useful for estimating the costs of restoration or preservation.

4.4 Main aspects of the Research

In order to provide experts with support in computer aided analysis of states of conservation, a research was begun and continued within the framework of two Italian National Research Council projects, the Strategic Project "Knowledge through images: an application to Cultural Heritage" (1994-1996) [25] and the Special Project "Safeguard of Cultural Heritage".

Within the initial framework, the research methodologies were verified in a study-case, the Roman Theatre of Aosta. This is a very typical building of Augustean age whose component materials are mainly travertine and pudding-stone. In the first project, image analysis and synthesis procedures were investigated and a prototypal database, including all the information collected on the theatre, was also provided [26] . In particular, together with geometric and architectonic data and images regarding both the building and a representative set of the component ashlars, also alphanumeric information coming from "naked-eye" analysis was included. This description was organised, in compliance with the lexicon of Normalisation Groups, by means of a subdivision into the following typologies: material and texture types (fine grained, medium grained, coarse grained), chemical, physical and biological degradation, organised into four fundamental families (increase in material, lack of material, breakdown in continuity, colour alteration) and structural degradation (such as cracking).

The second project deals with the definition of tools to support an expert at two levels. The first level aims to define techniques for making the "naked eye" analysis objective (this analysis is usually followed to diagnose the state of conservation of a building or work of art). The second level simulates "future" scenarios of further degradation and consequent restoration, which is useful for deciding specific treatment methodologies.

To reach these aims, a prototypal visual computing environment, called C.H.A.A.T. (Cultural Heritage Assisted Analysis Tools) has been developed. This system is oriented to both the analysis of complex images and the simulation of pictorial dynamic events in the field of the conservation studies of historical building monuments. Using a high-level user-interface C.H.A.A.T. allows access to a data archive including geometric, descriptive information and images of stone [27] .

C.H.A.A.T. has been designed with a typical Windows programming interface providing easy interaction. It deals with a Multiple Document Interface which permits contemporary operations on more than one document. The user interacts with the application by means of the frame window in order to efficiently access to the system functionality's.

4.4.1 Image characterisation and recognition

Two types of image characteristics should, generally speaking, be analysed: morphometric and densitometric.

The morphometric information includes geometric, topological and metrical properties of the image [20]. An image is described by a set of primitive entities (points, lines, curves, regions) and their relationships.

A description based on densitometric characteristics is based on the spatial layout of the pixel colours, that is its image texture [35], [36].

The fusion of texture analysis and synthesis is one of the most widely used tools for characterising image regions. In fact, the first task in texture analysis is to extract features which most completely embody information about the spatial distribution of grey level variations in real images [35]. Usually, texture analysis can be carried out following either numerical or syntactical approaches [36], [37] . Among these numerical approaches are fractal geometry, statistic analysis, co-occurrence matrix and numerical filters. In synthetic images, texture is an important surface attribute which provides information about the nature of a scene, acting as a fundamental descriptor of pictorial regions [38] and, for instance, as a characteristic of the surface material usable for introducing perturbations of geometric and spectral properties of the surface itself. In [39] a taxonomy is proposed based on the computation of geometric and spectral properties.

4.4.2 Implementations

The following subsections include a short description of the techniques we implemented for characterising regions, with respect to the component materials typology and different degradation shapes. In [22], the problem of how to deal with texture in integrated environments for analysis and synthesis is examined and a unified model is proposed. Here, among the various techniques which can be used to both extract and produce textures, we choose those suitable for a unified approach. In other words, we selected analysis procedures which use parameters that can be easily manipulated in the synthesis phase. This is, thus, the guideline of our research.

4.4.3 Characterisation of the component materials typology

In order to characterise the component material typology and, in particular, materials with different grains, statistic and geometric approaches have been merged [22], [25] . The former approach allows the regions to be characterised in terms of their statistic properties, such as standard deviation or entropy. For instance, the exam of several images dealing with pudding-stones of different grains (from coarse to fine grain) gives the results shown in Figures 14 and 15.

Figure 14 shows the behaviour of the standard deviation function: for coarse grain it is higher than the fine grain. In fact, the fine grain image is more "uniform" irrespective of where is the average of the intensity levels is.

Figure 15 shows the behaviour of the entropy function: note the decreasing values from coarse to fine grain. Infact, the more "irregular" the image (higher entropy), th ehigher the quantity of the information included. A coarse grain material surface is certainly more irregular than a fine grain one.

The geometric approach deals with the computation of the normal vectors field [22]. The grey level of an image pixel is related to the geometry of the object that the image itself represents. This assumption derives from a law - which is valid in the case of light sources that can be characterised by an infinity of parallel rays that have an equal sense and direction - which states that the intensity of each pixel is directly proportional to the light source and the geometric normal vectors. The geometric normal is thus of fundamental importance for the image characterisation and reconstruction. Figure 16 shows three different grain pudding-stones, at the top, and the visualisation of their normal fields, at the bottom.

All the above mentioned procedures included in C.H.A.A.T. start from an image analysis technique and produce synthetic images: in the first case, they are graphs while in the second one they are visualisations of vectors on a two-dimensional space.

4.4.4 Characterisation of degradation shapes

One of the main problems in the analysis of images showing details of materials surfaces is the extraction of basic features of degradation shapes.

These features are particularly relevant with respect to both recognition and synthesis, for instance, the simulation of a further degradation process. Nevertheless, the study of the degradation could be complicated because of the presence of irregular structures in the material itself.

In order to extract significant characteristics of an image relative to degradation shapes, co-occurrence matrix and Wavelet Transform (WT) approaches can be used.

The first technique obtains image segmentation, that is, regions with particular densitometric features are identified and separated. In order to obtain densitometric data. C.H.A.A.T. also includes the co-occurrence matrix approach [25], [37], [41] . Texturally homogeneous regions can be identified and extracted.

The point of view of the second technique, based on the wavelets, is the edge detection at different scale levels. This technique can be used when the available images are difficult to treat, i.e. when edges cannot be detected because of particular features of the material (such as texture, etc.). In fact, WT is considered a powerful tool for space-frequency multi-resolution characterisation [32]. A given image can be decomposed at several scale levels and the procedure allows different shapes of degradation to be coarsely characterised. Moreover, this representation means that a shape of degradation can be separated from other image features, for instance noise [43]. This procedure can be applied when the "useful signal" and other features are localised in different areas of the frequency domain. When this condition is not satisfied, the given image should be "pre-cleaned", using well-known enhancement techniques.

In Figure 17 the shapes relative to degradation zones can be extracted by means of the wavelet transform (Bior 2.4 type). This analysis is also implemented in C.H.A.A.T. using an appropriate sub-module.

