INTEGRATED 3D-DATABASE FOR DIAGNOSTICS AND DOCUMENTATION OF MILAN'S CATHEDRAL FAÇADE

G. Giunta[a], E. Di Paola[a], B. Mörlin Visconti Castiglione[b], L. Menci[c]
[a]EniTecnologie S.p.A., Via Maritano 26, 20097 San Donato Milanese (MI), ITALY – ggiunta@enitecnologie.eni.it
[b]Veneranda Fabbrica del Duomo, Via Arcivescovado 1, 20122 Milano, ITALY – fabbrica@tin.it
[c]Menci Software s.r.l., Via Martiri di Civitella 11, 52100 Arezzo, ITALY – luca.menci@menci.com

KEY WORDS: Database, Photogrammetry, conservative restoration, stereoscopic model, diagnostic

ABSTRACT

The Gothic Cathedral of Milan is one of the most important italian monuments: its façade is 65 m high with 12 spires and has a surface of about 4500 m^2, rich of Candoglia marble carved decorations and sculptures. The conservative restoration and maintenance of so complex an architectural structure needs advanced computerized tools for storing, analysing and updating all the produced data. A multidisciplinary approach was adopted to build an integrated tridimensional database (63 GByte). The basis is a stereoscopic model (by StereoView - SVPlotter AC software) which makes it possible to navigate through many photograms all over the façade, to measure accurately the dimensions of architectural details and to draw structures with a millimeter precision. In this way a tridimensional 1:20 CAD model of the façade was created, in which every block is a single geometric unit. Moreover, a specific software tool was developed to insert photos, documents and texts in a geo-referenced way and to constantly update them. A thematic layer organization was used to store and integrate the architectural information and the diagnostic investigation results. The former includes, for example, the material distribution (i.e. marble, stuccos, metal cramps), missing parts, removed and replaced blocks, restored areas etc. The latter consist of the non destructive *in situ* analysis data, concerning both the surface (XRF, colorimetry, thermography) and the bulk (georadar or GPR), not only for pre-restoration diagnostics but also for assessing the quality of effected operations. In particular, a specific software, called ETRadar (AutoCAD application), was created for structural analyses: it makes it possible to insert 3D radargraphic maps, to draw inner fractures and cavities revealed by georadar inside the masonry and to assign a volume to every stone block, as determined by GPR. In this way critical areas were localized and helped the definition of the working plan. The restoration work is still in progress.

1. INTRODUCTION

The Milan's Cathedral is a very important italian monument: it is constructed of Candoglia marble in gothic style and enriched with a great many marble carved decorations and sculptures.
The Veneranda Fabbrica del Duomo is the institution entrusted with the conservation of the Milan's Cathedral and is responsible for the structural and aesthetic preservation of the monument.
In the last century important conservative restoration works have been done and still today the Veneranda Fabbrica plans continuously the necessary interventions on the principle of preventive maintenance (Ferrari da Passano, 2000). For this reason, a complex control and monitoring system of the monument is operative: systematic checks on the verticality of counterforts, on levelling measurements, on groundwater level and on vibrations from the traffic and the underground are run.
The Veneranda Fabbrica entrusted the diagnostic control of the interior walls and of the Façade to EniTecnologie.
EniTecnologie carried out both an overall 3D survey of marble structures and their mapping with non destructive techniques (Giunta, 2003).
The façade is 65 m high with 12 spires and has a surface of about 4500 m^2. These values explain why an innovative software tool for storing, analysing and updating all the produced data was needed.
The *stereofotocarta* (Albery, 2000a) was chosen as three-dimensional metric support through a stereoscopic vision. It makes it possible to navigate through oriented and connected photograms, to measure dimensions (positions, distances, areas and volumes) and to draw structures and material thematic maps. Custom-made AutoCAD applications were programmed to construct the Milan's Cathedral 3D database directly on this platform.

2. SURVEY TECHNIQUES AND EXPERIMENTAL CONDITIONS

2.1 Laser Scanning

A preliminary laser scanning survey was done to provide a fast metric support to plan and quantify the restoration activities. The resulting DSM (Digital Surface Model), in fact, provides a cartographic support to generate an orthophotomap (Fig. 1). An orthophotograph merges the information of photos into the metric data (distances, areas, volumes) (Balletti, 2002). A Riegl LMS-Z210 (Nikon Instruments) laser scanner was used. Two acquiring stations were placed in front of the Cathedral, at a distance of 90 m from the Façade. The point cloud has a nominal accuracy of ± 30 mm.

