AUTOMATIC DEM GENERATION USING DIGITAL SYSTEM InduSCAN: AN APPLICATION TO THE ARTWORKS OF MILANO CATHEDRAL FINALIZED TO REALIZE PHYSICAL MARBLE COPIES

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ABSTRACT

In this paper is presented a method to realize copies of sculptures using numerical control milling machines. The carving is obtained from the survey and D.E.M. reconstruction of their surfaces. The starting point for this study has been the need of the "Fabbrica del Duomo di Milano" to realize automatically copies of marble artworks which are decaying for the pollution. The most complex technical problems to realize such an automatic process are the precise object survey and its physical reproduction driving the tool of a numerical control machine. The first item has been carried on using the "photogrammetric industrial measurement system InduSCAN" by Zeiss Jena. The second problem has been solved transforming the D.E.M., from InduSCAN, in the path-tools of the milling machine. The physical execution of the copy has been made by BOVERE GRANITI (Italy). To verify the feasibility of the whole process, a survey of two sculptoral marble elements of the Cathedral has been realized and copies of some elements of these have been made.
This study has defined a process able to reproduce in a semi-automatic way the statues of the Duomo. The work of the sculptors is so reduced to an indispensable finishing touch only.

1. INTRODUCTION

This paper deals with a project that is trying to save one of the most important monuments of the Northern part of Italy: the "Duomo di Milano". Due to the high value of the pollution present in the air of Milan, the marble decorations of the Cathedral are under a quick process of decay. At the moment, under the supervision of the chief-engineer of the "Fabbrica del Duomo", some sculptors spend their working-days making physical copies of the most damaged decorations and statues of the "Duomo". The costs of this process are always higher and the number of elements that can be copied is very small.
It is important to underline that the connotation of this copy-making are somewhat different from those of past ages, when they preeminently satisfied the interest of private collectors. Today the copy-making is mainly due to the acceleration of decay by environmental agents and to a more heedful attitude towards the conservation of the cultural heritage.

The aim of this paper is to present an innovative methodology to make marble copies of the main artworks present in the Cathedral. The innovation consists on an effort to create an almost completely automatic surveying and reproduction process. A description of the surveying and reproduction process are here presented.

2. THE REPRODUCTION PROCESS

A complete system suitable for the sculptures reproduction has to be composed by two moments: the *survey*, defining the objects surfaces D.E.M. and the *physical reproduction* using numerical control (N.C.) milling machines.
A two steps process can permit to survey the artworks in their own position in the monument, while the marble copy can be made later in a suitable milling-workroom, so to avoid damaging the sculpture during the removing-works and before its survey.

The survey methodology must garantee the possibility to define with high accuracy (0.1÷0.2 mm) the D.E.M. of also large dimension objects as architraves, sculptoral groups, alto-relieves. A non-contact technique must be used, considering the marble artworks brittleness.
For all these reasons the more interesting survey method seems to be the photogrammetric one. Therefore *digital photogrammetry* sounds the technique of the future, due to the quick evolution of digital cameras and the availability of always more powerful computers at low cost.
At the moment the *scanner-laser* technique is usually applied to survey small bas-relieves; unfortunately this method becomes unusable for full relief and large dimensions sculptures. Infact in these cases the D.E.M. generation has to be divided in different phases, and the laser technique cannot define tie points indispensable to joint the several D.E.M.s [Scaioni,1995].
The "digital photogrammetric measurement system InduSCAN" by Carl Zeiss Jena GmbH (Germany) seems to be the more suitable tool to solve the survey problems before described [Kludas,1995].
The automatic copy realisation from D.E.M. can be nowadays carried on using of the high technology level of the N.C. milling machines. Big problems are still present to define the correct path of the N.C. milling machine tool and for the memory dimension of their controller (usually used with smaller set of data) [Monti,1994].
In the next paragraphs the different items will be described. The methodology exposure is carried out describing the theory and its application (survey and physical reproduction) at two marble elements coming from the Duomo.