4.4.5 Shape processing

The classical problem of pattern recognition can be represented in our case by the recognition of shapes which characterise subparts of the image, for instance degradation zones. In all our procedures, the expert plays a fundamental role in suggesting the criteria and rules concerning measures to identify the class a region belongs to.

Here we describe the first approach, used within C.H.A.A.T., to recognise which class a region belongs to [44]. Starting from a visualisation of segmentation boundaries the user is requested to give information about significant measures. For instance, the user is requested to give the minimum area a region must have in order to be significant. In fact, Figure 18 shows green colour filled regions that are positive to this test. In such a way, cavities derived from a degradation process can be distinguished from cavities due to structural properties of the material.

4.5 Conclusion

This contribution deals with approaches to computer aid for experts and operators in the field of analysis of the state of conservation of building of historical importance. We have focused on the problems of characterisation and recognition of parts of images directly derived from the stones that belong to such buildings.

All these functionalities are included in the C.H.A.A.T. system, which was developed to facilitate users in accessing data archives, in extracting parameters from images for performing interactively various evaluation processes and in applying efficient methods for studying properties or simulating pictorial events.

Future research will be addressed to the development of other techniques for such computer aided diagnosis and to the improvement of user friendly environments to use these techniques, such as C.H.A.A.T.

5 Experiences on characterisation and recognition

5.1 Introduction

This contribution examines how the characterizations and recognition techniques can be used in order to extract the information contained in digital images showing degradation events. This kind of studies must be considered as a fundamental tool to support the naked eye analysis traditionally carried out by Cultural Heritage experts. Even if Cultural Heritage experts developed a formal description of material degradation kinds, on the basis of their features [83], the available representation of the experts knowledge is both very subjective and described by a very precise terminology. It is clear so that there is the possibility to generate an automatic characterisation, i.e. a more objective representation of this knowledge containing the experience of Cultural Heritage experts. It must be stressed here that the role of experts is fundamental at many stages.

A general overview on the characterisation problem and the image processing techniques for the feature extraction is already proposed in Chapter 4. Here we want to give an overview on a promising technique for the recognition of the various degrees of degradation, the neural network approach. A review of recent works in which the characterisation of different kinds of material degradations and the recognition with a neural network approach has been done with successful results is also included.

5.2 Neural Networks and the recognition problem

A neural network is a large network of single interconnected processing elements, called neurons [81]. A weight w_{ij} (coupling strength) characterizes the interconnections between any two neurons i and j. The input to each neuron is a weighted sum of the output incoming from the connected neurons. Each neuron operates on the input signal using his activation function f and produces the output response. The typical activation functions are linear, threshold, and sigmoid.

Normally the neurons are organized in an architecture with input nodes, interfacing the neural network and the external world, output nodes, producing the network's responses, and hidden nodes, having the task of correlating and building up an internal representation of the analyzed problem. Network's capacity and performances depend on the number of neurons, on the activation functions used, and on the neurons' interconnections.

We consider the feed-forward neural networks: in this kind of neural networks there is an information flow from input layer to the output layer through the hidden layers. Among the neurons of the same layer the connections are absent.

The fundamental feature of neural networks is that it can learn, i.e. there is a way of modifying the weights according to external excitation presented to the network. The first basic approach to the learning problem was based on the Hebb rule, i.e. a weight increases in proportion to the product of the activation status of the two neurons involved. This reflects the obvious notion that the coupling constant has to be larger if there is a strong coupling between the input stimulus and the output reaction. Problems with this early approach are among others the non-limited growth of the weights. A fundamental way of implementing a learning process is to use an external supervisor, and to adjust the weights on the basis of an error correction procedure, called Generalized Delta Rule.

The network, as a response to an input pattern A_p, (where p ranges on the the number of input patterns), produces an output O_p, which is compared with the desired output T_p. The weights change proportionally to the difference between T and O:

$$\Delta w(i,j) = \eta[T_p(i) - O_p(i)]A_p(j)$$

where η is a parameter, called *learning parameter* which is chosen such that one can jump out of local minima. It can be modified during the learning process. Remember that the output of a neuron is a function of the weighted sum of the inputs.

$$O_p(i) = f[\sum_j w(i,j)A_p(j)] = f[s_p(i)]$$

In the simple case of linear units the Generalized Delta rule implements a gradient descent in the weight space, minimizing the global error E

$$E = \sum_p E_p = 1/2 \sum_i (T_p(i) - O_p(i))^2$$

and

$$\frac{\partial E_p}{\partial w(i,j)} = \frac{\partial E_p}{\partial O_p(i)} \frac{\partial O_p(i)}{\partial w(i,j)} = -\delta_p(i)A_p(j)$$

In conclusion

$$\Delta w(i,j) \propto -\frac{\partial E_p}{\partial w(i,j)}$$

If the neuron response is

$$s_p(i) = \sum_j w(i,j)A_p(j) + \theta(i)$$

the threshold θ can be learned as any other weight. For non-linear units, the error for the neuron i is modified as

$$\delta_p(i) = -\frac{\partial E_p}{\partial s_p(i)}$$

For an output neuron, this result in

$$\delta_p(i) = [T_p(i) - O_p(i)]A_p(j)f'(s_p(i))$$

The definition is consistent with the case of linear units. It still corresponds to implement a gradient descent in the weights space. However, while the function E has only global minima for linear units, this is no longer the case here.

When hidden neurons are present, the error $\delta(i)$ is propagated backward in the network (backpropagation). For each hidden neuron i, $\delta(i)$ can be computed when the $\delta(k)$ of all the neurons which receive input from neuron i are known.

In conclusion, the first phase of the learning procedure is the modification of the weights (for instance, using the backpropagation procedure). The set of patterns used to minimize the error function is called the learning sample. The second phase of the learning process is the test of the neural network on a different sample, called the test sample. Too many hidden neurons (compared with the size of the learning sample) lead to an overtraining of the neural network. The network begins to memorize events, and does no longer generalize. Overtrained neural networks improve on the learning sample and deteriorate on the test one.

5.3 Research experiences

In the last years a big effort devoted to develop techniques and methodologies able to solve problems relative to Cultural Heritage field has been made by many researchers. A unified approach has been proposed in [80] where, considering digital images, many attempts have been faced, in particular, to make objective the "naked eye" analysis.