Figure 1. Orthophotograph of the Milan's Cathedral Façade by laser scanning survey.

2.2 Digital Photogrammetry

The photogrammetric survey was a highly complex process because of the imposing dimensions and of the complex geometries of the architecture (Kasser, 2002). Different frames of reference and coordinates' systems were taken to avoid the presence of numerous details, overhangs and relieves with different thickness and orientation. Especially on the lateral sides of the counterforts (about 2m in width), a multi-stereoscopic overlap (both horizontal and vertical) was necessary to cover partially hidden or secondary plane elements. A preliminary 1:100 survey was done.
For the 1:20 survey, a Wild P31 camera (45mm, 100mm and 200mm focal lens) was used; 205 photograms on the frontal view and 211 on the lateral sides of the counterforts were acquired from distances of 19 - 22 m. The photographic reference points were measured by a TDA5000 topographic system.
The photographs were digitalized (1600 dpi resolution) by means of a calibrated scanner; then they were oriented with the Bundle Block Adjustment method by means of specific software of the StereoView® (menci software) system.
Once the photographs were internally and externally oriented, the stereoscopic model was created and the three-dimensional vectorial model was produced (Menci, 2000a).

2.3 Cyclop Photogrammetry

CYCLOP is a fast digital photogrammetric system based on a "single camera" arrangement. It consists of a calibrated camera, fixed on a metallic bar, on which can be rigidly moved: a pair of parallel photos at known distance are acquired and directly joined in a stereoscopic model, without scanning and orientation. In this model geometrical measurements and 3D stereo plotting of the objects were carried out. Some sculptures located in the lower part of Façade (12 carved panels) were studied and their detailed CAD models were edited on a scale of 1:10 (Fig. 2). A Nikon Coolpix 5000 digital camera (14.55 mm focal) was used; the photos were acquired at distance of 2.5 m with a digital resolution of 2560 x 1920 pixels (Menci, 2000b). After the scaffolding was raised on the Façade, also some sculptures on the higher part were surveyed. In the last case, an improved Cyclop system equipped with a high resolution (3024 x 2016 pixels) calibrated Fuji FinePix 2 digital camera and Nikkor lens was used.

Figure 2. Cyclop stereoscopic model (1:10 scale) overlapped to the 3D vectorial model.

3. STEREOPLOTTING

The stereoplotting of photogrammetric data is a highly critical process: the representation of the object depends, in fact, not only on its geometry but also on the interpretation of the technical designer (Fig. 3). The great advantage is that the CAD vertexes are not uniformly distributed but are geometrically dependent: i.e. more vertexes are necessary to describe complex decorations while only few to define easy structures (Albery, 2000b). The stereoscopic navigation is continuous through the aero-triangulated high resolution photograms. The stereovision needs a polarized screen and passive glasses.
SVPlotterAC is the StereoView software that makes stereoplotting directly in the vectorial model of AutoCAD as a three-dimensional entity possible (Fig. 3), by means of an integrated visualization engine. The stereoscopic model and the CAD one, in fact, are connected and have the same frame of reference and synchronized cursors. The focus in the collimation mark point of the stereoscopic window, controlled by a trackball, determines the z co-ordinate in the vectorial model, controlled by the mouse. The product of this process can be expressed both in a graphic form and in a numerical form (x, y, z terns of co-ordinates).

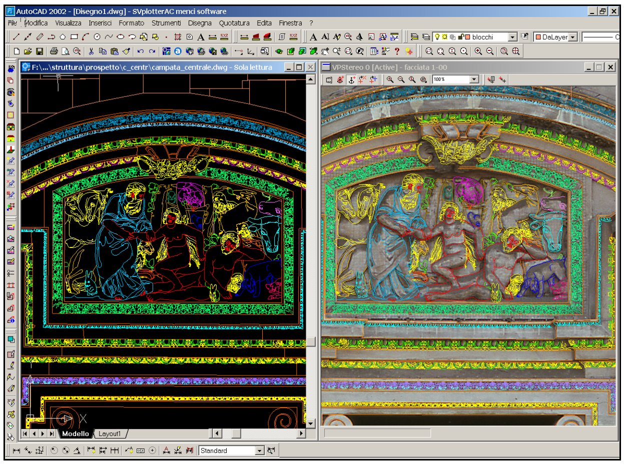

Figure 3. Stereo plotting of 1:20 vectorial model of the Façade by means of SVPlotterAC application