3. SURVEY AND D.E.M. GENERATION WITH InduSCAN SYSTEM

The survey of the sculptures has been realized using "InduSCAN system" by Carl Zeiss Jena, usually employed in high precision 3-D industrial measurements. The task was to obtain a 3-D D.E.M. of these objects [Claus,1988].
Ahead to begin the technical description of the different survey phases, it is necessary to define the accuracy level and the final quality. The Cathedral sculptures are nowadays copied with a traditional methodology: a sculptor makes the statue observing the original. The aid of the modern technology is restricted to the application of pneumatic rock-drills to work the marble and milling machines for the blocks rough-shaping. The reproduction accuracy is strictly committed to the sculptors, which use suitable three-dimensional pantographs to report the original measures on the copy.
For all these reasons a survey accuracy of $\sigma=\pm 1$ *mm* in X, Y, Z directions can be considered as enough. However in the tests later described we have looked for the best accuracy, so to check and validate the whole methodology.

Fig. 1 - Image acquisition with InduSCAN

3.1 The sculptures survey

Two sculptoral elements, very representative of the artwoks typologies present in Milano Cathedral, have been surveyed:

- a *statue* (dimension 50x50x160 cm);
- a *little spire* (dimension 40x40x140 cm).

These two handmades have been carried from the Cathedral to "Cantiere Marmisti"* , where a room has been prepared for the survey with InduSCAN (see figures 1 and 2).
The elements to survey have been placed on a 50 cm height bearing, in the way to permit some takens from down toward up. The room was darkened to allow the statue lighting with a projector.
The pieces have been signalized with some retro-reflective targets, later used for the image orientation.
The targets have two main tasks for their use in the bundle adjustement process:

* A workshop in Milano where usually the marble copies are created.

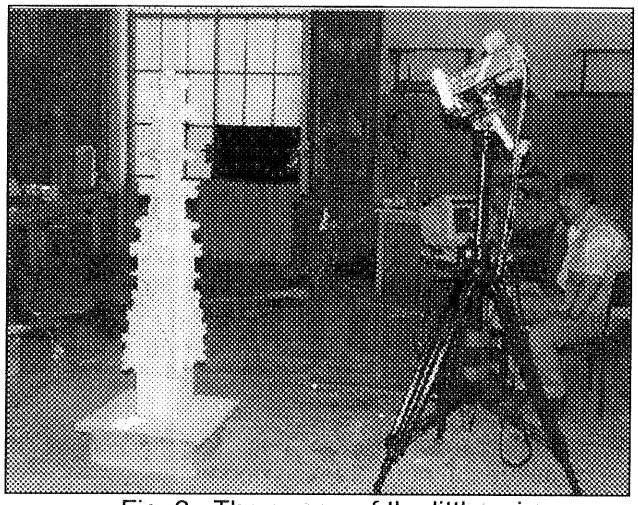

Fig. 2 - The survey of the little spire

1. some of the tie points are used as control points (they have a little black point in the centre of the reflective circular zone). The criterion of their layout derives from the shape of the object to survey and from the geometry of the takens;
2. the other targets are used as tie points.

In table 3 is shown the number of targets used for the survey of the two sculptures.

	images	control points	tie points
statue	108	11	150
little spire	90	12	140

Table 3 - Some data of the sculptures survey

3.1.1 Topographic measurements. The object coordinates of control points have been measured using a first order theodolite. A net with forward multiple intersection has been used, employing an horizontal invar rod to measure the base. After a least squares adjustement, with this method has been possible to reach a R.M.S. of $\pm$ *0.2 mm* in the control points object coordinates.