One of the more interesting aspects is, there, the recognition of different kinds of materials degradation. To do this, in [91] a model able to recognize different classes of material degradation using a neural network has been proposed. We focused our attention on a particular class of material degradation where shape contours are the discriminant features. Indeed, the hypothesis that the most information is contained in the edges is true for several kinds of material degradations relative to buildings of historical importance, such as lack of material, i.e. cavities, or breackdown in continuity, i.e. fissures. In these cases, basing the analysis on the information contained in digital images, the texture inside the analysed regions can be coarsely considered uniform. The model developed in [92] can be described by three steps: feature extraction, feature representation and feature classification. The last two steps are strictly linked: the kind of classificator that we choose promotes some representations more than others; and, on the other side, a given choice of the representation can conditionate the performance of the classificator to separate different classes. This approach is simple but powerful: it is able to examine complex images considering the different significant features in different steps with a considerable reducing of complexity, and also permits the evaluation of which basis set is more appropriate for any particular task.

We selected a three layer backpropagation network as classificator and three different ways for the boundary representation:

- original image;
- Fourier Descriptors (FDs);
- two dimension Discrete Fourier Transform (2DFT).

The reason why we use the original image too as representation is that in pattern recognition problems is often difficult to trace emerging problems to inadequate representation; the responsibility can be divided between the feature extraction and the learning stage if the results obtained with the original images are compared with the ones obtained with their representation.

The obtained results can be considered interesting, because the network was able to classify two different degradation kinds.

Nevertheless, a noticeable improvement of an automatic recognizer could be attained by means of a preliminary classification of the material where the degradation kinds are. In other words, a preliminary recognition of the material we are considering could allow us to focus on a small set of possible degradation kinds.

In this sense in [93] a texture classification using a *Weak Continuity* based (WC) representation is proposed. Particularly, the model is based on the characterisation of textures using statistics of their coarseness [86]. The coarseness is, in fact, one of the features that the human eye takes into account when a discrimination is required. Furthermore, different types of degradation are, generally, mapped to different material coarseness. Obviously, the coarseness depends strongly on the scale level we are considering the scene. So, an useful tool should detect the discontinuities of an image, at many scale levels -even if only one, opportunely selected, is sufficient.

It is well known that the WC approach is a very efficacious tool for edge detection. In particular, besides allowing a multi-scale detection, its non linearity leads to a selective smoothing and thus to a high robustness to the noise. Thus, considering squared windows of a given size, the edges detected can represent the input of a neural network oriented to classify different textures. The results obtained on stones relative to the Aosta Roman Theatre show the efficacy of this representation and, at the same time, encourage the development of this approach.

5.4 Conclusion

In this contribution we presented our proposal for an application of techniques and methodologies of image characterization and recognition in order to support the Cultural Heritage experts in the study of degradation events. We have proposed the neural network approach for the recognition problem because the neural network methodology may allow a more direct and general approach to it. The recognition of complex differences in different pattern representing the detectable classes, with the help of a neural network, is an approach that may be closer to the learning problems in human observer.

Two different research experiences based on this approach are proposed as examples of succesful results for the recognition and the classification of different classes of material degradation such as loss of material and breack down in continuity and in the classification of different kind of material grains. Further studies are carried on in order to extend this proposed approach to other classes of material degradation.

6 Virtual reality and photorealistic representation of ancient monuments

6.1 Introduction

The documentation and examination of the large amounts of data describing the state and history of ancient monuments open complex problems to cultural heritage experts, whose background in computer technology is usually small, and who are interested in using computer methods to explore "what if" alternatives in order to select techniques for restoring and preserving monuments. Moreover, the richness of historical, artistic and technical information cannot be easily explained to non experts, to give them a better appreciation and understanding of the cultural heritage. Multimedia techniques are now available not only on off-line basis (e.g. CD

ROM), but also on-line, for accessing remote repositories of data using Web technology. The best methods to convey a complex knowledge in the field of cultural heritage to experts and non experts are the visual representation and the visual interaction. The visual interaction has been extensively used in off-line CD ROM's, while only recently Internet technology has made advanced levels of visual representation available to the lay public. In order to explore the feasibility and effectiveness of these new technologies, a prototypal and experimental data base has been used which collects a variety of data describing the ancient Roman Theatre of the town of Aosta. In particular, it includes geometric data, images, descriptive information collected by the cultural heritage experts and data generated by previous computations. These descriptive and pictorial data have been used to extract other data to further improve the degree of detail and accuracy of the ancient building description and representation. In particular, shape and visual appearance properties have been extracted by reconstructing 3-D models of stones and measuring in laboratory color parameters in different conditions (that is, after cutting and polishing the samples, bringing them to their original conditions and after a cleaning process on site). A 3-D reconstruction of the whole Theatre, exemplified in Figure 24, has been carried out to create a VRML model which becomes the basis for accessing the collected information and navigating by using Web browsers.

An Italian multi disciplinary team is carrying out this project, which aims at developing methodologies and software tools for two main applications:

- a support for experts and specialists in conservation and restoration of ancient monuments;
- a platform to implement educational multimedia for the general public.

The underlying data-base is a fundamental professional help for specialists, who can collect data, analyse results and, also, keep track of on-going or past conservation activities. Advanced graphics rendering and image analysis tools are necessary for using the system as a kind of "what if" environment, to explore the effects of the simulation of conservation or restoration hypotheses, and to provide a feeling of the original aspect of the building. The better way to display a realistic representation of a complex object is to use photorealistic techniques, rather than impressionistic methods, which are based on textured pictures. The link between photorealistic rendering and optical and physical properties of materials can be used by the expert to control conservation and restoration processes better.

The visual interaction, made possible by Web navigation tools, proves itself to be extremely powerful, simplifying both the access to information and data and their maintenance and update. The same navigation tools are the major factors that can help to attract the general public to understand better the value and importance of an ancient building.

6.2 The work

In order to test the methodologies developed in the project, a case study has been selected in cooperation with the ICR (Istituto Centrale di Restauro-Ministero per i Beni Culturali e Ambientali, Roma): the Roman Theatre of the town of Aosta (see Figure 25). A significant amount of data were still available for the Theatre when the project started and other data were successively collected with the financial support of the project. A prototypal and experimental data base has been structured by experts working at the ITABC (Istituto per le Tecnologie Applicate ai Beni Culturali - CNR, Roma).

A large variety of data types is included in the data base. The main data types considered were derived from the following activities:

- conventional geometric survey and reconstruction made by a professional study;
- black and white images and geometric data of pudding-stone and travertine ashlars (material composing the Theatre) coming from to the photogrammetric survey made by a professional study;
- color images of pudding-stone and travertine ashlars acquired and chromatically corrected by DIE (Dipartimento Ingegneria Elettronica-Firenze);
- descriptive information coming from a visual inspection made by cultural heritage experts (Soprintendenza per i beni Culturali e Amabientali - Aosta) structured in a data base by ITABC;
- spectrometric and colorimetric analysis of pudding-stone and travertine ashlars samples, to get chemical composition and reflectivity curves, by DCOMA (Dipartimento di Chimica Organica, Metallorganica e Analitica- Universita' Milano); these analyses have been conducted on samples in their natural state and after cutting and polishing, and on cleaned samples to get reflectivity curves in different conditions.