To supply the restoration activity from the beginning, a vectorial drawing on the scale of 1:100 was performed (Fig. 4). The CAD model on the scale of 1:100 was carried out with the same coordinates system of the 1:20 one. In this way all the objects edited and all the data stored before (see par. 5) were automatically transferred in the second CAD model when it was completed. The 3D CAD model on the scale of 1:20 has a very high level of architectural detail and drawing quality (Fig. 5). The accuracy of the stereoscopic plotting is 1.5 mm, i.e. the dimension of 1 pixel of the 1600 dpi photograms. The accuracy of the stereoscopic plotting is approximatevely equivalent to the precision of the CAD drawing.
The CAD model on the scale of 1:20 is made up of more than 9 million of vertexes; 8200 marble blocks were edited. Only a few areas on the lateral sides of the counterforts were not represented because they were not contemporaneously visible on two pairs of photograms.
The CAD model size is more than 500 Mbyte and the full 3D stereoscopic and vectorial model is more than 62 GByte (30 Mbyte for m^2 extent can be estimated). A lightening of the consulting functions and an optimization of the photogram loading was programmed in order to open models that exceed the memory capacity of the workstation (see par. 5).

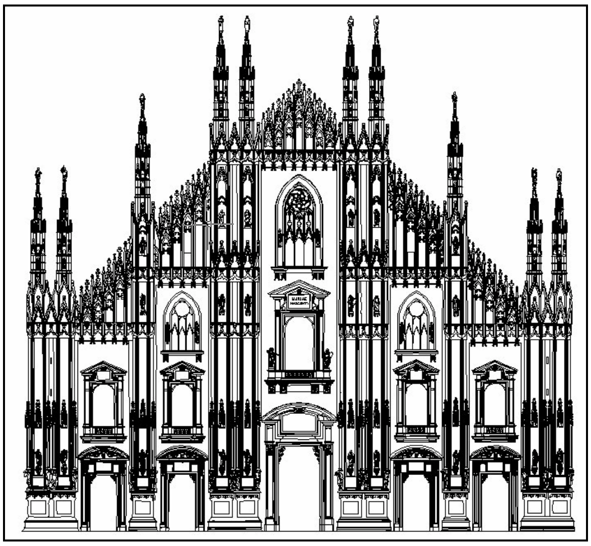

Figure 4. 3D CAD model (1:100 scale) of the Milan's Cathedral Façade.

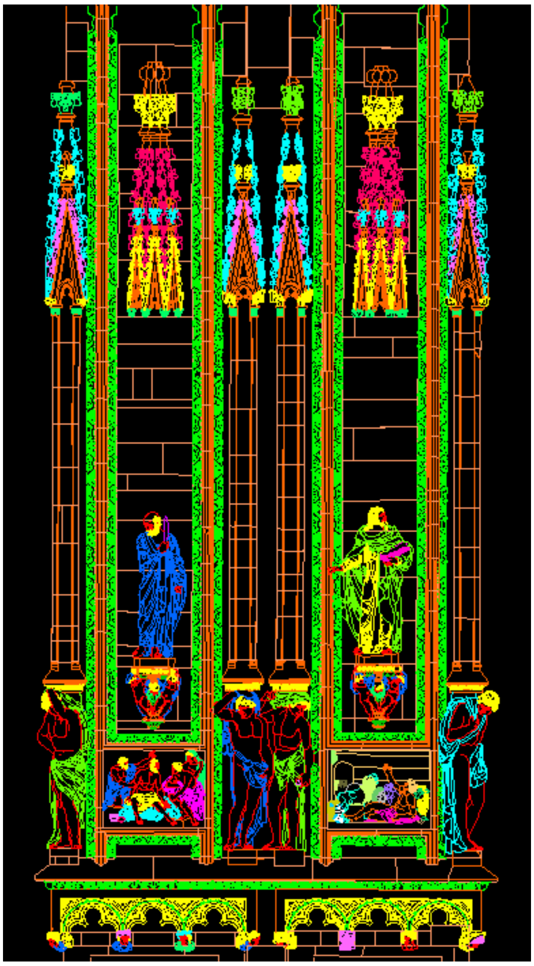

Figure 5. Detail of the 3D CAD model (1:20 scale) of a counterfort.

