DEVELOPEMENT OF INTEGRATED PROCEDURES FOR SURVEY, ANALISYS AND MONITORING OF HISTORICAL BUILDINGS AND ANTIQUE MONUMENTS

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1. Introduction

The high number of experiences and papers produced in the last years in archaeological and architectural fields testify the increasing diffusion and application of information technologies to the cultural and artistic heritage.

Digital archives allow to make it easier to monitor deterioration processes and to plan restoration interventions. From the educational point of view, digital models allow large audiences of experts and common people to access the most important monuments ant archaeological sites even from remote locations .

The integration with Finite Elements numerical techniques and with rapid prototyping technologies allows to carry out deeper and more reliable structural analyses and to test, by means suitable numerical simulations, the effectiveness of the consolidation solutions proposed.

As a matter of fact, the D.I.A.P.RE.M. aims at achieving such goals through a series of activities, i.e. it :

develops surveying procedures with 3D laser scanners with the aim of checking measurement and morphological data and creating 3D digital models of architectural structures and sites for evaluation and assessment of various kinds (e.g. dimensional, structural, colorimetric).

formulates procedures of digital acquisition of surface specifications, including chromatic descriptions, material and morphological aspects, macroscopic alterations linked to degradation; one of the aims is to identify connections between structural specifications and states of alteration and degradation provided by the external reconnaissance picture; this kind of investigation is also developed through the processing of reflection data acquired in the 3D scanner laser ray reading (limited to a precise band of the spectrum).

provides formulation of 3D virtual models in the form of 3D hyper textual data banks which may be consulted online and which supply direct support for planning, allow for interaction between various people working on the process (designer, electrician, builder, historian, librarian, etc.) and supply, at planning stage or on completion of work, all information related to the final product.

deals with the modelling of Structural Mechanics problems and their solutions with finite elements numerical technique (FEM). The FEM codes used are MARC and ADINA, with which it is possible to solve static and dynamic problems in 2D and 3D, in elastic, linear and non-linear field, and in elastic-plastic field. In particular, these codes, which allow for the implementation of constitutive laws regarding fragile materials such as brickwork, or special anisotropic materials such as wood, lend themselves to the analysis of the mechanical behaviour of historic constructions in brick and wood.

studies possible direct interface of structural calculation programmes with programmes of 3D modelling used in computer graphics, with the aim of making maximum use of survey results and enabling structural analysis of the construction on the basis of its actual geometry rather than referring to a 'standardized' model.

The following case studies are meant to explain the integrated use of the aforementioned methodologies by the D.I.A.P.Re.M. Centre in two different contexts.

2. Case Studies

2.1 The "Sala" Estense and annexes of the City Hall of Ferrara

The experiences of the last decades have proved that traditional techniques have become quite cumbersome in surveying with the accuracy required nowadays the archaeological and architectural heritage; moreover the necessity of providing digital data bases is stronger than in the past because of the rapid development of the information techniques. That determined the need for updated survey techniques, such as the 3D laser scanner technique, able to create complex model of polygons or 3D clouds of points. Moreover, by means of specific softwares, it is possible to reduce the complexity and the richness of data acquired in order to create digital and paper outputs to be used in restoration, urban and architectural design and structural analysis

2.1.1 Historical notes
The building appear in a historical map of Ferrara for the first time in 1390 with the name of "Palazzo Estense" The realization of the stairs and the termination of the building is dated in 1471-1473 followed the leaden roof of vetian kind.

Fig. 1 – Front view of Palazzo Comunale in Ferrara

Between 1476 and 1479 Benvenuti builds the flat for duchess, to wich belong the eight windows of white marble that steel appare in north side of the actual municipal square and the loggia in west side. Built with two overlapped orders has been lost in the last century when they gave it the actual aspect, so the original shape is visible only in a old drawing of 18th century.
In 1598, after Alfonso II died, Ferrara become a domain of Pontifical Country and the building ceased to be a ducal residence, to become later during the streming of centuries an architectural system divided between different owners.
Between 1800 and 1924 in the "ex Cappella Ducale" are realized many renovations to convert the building from a religious use to a cinema, until the last use as Sala Estense, used for discussions, conferences and shows.