The critical problem in realistic rendering of complex models, like an existing ancient building, is to control its visual appearance. A possible choice is to adopt texture mapping methods thus arriving at an "impressionistic" rendering. This is an efficient solution given the availability of display system with specific architectures to support real time navigation through textured data, but is limited to give only a rough idea of "their real aspect". In order to increase the degree of accuracy it is necessary to use photorealistic methods; ray tracing has been adopted. The limitation of this method is the impossibility of real time rendering, but the results are of great interest when a link between structural and chemical characteristic of the samples has to be maintained with their visual appearance.

Therefore, interactive navigation is implemented using impressionistic rendering with textured images, while accurate rendering is used for single viewpoint displays. The expert user can interactively choose to generate the rendering of a particular element or the entire building from a desired viewpoint.

The geometric data description and photogrammetric properties of the ancient building have been used as the input to a photorealistic image synthesis program, based on the ray tracing method global illumination model as shown in Figure 26 .

To better understand the approach, it is worthwhile to recall how the light material interaction is simulated with the ray tracing based program that we have used. Most of the rendering programs used in synthetic image generation systems, adopt an approximate illumination model to compute colors following an implementation of the tristimulus theory. On the contrary, in our advanced rendering system, the reflected radiance is computed for spectral samples between 380 and 780 nm with 5 nm step intervals, and integrated to compute values in short, medium and long wavelengths only in the final image display step.

The program that we have used to generate the photorealistic images is based on a physical model for the light-material interaction simulation based on the Cook-Torrance local illumination model which allows us to approximate bi-directional reflectance (BRDF) from known refraction indexes (in dielectric materials), with:

$$\rho(\lambda) = k_d \rho_d(\lambda) + k_s \rho_s(\lambda)$$

where:

- $\rho(\lambda)$ is the spectral bi-directional reflectance of the material split into the two components;
- $\rho_d(\lambda)$ diffusive;
- $\rho_s(\lambda)$ specular;
- weighted by the two arbitrary factor k_d and k_s, where $k_d + k_s \leq 1$.

The two components of the BRDF are computed on the basis of the material spectral real refraction index n() that is a function of the wavelength. Under the hypothesis that the material is Lambertian, i.e purely diffusive, the computation is simplified. Thus, the luminance reflected from a diffusive object is computed with:

$$L(\lambda) = \rho(\lambda) E(\lambda)$$

where $E(\lambda)$ is the spectral irradiance incident on the sampled surface point and computed by the global illumination model from the light sources and from other bodies. So, given $L(\lambda)$, the radiance of the sampled ray reflected by the object surface and reaching the observer's retina, we compute the CIE tristimulus values X,Y and Z with the classic integration:

$$X = K_{max} \int_{380}^{780} L(\lambda)\overline{x}(\lambda)d\lambda$$

$$Y = K_{max} \int_{380}^{780} L(\lambda)\overline{y}(\lambda)d\lambda$$

$$Z = K_{max} \int_{380}^{780} L(\lambda)\overline{z}(\lambda)d\lambda$$

- where $K_{max} = 683lm/W$ is the max value of the human photopic luminos efficacy function
- $\overline{x}(\lambda), \overline{y}(\lambda), \overline{z}(\lambda)$ are the CIE standard color matching functions;

As a final step, to display the CIE tristimulus value on the display device (in general a monitor) we use the linear transformation:

$$\begin{matrix} X \\ Y \\ Z \end{matrix} = M \begin{matrix} R \\ G \\ B \end{matrix}$$

with

$$M = \begin{matrix} 0.193885 & 0.058885 & 0.060230 \\ 0.095496 & 0.199087 & 0.034417 \\ 0.000000 & 0.022432 & 0.335568 \end{matrix}$$

This equation gives the R, G and B value in the color space of the given device (a CIE standard NTSC monitor), whose color features are described by the tristimulus value of the red, green and blue phosphors respectively. The above described process suffers of some weakness arising from the limitations of the tristimulus theory and from the reduced dynamic range of typical display devices. As a consequence of the integration step defined in the CIE theory to get the tristimulus values, the results are proportional to the energy flux associated with the radiance L() reaching the observer retina, and these values may vary more than 103 times under changing illumination conditions from artificial illumination to sunlight. For the same reason, the reflected radiance is strongly influenced by the light source spectral emission, thus leading to a strong color influence of illuminants on object colors. Also the R.G.B color space of the display device has an obvious limited dynamic range and the linear transformation may easily generate R,G, B values that are outside the maximum displayable range. Finally the tristimulus value of the red, green and blue phosphors of a particular display could be unknown and may be computed from the chromaticity coordinates of the same phosphors (xR, yR, xG, yG, xB, yB) and from the chromaticity (xW, yW) and maximum luminance (YW) of the white of the display device. These parameters may depend on the display lifetime and on its calibration status.

Having clarified all these limitations, we have therefore generated the images, giving the refraction indexes of each materials and the spectral composition of the following CIE D65 standard illuminant.

Web integration presents three main aspects: navigation within the descriptive information, visual navigation within the ancient building (keeping its appearance as it is at present, or changing its appearance according to different hypotheses), interactive access to programming tools for supporting the "what if" analysis. The user access to the descriptive data is made through HTML pages that include the required information. By means of VRML a general model of the Roman Theatre has been created by converting a DXF file and by dividing it into the most relevant parts. Texturing and material data description have been associated to these parts. The VRML model has also been used as the query interface to retrieve the descriptive data as well as an access point to exemplify "what if" results; for this purpose, simple anchor nodes have been associated to the parts. A Java application has been implemented to assist the expert in exploring "what if" hypotheses of restoration and conservation. As described above, the results of "virtual" restoration (based mainly on cleaning and/or polishing the stones) can be displayed on single samples or applied to the whole building or only to some of its parts, by texture mapping or coloring the model components (see Figure 27). The JAVA interface supports specific functions to: select a viewpoint, select stones or group of stones, apply colorimetric attributes (normal distribution and reflectivity) to the selected entities, define light sources, compute RGB values, compute ray tracing and generate a view of the selected entities.

6.3 Further work

Further developments of the research described in this paper will concentrate on a new implementation based on multimedia-oriented DBMS and on improvements of the algorithms for extracting necessary information and data from images to increase the quality of the photorealistic rendering. Moreover, in order to define characteristics and patterns "to search" into the images, a strong cooperation must be maintained with the cultural heritage expert which uses his/her proper own language (even if almost standardized but "sometimes foreign to informatics people") to describe the state of the monument. Such type of information has to become as more quantitative as possible in order to ensure its computational use.