4. DIAGNOSTIC INVESTIGATIONS

In this paragraph the *in situ* diagnostic techniques applied on the Façade are briefly described, just to understand what the integration of the diagnostic results in the final 3D database means. A closer discussion can be found in other works (Giunta, 2000).

The georadar or GPR technique provides volumetric structural information. It uses radar waves generated by an antenna moving on the surface of the object under examination (on the walls of the Façade, in this case). The reflected radar waves contain information on the materials composing the investigated objects and on its physical state (i.e. detachment, cavities, fractures, damps etc.) (Bungey, 1993). The results of the GPR survey are radargraphic maps, in practice a section of the object, where one of the dimensions represents the line of scanning of the antenna (meters) and the other one defines the time of flight of the radar wave (nanoseconds), which is proportional to the investigated depth (meters) (Fig. 6). Typical depth values for the Façade structures (marble and masonry) are 1-2.5 m. GSSI SIR 20 instrumentation, equipped with 400 e 900 MHz antenna, was used. By this technique, the thickness of about 4500 marble blocks of the Façade was determined. Typical values were 10-40 cm (Fig. 7).

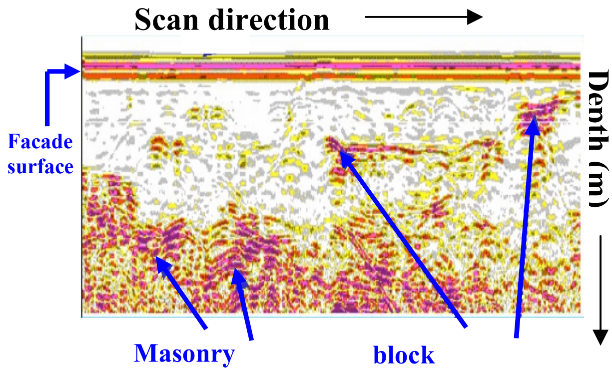

Figure 6. Example of a radargraphic map acquired on the Façade (900 MHz antenna)

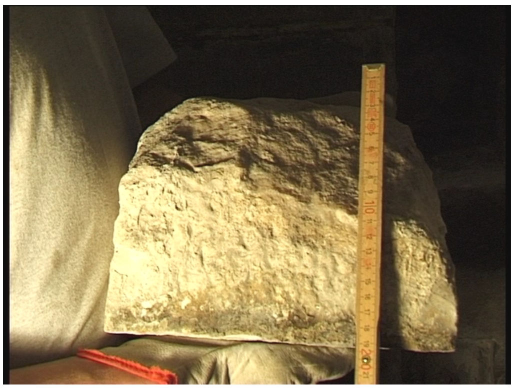

Figure 7. Example of the shape and thickness of Candoglia marble block.

Thermography provides information about critical situations related to the presence of metallic elements, to detachment of plaster or to residual moisture, for example. It measures the infrared radiation emitted by the material and supplies a thermal map of the surface, distinguishing between cold and warm regions (Giunta, 2000). A digital thermo camera ThermaCAM SC1000 of Inframetrics-FLIR was used. The adhesion control of the applied stuccoes to the marble substratum was the main task.

X-Ray Fluorescence (XRF) provides the chemical composition of the surface of the investigated material. A portable XRF spectrometer, equipped with both Pd and W anode and with an SDD detector, was used. It is useful to study the state of conservation of marble, the presence of pigments, the residue of previous surface treatment and the pollution effects.

5. 3D-DATABASE

The guiding principle of the 3D database was the integration of the multidisciplinary data produced: the pre-restoration diagnostic results, the historical and artistic bibliography, the restoration documentation and the monitoring data (Fig. 8). Another basic idea was the use of a common software platform, like AutoCAD, to make the database both readily and economically usable.