2.1.2 3D Survey, Modelling & Structural analisis
The research project concerns the acquisition and management of a 3D data-base of some parts of the architectural heritage of Ferrara. In particular the survey of the Sala Estense (a theatre built at the beginning of XX century), in Palazzo Comunale of Ferrara, is an application of the afore mentioned techologies, in which the integration among survey, 3D modelling and data processing has turned out to be useful even to the structural analysis of the masonry building. This experimentation aimed not only at a data recording but also at an accurate analysis of the morphologic and qualitative information collected in the 3D model of the surveyed building.
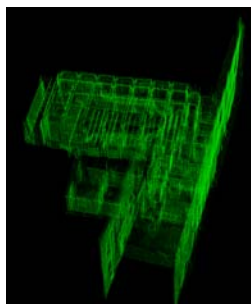

Fig. 2– Point clouds model

This is very rich in decoration and mouldings and its architecture is quite complex; therefore the proposed 3D survey technology proved to be suitable in this specific context. In particular, the research team set up an automatic procedure for the acquisition and the processing of all the survey data (dimension, shape, surface quality and colour) which could guarantee, at same time, the integration of conventional methods of analysis.

An integrated process was used to work in this area by means of the 3D Cyrax 2500 laser scanner and the total station Leica TCR 1101. The laser scanner used to scan the building is the HDS Leica Cyrax 2500, an instrument aimed at surveying wide spaces and buildings (range of scan up to 100-200 m). It sends forth a laser beam of five rays in green band spectrum, directed to the object with a range of scan up to 40°x40° by means of a system of rotating mirrors: this is an automatic procedure able to include all the area to be surveyed.

The measure of the position of each surveyed point is based on the time of flight which is the time elapsed between the emission of the laser beam and its reflection by the object to be surveyed. The reflectance data are acquired as well as the metric data; reflectance allows the visual recognition of the different materials as well as the automatic spotting of reference targets, which are landmarks for scan registration used to put together all the different clouds of points.

General shots were integrated with a progressive sequence of thicker scans with 0.5x0.5 cm grid for more relevant details, particularly stucco decorations of Sala Estense.

This survey procedure allowed to build up a 3D model by changing the scanner position 37 times, making 124 views and 335 scans: a total of 116.182.631 points were measured by the laser scanner. The model was made by scans with a thick 1x1 cm grid because of the complexity of the decorations. The work required a total of 7 days.

In order to better organise the registration time, the data processing and recording, the building was divided in four different areas, homogeneous for dimension and morphologic features: the former Bazzi drug-store, the "Sala Estense", the "Giardino delle Duchesse", the front.

Two different integrated techniques of shot registration were applied: the self-reference, with al least three homologous points (targets), and the geo-reference on the surveyed targets by means of a total station in order to increase the level of accuracy and to link the scans to a topographic net of reference points.

The complete 3D model of both metric and morphologic data and the visualisation of the various scans allowed to check the reliability of the survey.
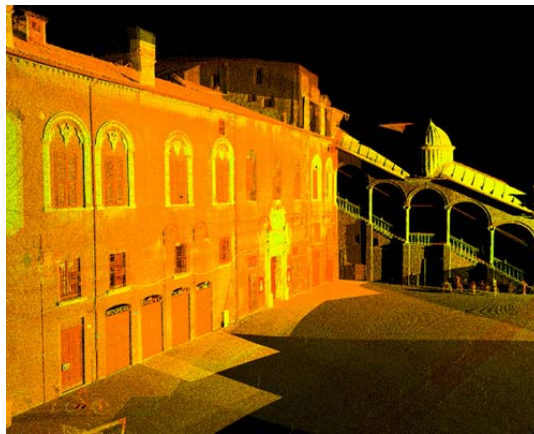

Fig. 3 - Piazza Municipale in a 3D visualisation by point clouds

The scan registration, the removal of all the elements of the 3D model not necessary to the purpose and the assemblage of the different shots into a single model did not require a long work time, whereas the 2D CAD drawing phase turned out to be more complex. Despite the use of an interface plug-in between the cloud of points and a standard CAD software (e.g. Cloudworks applied to Autocad), the 2D drawing phase was still complex was because the cloud of points gives usually too many information compared to those required for a 2D representation. Anyway, the 2D drawing time is shorter than the traditional metric survey time.

The representation of a building as the Sala Estense involved a reduction of metric information by the drawer, who has to make usually a representation choice; as a mater of fact, the architectural survey rarely requires full size scale representations, whereas more frequently 1:100 or 1:50 or 1:20 architectural scales are used.

In the specific case the identified scale was 1:50: a very detailed representation which required about 200 hours with CAD.