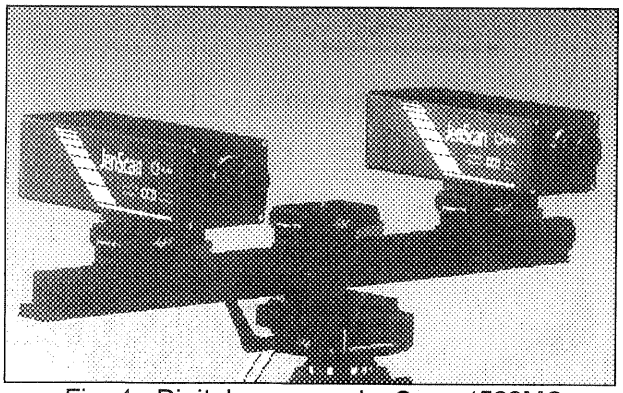

Fig. 4 - Digital cameras JenScan 4500MC

3.1.2 Digital image acquisition. The "InduSCAN" system permits to get the takens of the object to survey with different camera models. In this application digital cameras "JenScan 4500MC" has been employed (see figure 4); they are a very good arrangement between price, quality and simplicity of carriage and use [Godding, 1993]. The image acquisition is controlled via software, and it is possible to select also the most adaptive resolution. The survey of two sculptures has been made with a resolution of 2992x2048 pixels, corresponding to a CCD array of 8.228x5.632 mm, with a pixel size of 2.75 μm.

The objective employed is a Lamegon 3.5/14 mm, which permits to realize also some takens of the object details. The high quality of this optical system, added to the small dimension of CCD array, permits to obtain some images with very low radial asymmetric and tangential distortion.

A pair of cameras is mounted on a tripod, in the way to realize directly the stereoscopic images (see figure 2 and 4). To put right the absence of a texture on the objects surveyed, "InduSCAN" system uses a projector which creates a random pattern structure over the object surface (see figure 5).

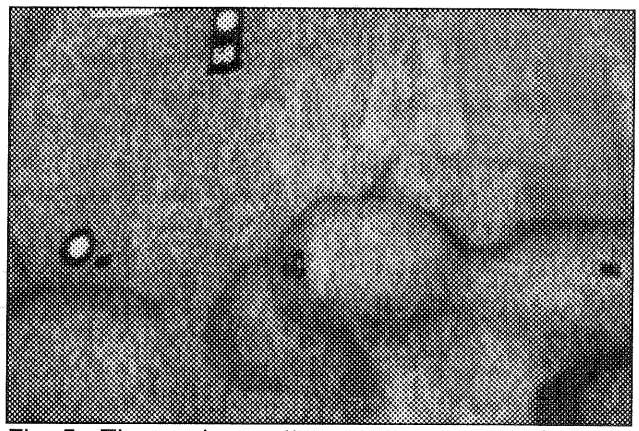

Fig. 5 - The random pattern structure created by the projector on the object surface

This procedure creates an high number of distinct particulars, forming the pairs of homologous points for the stereoscopic restitution and D.E.M. reconstruction. The projector is mounted on the tripod between the two cameras and for this reason the portions of the object present in more than one image pair have a different pattern. Therefore the restitution of not signalized points is strictly limited to the stereoscopic models.

The lighting is integrated with two circular fluorescent lamp placed around the objectives of the cameras.

The base used for the takens was nearly 30 cm and the mean object distance was nearly 1.50 m.

The criterion was to realize at first a series of images from different angle-shots, containing a big part of the object; afterwards some images of details were acquired.

3.2 Image orientation

3.2.1 Automatic target measurements on digital images. After the image acquisition, the position of the centre of the retro-reflective targets is measured with software DIAMANT, running on a PC-486 connected to the cameras and, via Ethernet connection, to a Silicon Graphics workstation.
First a technician identifies the approximate target positions on each image. Then DIAMANT measures the image target coordinates with accuracy of few $\pm 0.1\ \mu m$, using some automatic algorithms or using zoom-function of some image parts. When a target has been measured, the software asks the user the distinctive number of it.