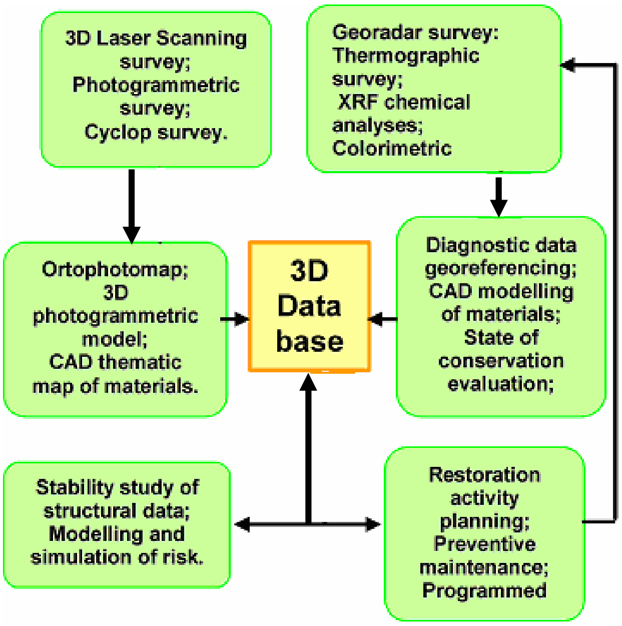

Figure 8. Diagram of the integrated 3D database of the conservative restoration and preventive maintenance plan of Milan's Cathedral.

Using the AutoCAD platform, difficulties arise when the vectorial model size becomes too big (about 1 GByte). A lightening of the loading of the vectorial model, overlapped to the stereoscopic one, was necessary.
A specific function (*3D Hatch)* was created to design three-dimensional closed polylines and to fill them on a medium plane with thematic colours or sketches (Fig. 9). It is very useful to create thematic maps (i.e. areas with the same kind of conservation or restored with a certain method), managed as *layers*.
For the documentation of the restoration activities and of the diagnostic investigations, also text documents are useful. The special functions *Insert Annotation* and *Pick Point* allow to associate the text box with every tridimensional point or object of the vectorial model. In this way the related information is georeferenced. The text documents can be consulted, modified or erased. They are pointed out by a specific symbol (Fig. 10), and can be managed by different *layers*.
To store and integrate the structural information by GPR technique (see par. 4) the custom-made software, called *ETRadar*, was programmed. It is an AutoCAD application too. It allows both radargraphic maps (bit-map images) (Fig. 11) and explained structural sections (vectorial *layers*) to be inserted in a semiautomatic way. So, every point of the bi-dimensional sections acquires a three-dimensional co-ordinate (x, y, z) in the photogrammetric model (Fig. 12). The shape of every building element (marble block, masonry and cramp) was drawn with its structural features (fractures, detachment and cavities) down to the investigated depth. Every marble block was defined as a 3D closed geometric object in the vectorial model.

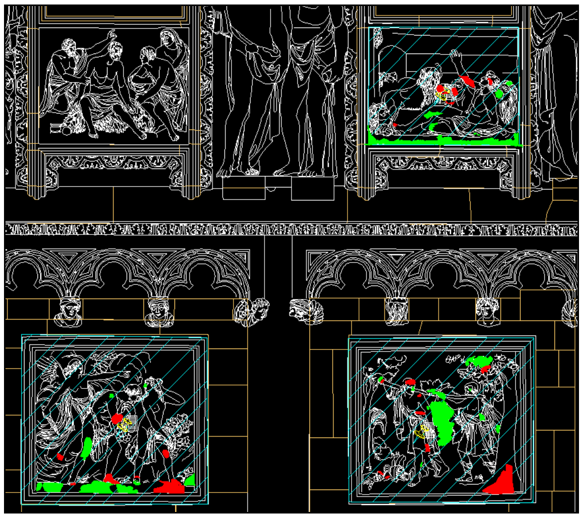

Figure 9. 3D thematic layers of thermographic survey: polylines filled with sketches by *3D Hatch* function.

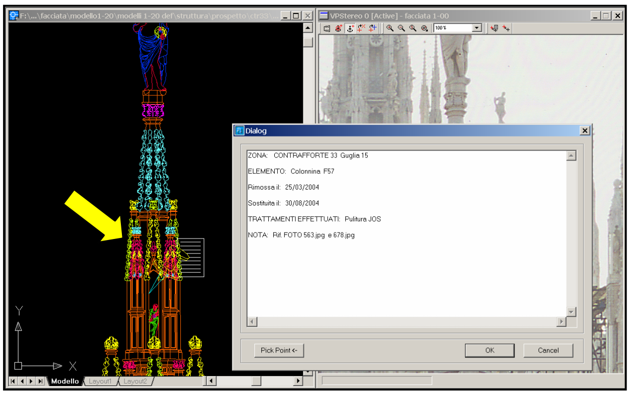

Figure 10. Example of geo-referenced document box insertion in the 3D vectorial model.