After the scan registration had been carried out, a point cloud model of the entire building, which reproduces the actual geometric configuration of the surveyed site, was obtained. The Cyclone TM software, supplied by Cyrax, was used. The survey metric data processing software allows the management, the cleaning and the aggregation of the point clouds as well as the creation of sections obtained by the intersection of the 3D model with oriented levels. Moreover it is possible to measure distances and volumes directly from the model, avoiding the interpretation of scaled drawings or other representations.
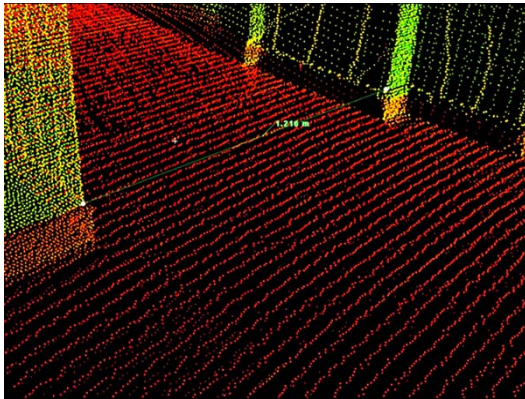

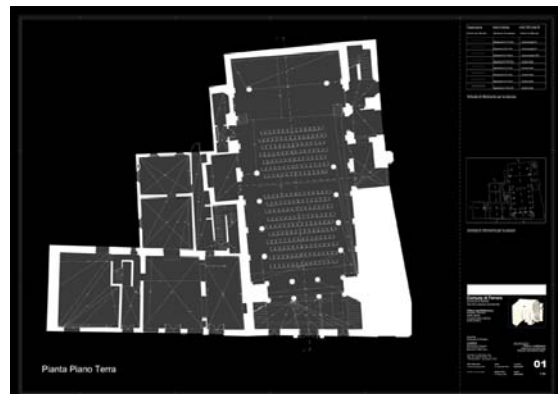Fig. 4 –Metric control on the point clouds model

Fig. 5 – Ground floor plan of the building in 1:50 scale, obtained by 3D laser scanner survey

The sections produced with the software can have any dimension, according to levels chosen by the user (generally the orthogonal ones); therefore, it is possible to get easily plans, vertical and horizontal sections and front views which can be directly exported into DXF format and then imported into any vectorial drawing software.
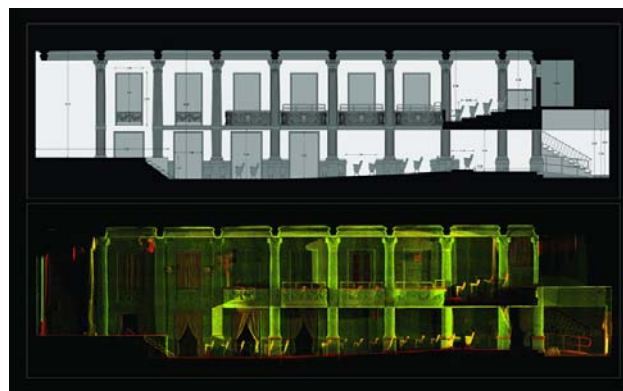

Fig. 6 – Longitudinal vertical sections of Sala Estense; CAD processing (1:50 scale); cross vertical sections of the Sala Estense obtained by Cyclone TM software

In the Sala Estense survey project Autocad, together with Cloudworks, were used to improve the sections obtained by the clouds of points. This application allows to visualize the cloud of points inside the most commonly used CAD software and to manage by means of tools various visualizations of the model. A horizontal section was taken every 50 cm, up to an 8 mt height. Afterwards the main levels to obtaine plans were selected, as well as the landmark points from which the surfaces of the tridimensional model were traced. Thanks the accuracy of the survey and the precision of the 3D model, horizontal and vertical sections are able to put in evidence out of plane deformations of the walls, differential settlements in floors and vertical walls, rotations etc.
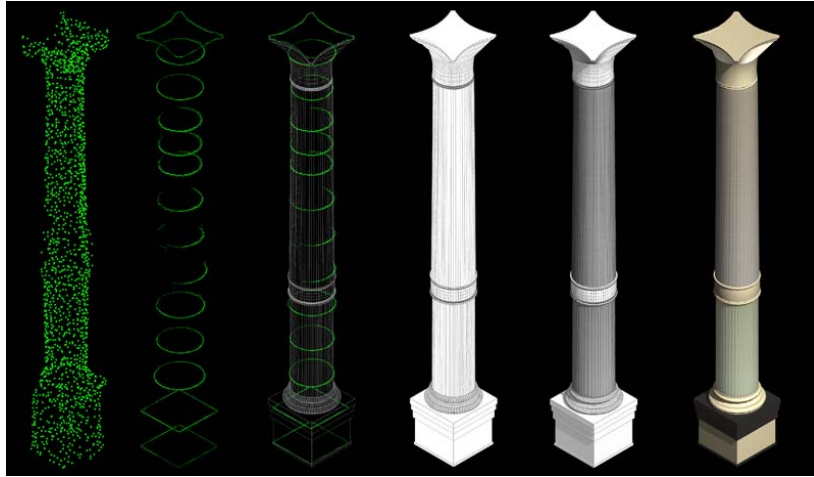
Fig. 7 – Processing of an architectural element, from the point clouds model up to the textured model