3.2.2 The Bundle adjustment. "InduSCAN" system permits to make the interior and exterior orientation of the images using the bundle adjustment software BINGO. The medium values of the R.M.S. of the object coordinates after the image orientation are reported in table 6.

R.M.S.	X (mm)	Y (mm)	Z (mm)
statue	±0.027	±0.029	±0.022
little spire	±0.019	±0.024	±0.017

Table 6 - The R.M.S. of tie points object coordinates after bundle adjustment

3.3 D.E.M. generation

The D.E.M. generation has been carried on with InduSURF software [Kludas,1995], implemented on a workstation Silicon Graphics IRIS.

Digital images have been elaborated model by model, with the possibility to select the area in which to built the D.E.M.; this technique allows to exploit in the best way all the images, choosing the most adaptive takens to reconstruct each singular part of the sculpture surveyed. All object portions built are integrated in same reference frame and they contribute to the D.E.M. of the whole element. This can be seen using software SURFACER, in order to verify how the processing works and to check which are the missing parts of it.
The method used by InduSURF has the following steps (see figure 7):

- interactively selection of an area on image;
- resampling of image pair (*normalisation*) to simulate the normal taken geometry;
- identification of the homologous points generated using the projector and computation of their object coordinates to build the D.E.M.; this operation is made using two methods:
  1. *feature-based correlation*, which permits to obtain a low-resolution D.E.M.;
  2. *least squares images correlation*, to measure the contours and to build the D.E.M. related to a regular grid.

InduSURF permits to build the object surface in which points are arranged by sections or following a regular grid in a reference frame in the object space.
The surfaces of the two Milano Cathedral sculptures have been reconstructed using 3 mm distance sections (see figure 8).