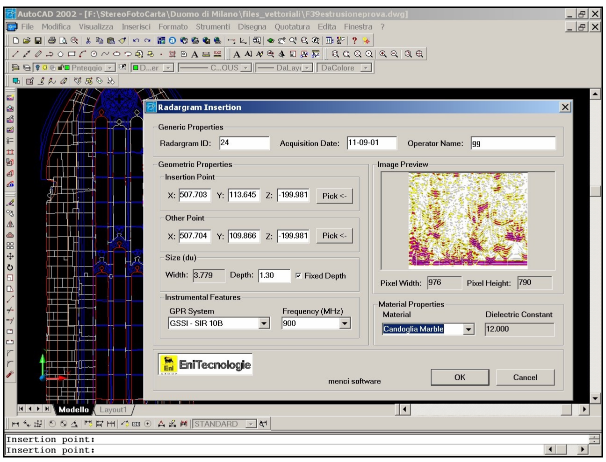

Figure 11. *ET-Radar* window to insert radargrams in the 3D vectorial model.

Then, the further function *Extrusion*, gives them a volume in the space up to the depth measured by GPR (Fig. 13).
It is possible to set critical values of thickness and to associate a thematic colouring: i) green means a sufficient thickness value; ii) yellow means an intermediate one; iii) red indicates a critical value (in this case below 10 cm). This volumetric representation of marble blocks could be used for structural stability calculations (finite-element model) of the Cathedral.
Diagnostic datasheets, containing information related to the date of the survey, the diagnostic technique, the experimental conditions, the file name, the results etc., can be stored. Moreover, the Veneranda Fabbrica inserts datasheets containing technical information about the restoration activities (i.e., cleaning of stone, marble block replacement, stuccoes application, etc.) (Fig. 14). Figure 15, for example, shows the thematic layer related to the replaced blocks on a detail of the 3D CAD model (scale of 1:20).

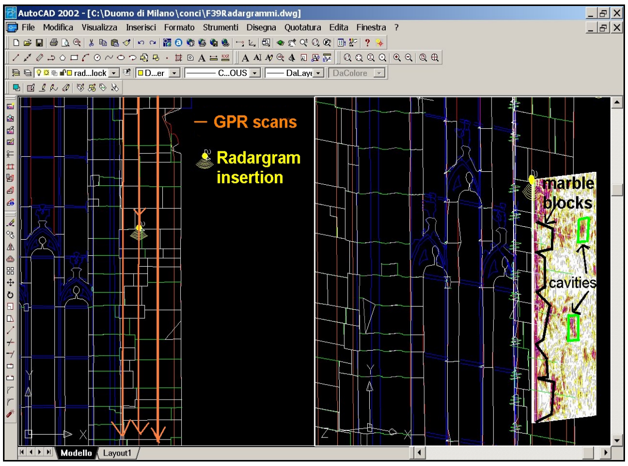

Figure 12. Example of a radargraphic map inserted in the vectorial model (front view on the left and rotated view on the right) by ETRadar application and related thematic map.

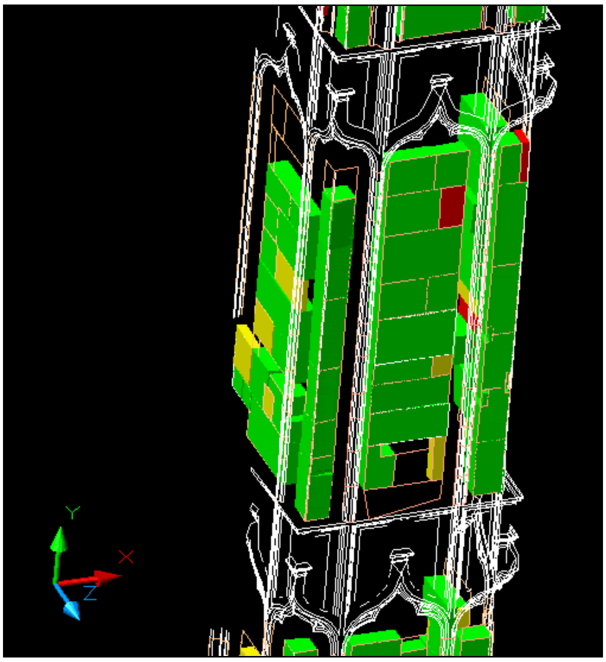

Figure 13. Example of volumetric extrusion of the marble blocks of a counterfort of the Façade by ETRadar application.