The display of computer generated images is also a critical step; synthetic images not only are subject to undesired effects in chromatic distribution, but also suffer from the limited dynamic range of typical computer displays. Originally addressed in the context of synthetic image generation, solutions to the problem, known as the "tone reproduction problem", have been devised for gray scale images. We are planning the implementation of an algorithm that simulates a Retinex filter. To test its validity we propose to work on computer generated images, computing a chromatic distance between a color and its Retinex filtered representation. This approach is very well suited to guarantee color constant image synthesis and reproduction under varying lighting conditions and can contribute to an effective solution to the problem of color reproduction and rendering on computer display.

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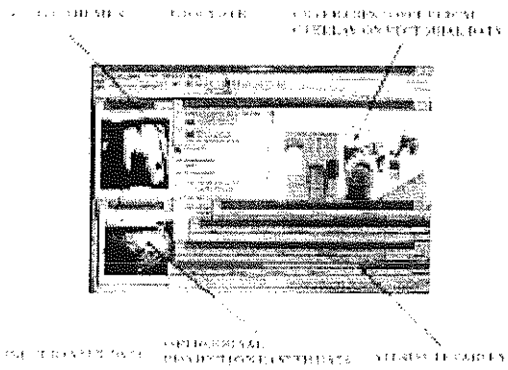

Figure 1: Typical ArcView window.

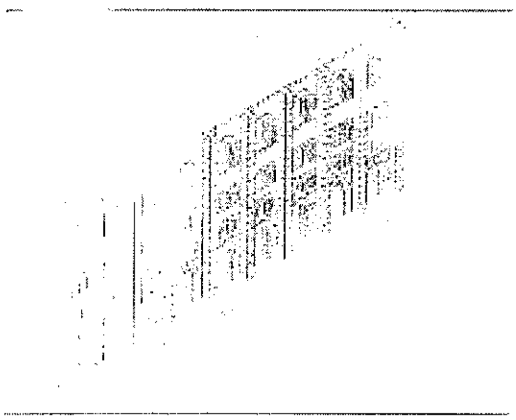

Figure 2: Topographical survey and CAD rendering of the entire facade (Studio Professionale Di Grazia of Rome).

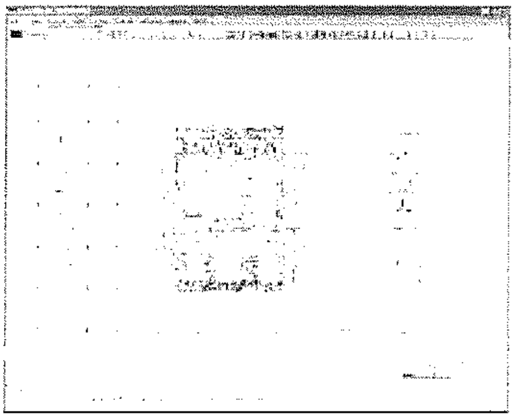

Figure 3: 6mx6m sector of the Theatre: photogrammetric survey (FO.A.R.T. of Parma).

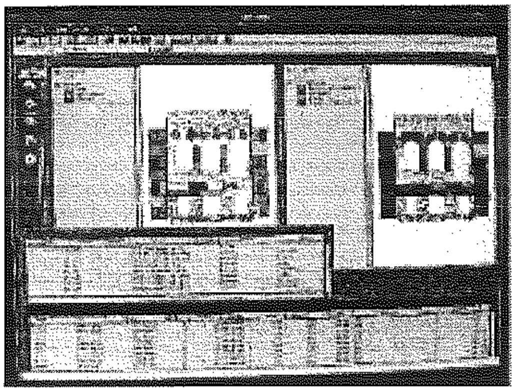

Figure 4: ArcView Environment: material and grain data processing by GIS referring to 6m x 6m sector of the Theatre (photogrammetric survey).

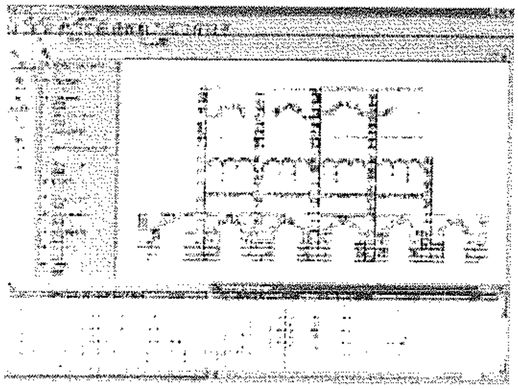

Figure 5: ArcView Environment: material and some degradation typology referring to the entire southern facade of the theatre (topographical survey: 2D geometrical reconstruction).

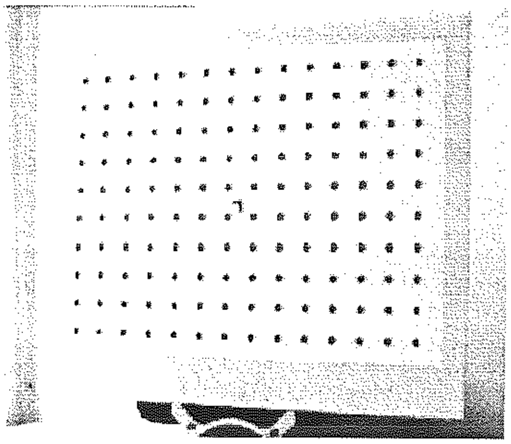

Figure 6: An example of planar target set used for calibration (a printed sheet of paper glued on a planar glass surface).

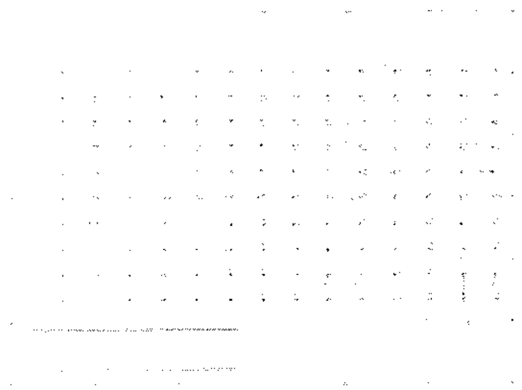

Figure 7: A-priori coordinates of the fiducial points of the target-set (laser-printed circles on a sheet of A4 paper, glued to a flat surface) and corresponding a-posteriori corrections estimated through self-calibration. The orientation of the (magnified) correction vectors denotes the deformation of the sheet of paper due to the action of the dragging mechanism of the laser printer.