Three kinds of 3D models were made for this survey: one, for the former Bazzi's drug-store, is a model with a QUAD4 finite element mesh used for an integrated structural analysis, *(Fig. 8)* the second is a model with a triangular mesh for the solid prototyping of a part of Sala Estense in 1:100 scale, and the last one is a model with a simple mesh for representing the complete model of the bulding.
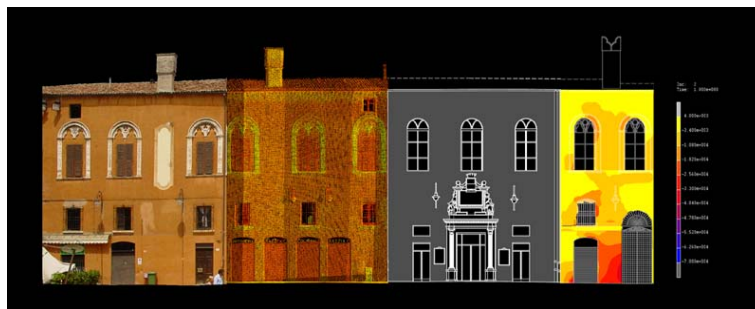

Fig. 8 – Schematic sequence from the preliminary phases of data acquisition up to the model with QUAD4 finite element mesh for structural analysis

2.2 The Traiano triumphal Arch in Benevento

In 2003 it has been developed a partnership among Archaeological Suprintendence of Salerno, Avellino and Benevento and the Department of Architecture of the University of Ferrara, aimed to the research about Traiano triumphal arch in Benevento.
The purpose of the research were: the survey of the arch by means of 3D laser scanner, the creation of a 3D model, , the realization of spectrophotometric research on stone surface and the 3D reporoduction of some sculptured pieces; in this way we meant to create a complete 3D data base in order to monitor the monument.

2.2.1 Historical notes
The Traiano triumphal Arch of in Benevento was built by order of the Senate between 114 and 120 a.C. to celebrate the Emperor.
The Arch is placed at the beginning of the street that Traiano himself wanted in 109 a.C., a street named after him (*Minucia Traiana*) which today leads to Brindisi. In this way the old route along *via Appia* was shortened, and an expansion of the trading with the East was encouraged.
Consequently the political and administrative centre moved to the high-end of the city, renamed *Regio viae novae*, under the Arch.
Two decorative tiles of the attic represent Adriano, Traiano's successor during the last three years of the Arch construction.

Thanks to the decorative richness and the stylistic features the Arch is a unique monument of great value.

The unknown sculptor, usually called *Master of the Arch of Traiano*, ruled a workshop of specialized employees each one with a peculiar style, recognizable among the Arch decorations.

The barrel-vault arch, completely covered with marble, arises upon a calcareous base. The Arch is divided by four fluted semi-columns, with attic bases lying on the stylobate. The capitals, of composite order, bear a ionic trabeation with a tripartite architrave, a continuous frieze and a denticular caisson cornice. The denticular cornice pattern is also present in the attic, which shows in each side the Senate and people dedicatory inscription, dated 114 a.C. The two fronts of the Arch are decorated by high-relief tiles celebrating the Emperor achievements.

In the Middle Ages the Arch was included in the city walls and became the main access to Benevento, so that it is also known as *Porta Aurea* because of its golden inscriptions, afterwards despoiled.