The database is continuously updated both by EniTecnologie and Veneranda Fabbrica, while the conservative restoration progresses. At the moment, the size of 3D database is 63 GByte; about 250 annotations are inserted, 10000 vectorial entities are drawn on thematic layers, 800 radargraphic maps are inserted and more than 4500 blocks are extruded.

Figure 14. Replacement of a damaged marble block on a counterfort of the Façade during the restoration.

Figure 15. Example of a thematic layer in the 1:20 vectorial model: the green areas represent the replaced marble blocks.

6. CONCLUSIONS

The 3D Milan's Cathedral database provides a very useful documentation both of diagnostic and of restoration operations. An important feature of the database is the AutoCAD platform: it was readily available to the Veneranda Fabbrica, which usually works with the *layer* management approach. Moreover, the custom-made applications (*ETRadar*) and commands (*3DHatch* and *Insert Annotation*) made it easy to insert, consult and modify data.

Its innovative and distinctive feature is the multidisciplinary approach and the integration of the non-destructive diagnostic data with the structural survey one.
All these data (texts, images, and vectorial entities) are geo-referenced in the 3D model. In particular, the material thematic maps included the following *layers*: missing parts, stuccoes, cramps, fractures, replaced blocks, metallic elements, decay, black crusts and pigeon dust.
The structural diagnostic data, instead, produced the following *layers*: detached blocks, thin blocks, critical areas, stuccoes, detached stuccoes, fractures, detachments, cavities, masonry, and marble structure.
In the future, it will be updated with the post-restoration monitoring data and with all the further maintenance activities.

7. REFERENCES

Albery, E., Belli G., Centroni, C. and Menci, L., 2000. Strumenti innovativi per l'analisi e la documentazione dei beni artistico-culturali, L'uso della stereofotocarta e STEREOSPACE nella Basilica di S. Francesco in Assisi". In: Atti IV Conferenza Nazionale ASITA, pp. 383-388.

Albery, E., Dequal S., Lingua A. and Rinaudo F., 2000. A new tool for architectural photogrammetry: the 3D Navigator. Int. Archives of Photogrammetry and Remote Sensing, XXXII/6W8/2, pp.177-182.

Balletti, C., Guerra, F., Lingua, A. and Rinaudo, F., 2002. True digital orthophoto of the San Marco Basilica in Venice. Int. Archives of Photogrammetry and Remote Sensing, XXXIV, Part5/W12, pp.43-48.

Bungey, J.H. and Millard, S.G., 1993. Radar inspections of structures. In: Proceedings of Instn. Civ. Engrs Structs & Bldgs, 99 (5), pp. 173-186.

Ferrari da Passano, C., 2000. La Veneranda Fabbrica del Duomo di Milano. In: Inter. Conf. "Quarry-Laboratory-Monument" Int. Congress PAVIA-2000, Pavia, Italy, September 26-30 2000, Ed. G. Calvi and U. Zezza, Vol. 1, pp. 23-34.

Giunta, G. and Calloni, G., 2000. Innovative applications of not-destructive techniques in the restoration of the St. Peter's Façade in Vatican. In: Inter. Conf. "Quarry-Laboratory-Monument", Pavia, Italy, September 26-30 2000, Ed. G. Calvi and U. Zezza, Vol. 1, pp. 333-338.

Giunta, G., E. Di Paola and B. Mörlin Visconti Castiglione, 2003. Innovative 3D information system for the restoration and the preventive maintenance plan of the Milan Cathedral. SPIE 10th Inter. Sym. Remote Sensing, Barcelona (Spain) September 8-12 2003, Remote Sensing for Environmental Monitoring, GIS Applications, and Geology III, SPIE Vol. 5239, pp. 296-305.

Kasser, M. and Egles, Y., 2002. Digital Photogrammetry. Taylor & Francis, London.

Menci, L., 2000a. Stereospace as idea for photogrammetric data collection. In: Proceedings of XIX ISPRS Congress, 16-23 July 2000, Amsterdam.

Menci, L. and Rinaudo, F., 2000b. Cyclop: un nuovo sistema per l'acquisizione di immagini stereoscopiche. In: Atti della 4° Conferenza Nazionale ASITA, 3-6 Ottobre 2000, Genova, Vol. 2, pp. 1087-1092.