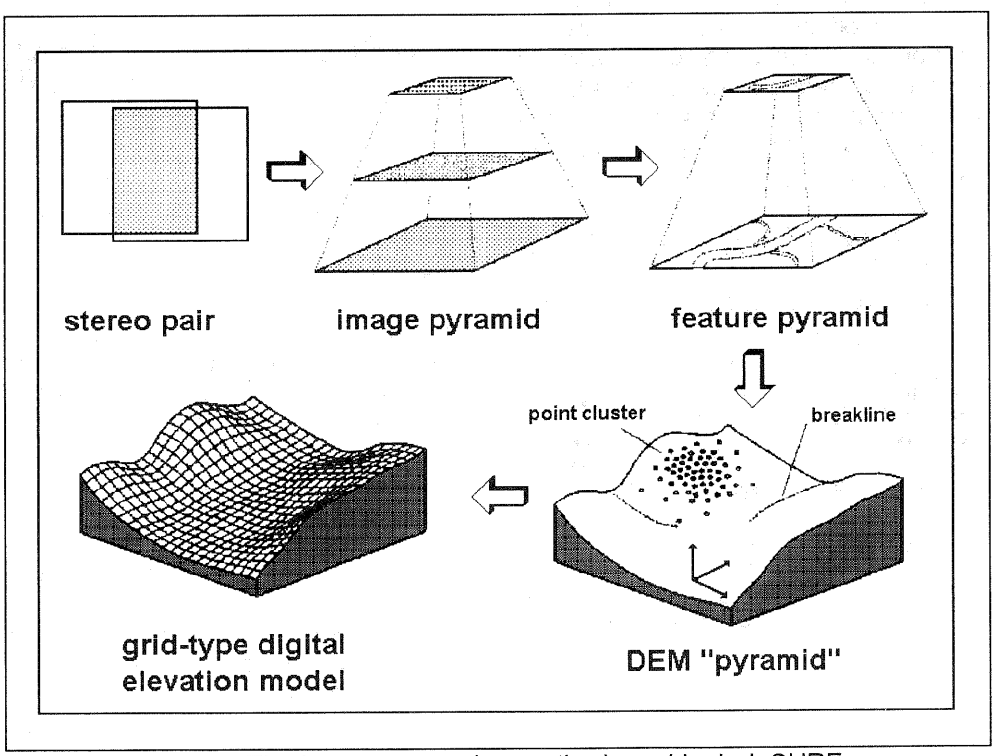

Fig. 7 - The image processing method used by InduSURF

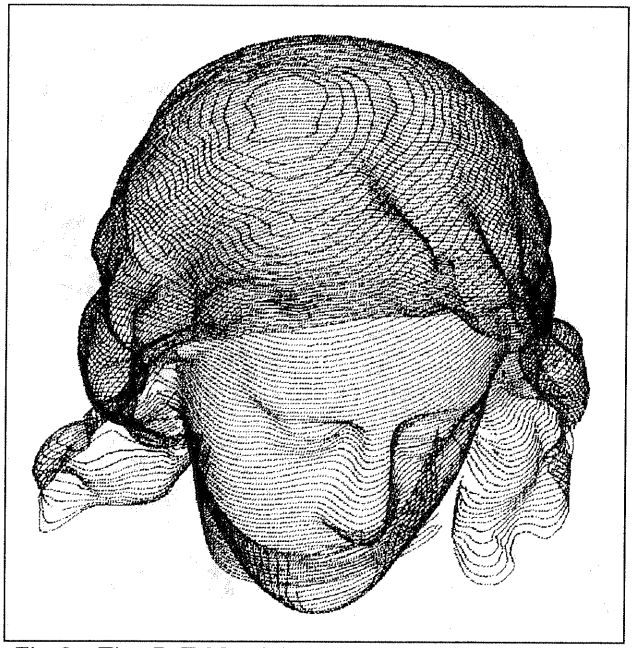

Fig 8 - The D.E.M. of the statue head realized with InduSCAN system

4. THE PHYSICAL MARBLE COPIES

The survey process has obtained as result to describe the sculptures with an high number of points structured in horizontal sections. The aim is now to realize the marble copies with a N.C. machine that is a "classic" problem usually solved with CAD-CAM software packages [Monti, Viazzo, Vassena,1994]. The main problem is to transform this large amount of data, composed by points in spatial coordinates, to a surface suitable for the CAD-CAM software. In fact the CAD-CAM packages are usually projected to work with well known mathematical surfaces and they are not able to manage surfaces described by a large number of points and characterized by high local discontinuities.

The task of the data treatment has been to create a $r = f(\alpha , z)$ cylindrical surface, built from the z constant sections, planned to work with a lathe machine having one rotation axis, along which the marble piece is mounted, and two linear axes. The first linear axis moves parallelly to the rotation one; the second moves perpendicularly to the rotation axis and parallelly to the tool rotation axis (see figure 10).

As first step has been necessary to define the position of the rotation axis in the cloud of points, in the way to minimize the dimensions of the original marble piece. Secondly the points coordinates have been translated, so to move the z axis to the position of the rotation axis, and later transformed in cylindrical coordinates. The set of data so obtained has been used to prepare the surfaces necessary to drive the N.C. milling machine tools.

The reproduction tests have been carried on with the help and the machines of BOVERE GRANITI (Premosello di Chiovenda - Italy), deciding to create a scaled copy (1:3) of the statue head. A four axes machine has been used, instead of three axes lathe one. In few months the lathe machine will be ready to store the large amount of data necessary for the reproduction of the whole sculptures (statue and little spire).

The copy shown in figure 9 has required 4 hours of N.C. milling machine work.

5. CONCLUSIONS

This test shows that is possible to realize high quality physical copies of art-works using an almost automatic process, from the survey, with InduSCAN system, to the reproduction. The chance to acquire and memorize a 3-D numeric image of art-works, can provide such a database of the cultural heritage. The choice to make copies of sculptures can be made only in critical cases, as for the Duomo di Milano, when to leave the art-work in its position could be dangerous and could carry to the completely loss of the element. It must be taken in account also the possibility to move important art-works from their position in museums, where can be better observed and saved by the environmental agents.