The first restoration was carried out in 1821- 1825 by Giuseppe Valadier which built a shelter to protect it. Pope Pio IX wanted the Arch to be isolated in 1854, and only in 1894-1899 the surrounding area was cleared. In those years the first structural intervention was made to restore the attic cornice, great part of which had been lost. There were a second intervention in 1932, after the approval of the Benevento town-planning scheme, and a third one in 1970, consolidating the Arch by means of metallic bars. The restoration of the marble parts, completed in 2002, became possible after the 662/1996 law was approved.

2.2.2 3D Survey, Modelling & Rapid prototyping

At the beginning of 2003 a research project concerning the surfaces and the morphology of the Traiano triumphal Arch in Benevento was set up by the D.I.A.P.RE.M. (Research Centre for Development of Integrated Automatic Procedures for Restoration of Monuments of the Department of Architecture, University of Ferrara). The research project was developed on the basis of a partnership between the Archaeological Superintendence of Salerno, Avellino and Benevento and the Department of Architecture of the University of Ferrara.

In 2000 the Archaeological Suprintendence completed the restoration of the Traiano Arch and, with reference to previous studies, the purposes of the current research were pointed out: the survey of the arch by means of a 3D laser scanner, a 3D virtual model, a spectrophotometric analysis on the stone surfaces and the 3D solid reproduction of some bas-reliefs.

The monument was surveyed by means of two different laser scanners working simultaneously (Cyrax 2500 and Minolta VI-900); in this way the practical organisation of the work could be planned by selecting the most appropriate technical and environmental solutions.

The survey of the whole monument (in order to obtain outputs at architectural scale) by means of a Cyrax 2500 laser scanner was not difficult thanks to the visibility of the monument from each side of the clear area in which the arch is located. The survey of the ornamental details, on the contrary, brought up a number of problems: the higher frieze was 9 m high above paving level and it was not possible to build a stable scaffolding able to guarantee accurate shots with the Cyrax 2500 laser scanner; so, since the Minolta VI-900 is able to acquire data rapidly (2,4 sec. for range map) the problem was solved by means of a moving crane able to lift operators and instruments up to the right height.

After the first inspection of the area to be surveyed, in March 27th 2003, the procedure to be followed was defined and the integrated survey started according to the purposes previously fixed.

Each scanner used during the survey required a precise arrangement because of the amount of the heavy and bulky equipment; so the first step was to optimise the use of the survey instruments.

The equipment for the survey included: the 3D Cyrax 2500 laser scanner, the Minolta Vivid VI-900 laser scanner, a lap-top for each laser scanner, a workstation for checking and recording the data and making the first scan-registration possible. Three digital cameras (Minolta Dimage 7, Kodak DC 4600 and Nikon Coolpix 995) were used for the photographic survey whereas the Minolta 503C spectrophotometer was used to acquire colorimetric data in particular significant areas of the monument. A generator with extensible cables supplied electricity to the scanner while the crane was lifted up. Flat and spherical targets completed the equipment.

The survey research project started in April 2003 and the work was carried out by 5 operators: 2 people for surveying the arch, two people for surveying the frieze and one person for the spectrophotometric and photographic survey.
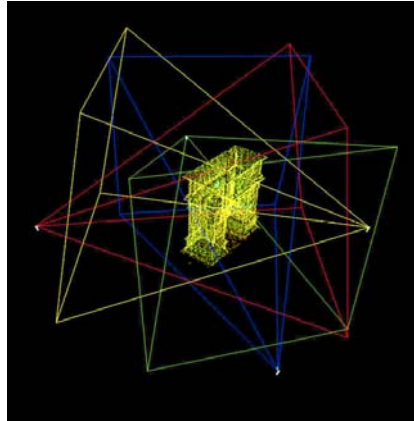
01 – 3D plan of the Scanner positions; each view is evidenced by a different colour.

The survey of the whole arch was made by two operators, for an amount of 24 hours of uninterrupted work; it had been decided to move the scanner in correspondence of the four vertices of the monument in order to include the urban area in which the arch is located.

02 - The equipment for the survey included the 3D Cyrax 2500 laser scanner, a lap-top and a battery.

The scans were performed by three layers, using grids with different distances between points according to the aim of the scans:
a 5x5 cm grid to scan the arch enclosing the area
a 2x2 cm grid to scan the whole monument surface
a 1x1 cm grid to scan the minor frieze and check the data acquired by the Minolta Vivid 900 laser scanner
The targets, landmarks for scan registration used to put together the different clouds of points, were applied to each side of the Arch base and inside the barrel-vault, up to the highest level, without using ladders.