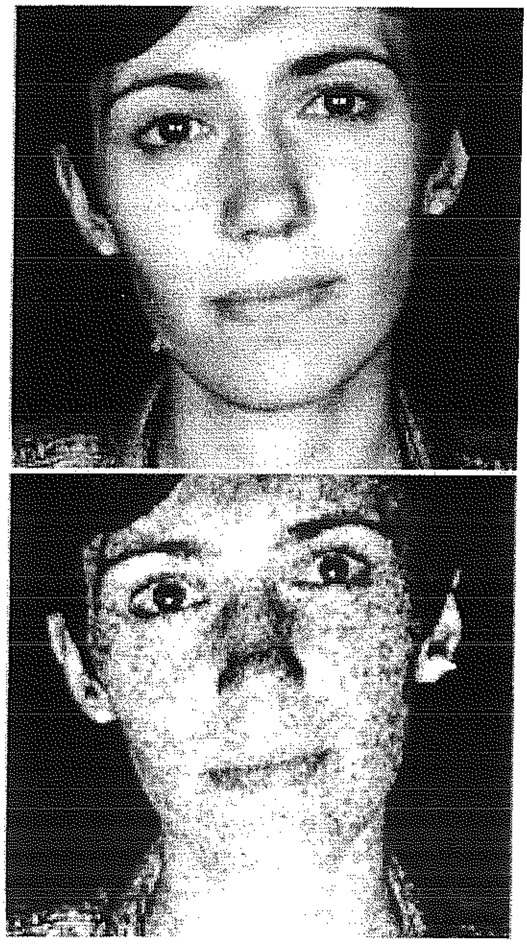

Figure 8: Example of 3D reconstruction of a face from three calibrated views. One of the original views used for texture mapping purposes (up); one of the views used for 3D reconstruction (down), obtained through projection of artificial texture (pseudo-random noise).

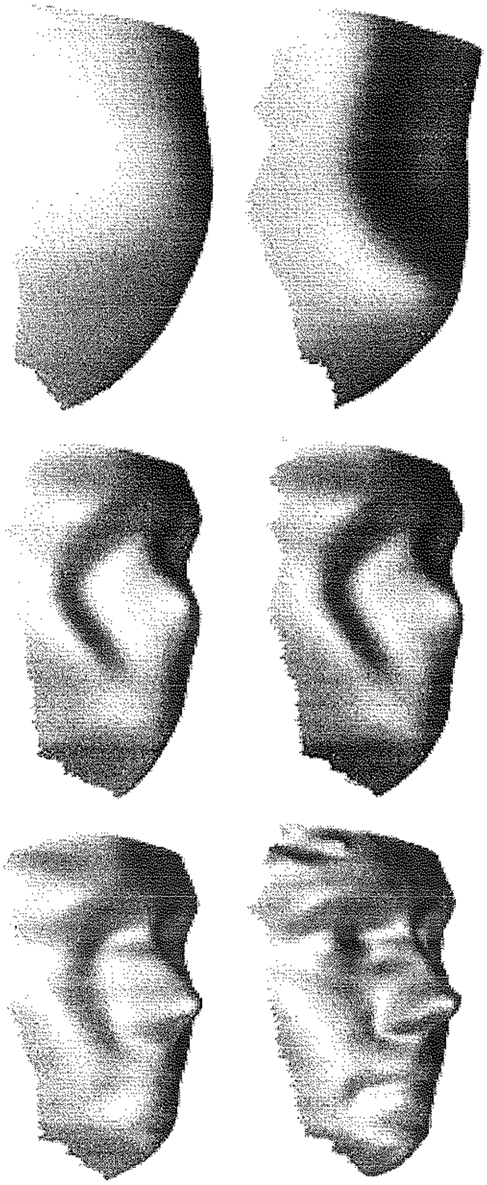

Figure 9: Progressive surface reconstruction of a face using multi-resolution area matching.

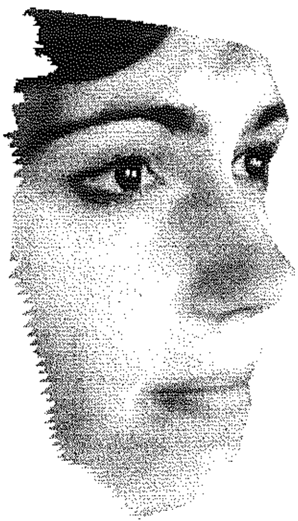

Figure 10: Final reconstruction of the face after texture mapping from the three available views without structured light.

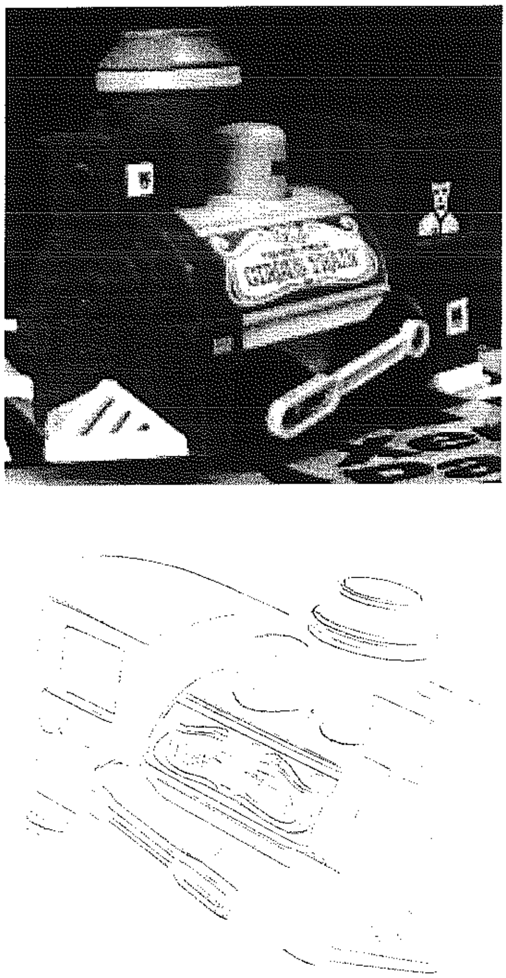

Figure 11: Example of camera motion estimation through optimal data fusion. One image of one of the available triplets of views (top). Optimal fusion of the 3D data extracted from several multi-views.