Fig. 9 - The marble copy of statue head

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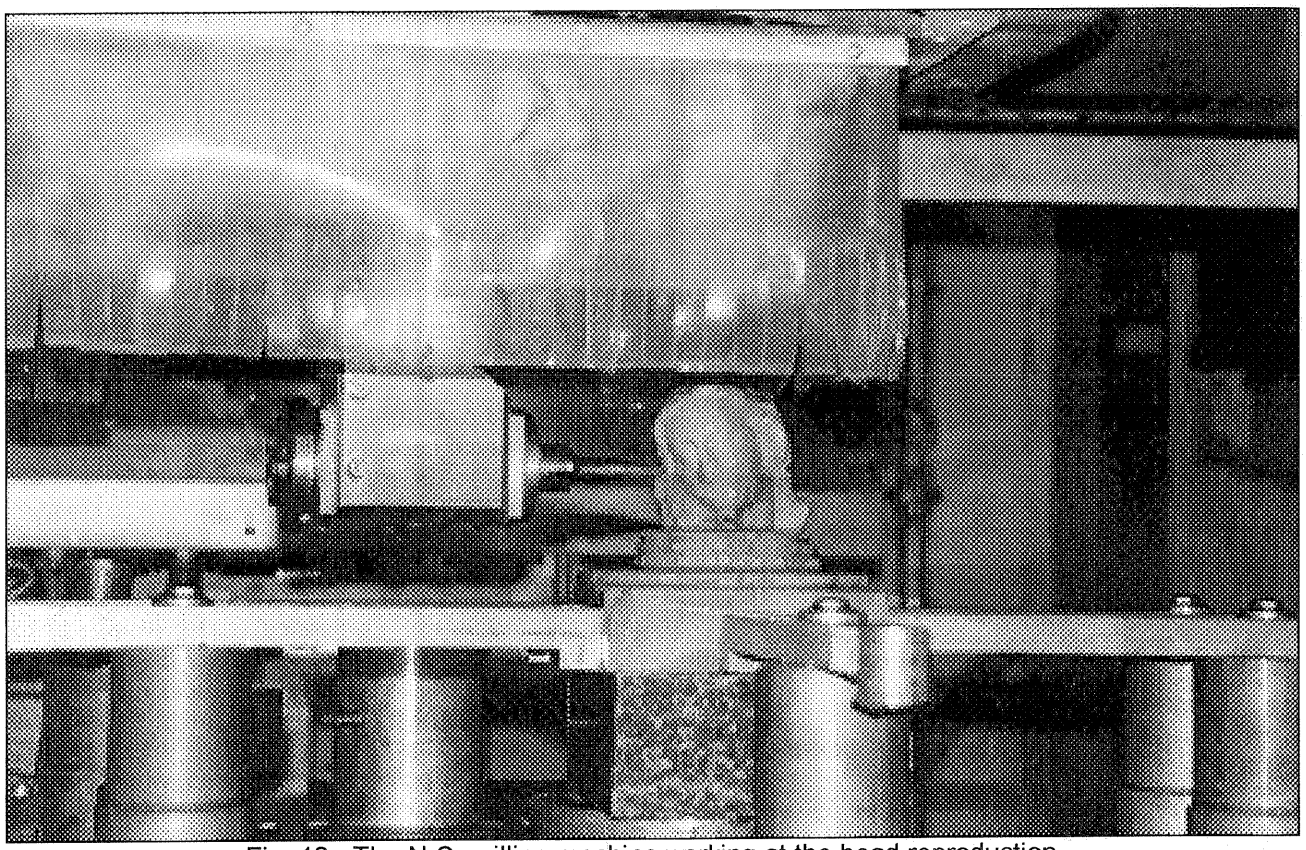

Fig. 10 - The N.C. milling machine working at the head reproduction

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