The scanner position under the barrel-vault, making three views, allowed to create the closed model. About 30 scans were performed from each one of the vertices whereas 8 views were taken from the barrel-vault station for an amount of 130 scans.

The survey session was completed in 40 hours of work by two operators.

The survey during the night was made easier because of the absence of traffic which, during the day, gives rise to shade areas.

The standard procedure for scan registration was applied by using three targets (spherical and flat) for each scan to be registered.
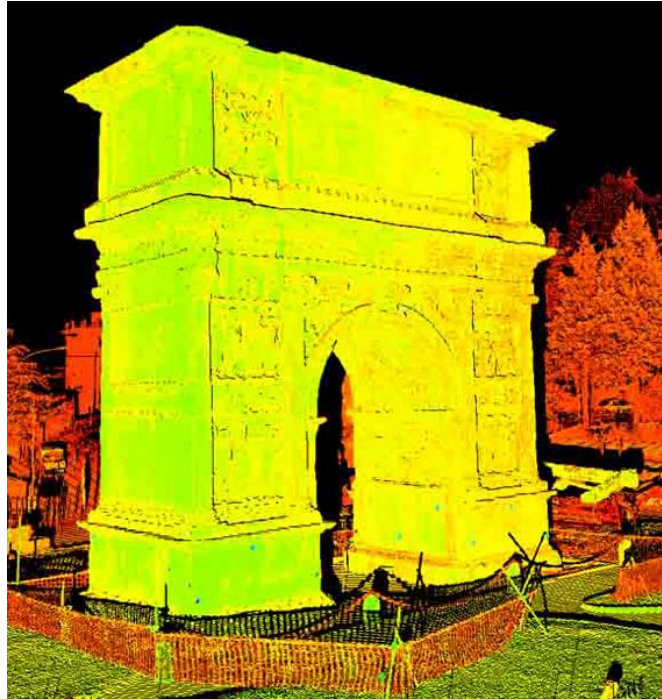

03 – A view of the surface model of the whole monument obtained by means of a 2x2 cm mesh.

Afterwards the detailed point cloud model was obtained; two different models were built up: the first one includes all the scans and parts of the area around the monument, the second one is the whole monument made "clean" of the external elements.

04 – By means of the 3D model it is possible to draw the measures of the architectural elements.

Starting from these two models and by means of a specific software it is possible to get data out; the rapid prototyping of a part of the momument in the 1:20 scale was also experimented.
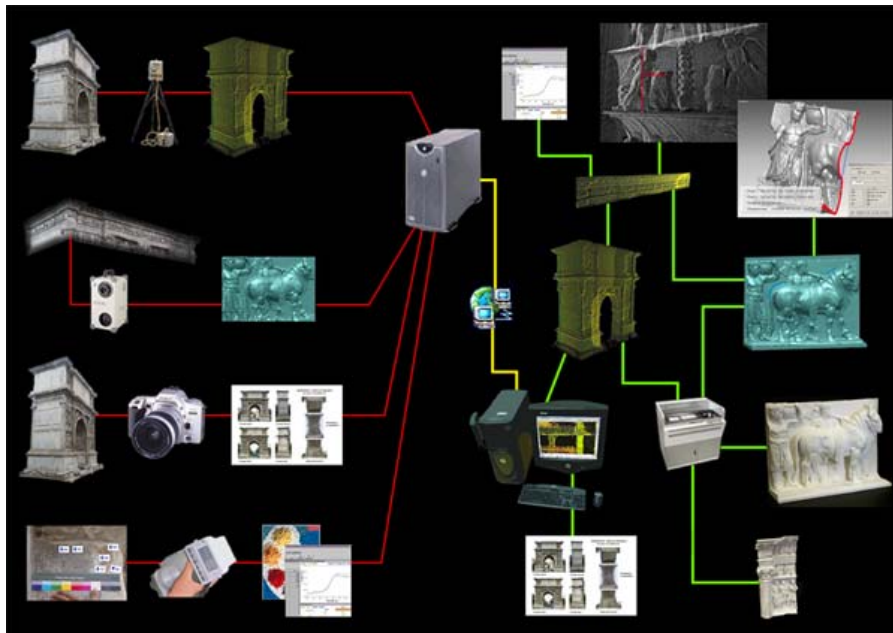

05 – An example of a 3D data base.