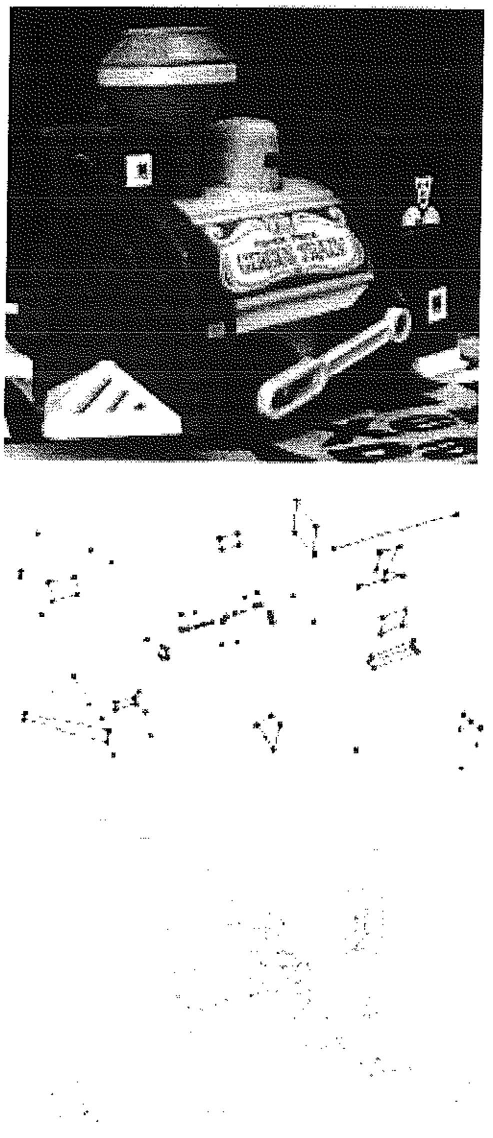

Figure 12: Example of local reconstruction from three uncalibrated views of a portion of a building. One of the three original views of the subject (up). Two views of the final densified cloud of 3D points after data refinement (middle and below).

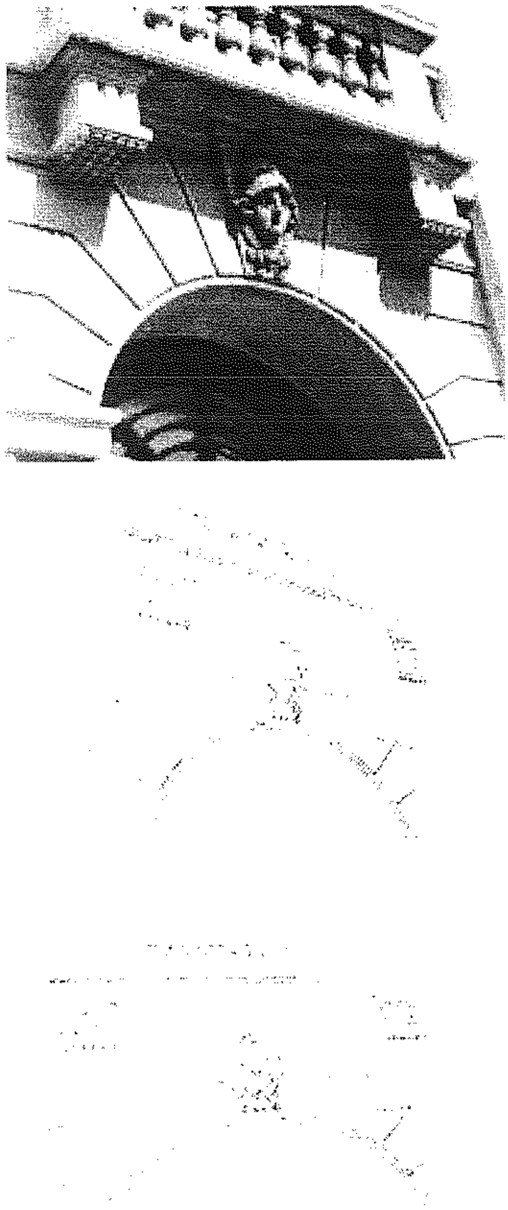

Figure 13: Example of local reconstruction from three uncalibrated views. One of the three original views of the subject (up). Reconstruction of a limited corner points in the 3D space, for tacking the viewpoint geometry (middle). Final densified cloud of 3D points after data refinement (below).

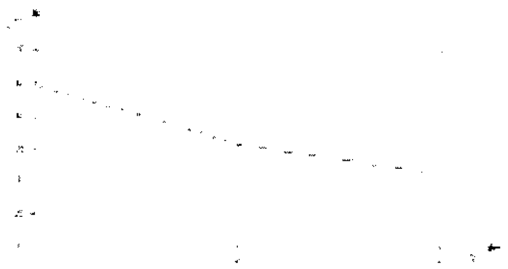

Figure 1: Behaviour of the Standard Deviation function (SD) depending on the Grain (G).

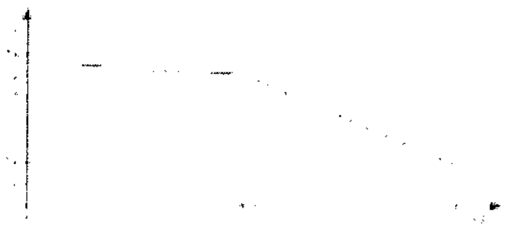

Figure 2: Behaviour of the Entropy function (E) depending on the Grain (G).

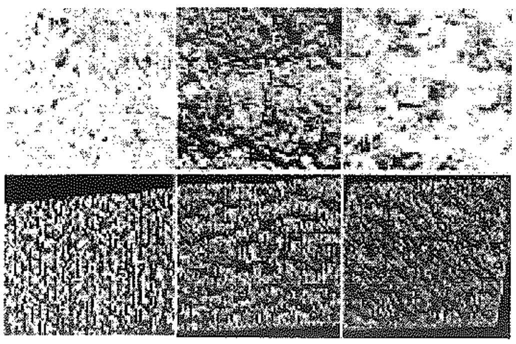

Figure 3: Normal fields visualisation for different grain pudding-stone imges: fine grain (left column), medium grain (middle column) and coarse grain (right column).

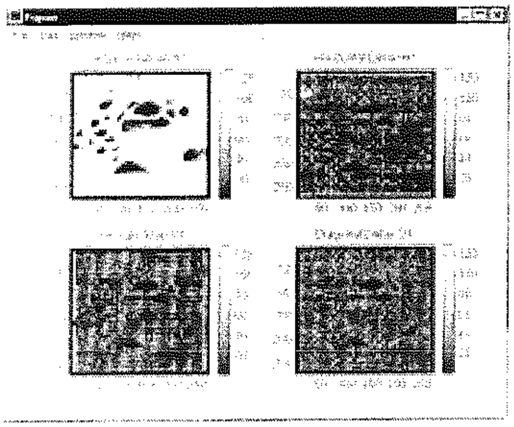

Figure 4: Extraction degradation zones relative to cavities and fissures.

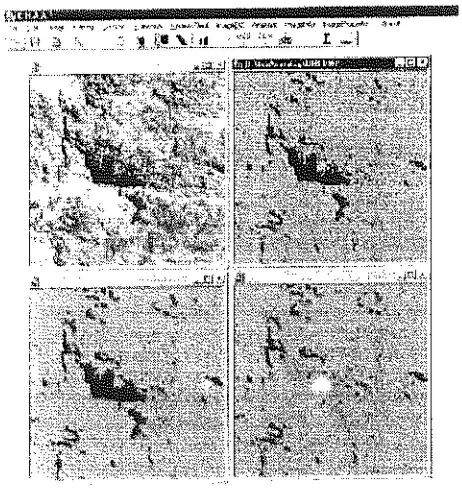

Figure 5: Lack of material analysis: original image (upper left); segmented image (upper right); region labelling (bottom left); significan region selection (bottom right).

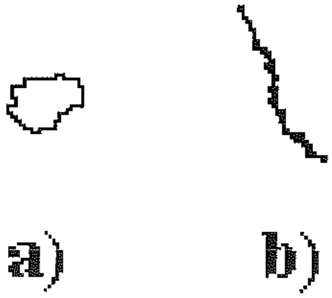

Figure 6: Two kinds of degradation belonging to the class of lack of material: a cavity (left) and a fissure (right).

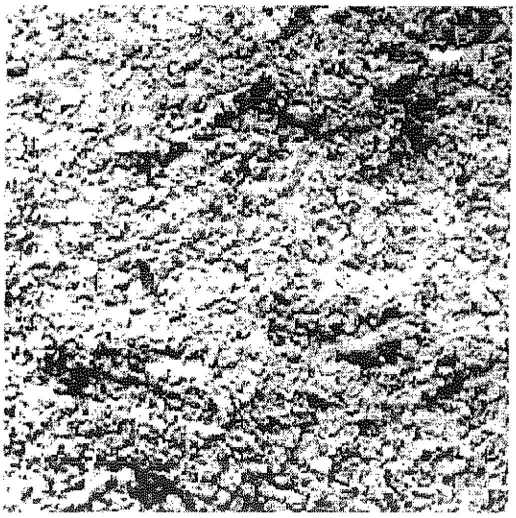

Figure 7: An image of pudding-stone (gross grain)

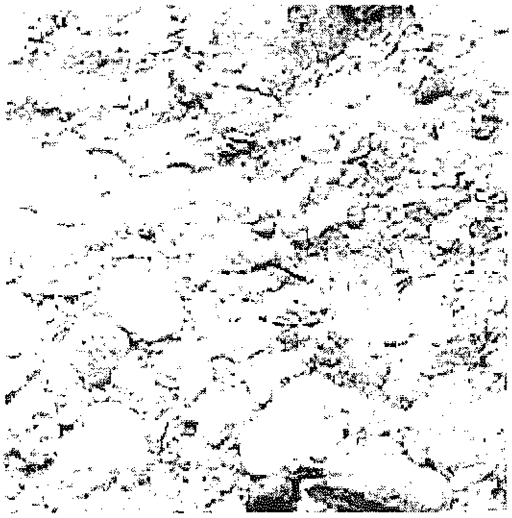

Figure 8: Figure 21 - An image of pudding-stone (thin grain)

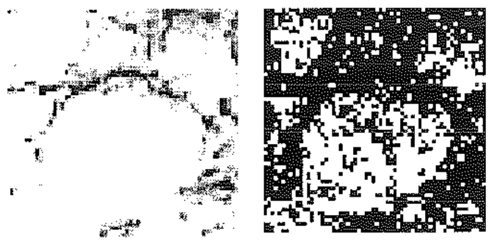

Figure 9: Extracted window and its Weak Continuity representation from a gross grain pudding-stone

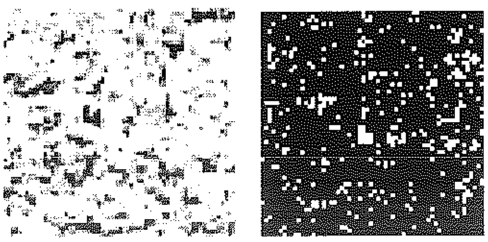

Figure 10: Extracted window and its Weak Continuity representation from thin grain pudding stone.

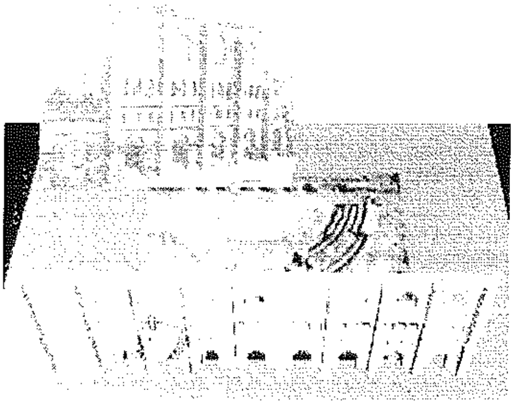

Figure 11: Base for navigation.

Figure 12: A case study reconstruction.

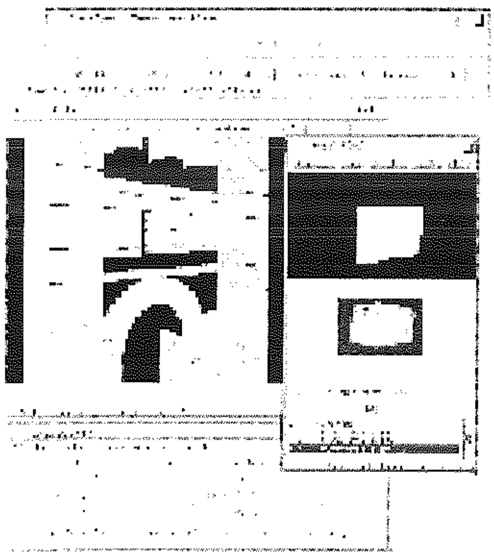

Figure 13: An impressionistic rendering.

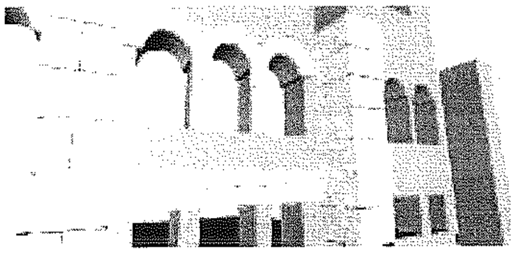

Figure 14: A result of virtual restoration.