The detailed metric survey of the superior frieze by Minolta Vivid 900 laser scanner involved a lot of difficulties: it was the first survey carried out in an external and so large area.

06 – The Traiano Arch minor frieze is 9 mt. high. One of the rapid prototyping purpose is to create a model to allow visitors to have a "closer view" of the ornaments.

It was decided to work during the night in order to exclude the solar interference in the data acquisition; at first a 6 night work session was estimated but the work was made in two different sessions. In the first one two sides of the frieze were surveyed (in one night) and the other two sides were acquired during the second work session (in two nights).
An amount of 750 scans were required to survey the whole frieze of the top because of the small area covered by each scans.
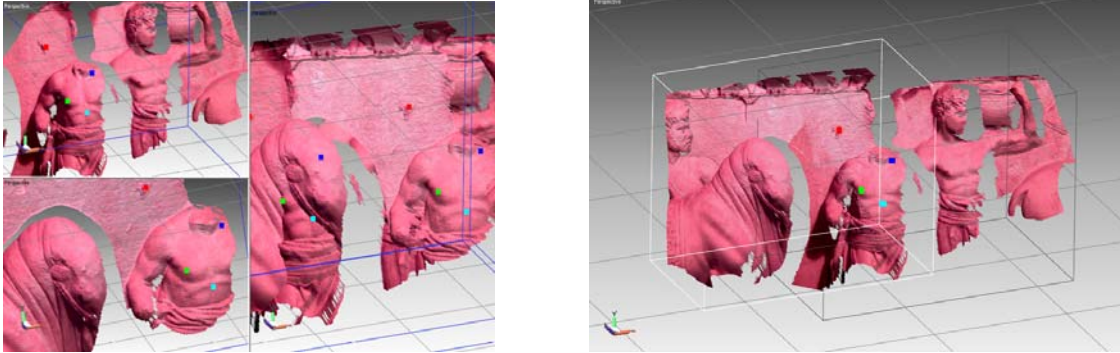
07 - The standard procedure for scan registration concerns the use of three homologous points at least for each scan to be registered.

The physical models of the bas-reliefs were obtained by using currently available prototyping techniques. Afterwards some tests carried out to check the most appropriate technology for 3D printing, it was decided to use plaster powder and glue and to build the model by 0.075mm thick layers in order to guarantee more accurate results.

08 – Detail of the minor frieze model before the starting of the prototyping procedure.

By means of this procedure it is possible to obtain models at any scale, from the full-size scale up to the 1:5 scale, without loosing in precision; moreover the material, which the solid models are made of, allowed to start experimentations concerning the colouring of the surfaces according to the requests of the Superintendence which emphasized the necessity of reproducing properly some details in the prototype.
Therefore a colouring procedure using tempera and watercolours was adopted according to restoration theories and techniques; the result turned out to be quite satisfying. This procedure introduces an innovative utilization of the Rapidprototyping.

09 - By means of this procedure it is possible, starting from the same virtual model, to build solid models of any scale, from the full-size scale up to 1:5 scale, without loosing in precision.

10 – The solid prototyped model of the west side of the Arch in 1:5 scale.

In the occasion of the latest *Fiera del Restauro* held in Ferrara in March 2004 virtual representation of the entire monument and of its details have been realized using the data-base acquired during the 3D survey and the details realized by prototyping , so it has been possible to exhibit both solid and virtual representations of the monument at the same time and in the same place, suggesting new and interesting setting in museum dressing.

11 – The Cyrax data are suitable for the architectural scale prototyping, from 1:100 up to 1:20 scale.

3. Conclusions and future developments

The described procedures can be extremely powerful in helping the historical analysis, checking and monitoring the architectural and sculptured items and setting up interactive metric databases able to provide at any time information about the surveyed object.

In particular the precision, the acquisition speed of metric data, the opportunity to use these data to build 3D geometric and physical models and to carry out structural analyses are very advantageous features which encourage the development of such integrated survey techniques.

The applications of the procedures briefly described in this paper can be extremely various, not only in the architectural field but also in all the other fields where virtual simulations based on 3D models morphologically corresponding to reality are required.

The D.I.A.P.RE.M., Centre of the Department of Architecture of the University of Ferrara, aims at promoting theoretical and applied researches in order to optimise the acquisition procedures in relationship to the problems regarding the conservation and restoration of monuments and structural analysis.

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