LASER TECHNOLOGY FOR CROSS-SECTION SURVEY IN ANCIENT BUILDINGS: A STUDY FOR S. M. MAGGIORE IN BERGAMO

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ABSTRACT

Urban landscape complexity points out the increasing importance of a detailed geometric knowledge, mostly for buildings with a historical and architectural value. So, an accurate building survey is needed, both for morphologic and dimensional documentations and for structural and material aspects.
A study for monitoring and analyzing building structure becomes of easy approach, thanks to periodical testing of its level of safety which can be realized through modern geo-technologies, referring to non-contact, often automatic, metric sensors.
This way, it's possible to acquire 2D-3D models of representation, to be used interactively for morphologic study, building preservation and risk assessment.

1. ANCIENT BUILDING KNOWLEDGE

Historical buildings play an important role in Italian cultural-heritage scenario: their main value is due overall to age, artistic and structural features and to surrounding environment.
All these elements can involve a risk condition both in everyday life and in emergency; therefore, ancient buildings have to be monitored over the time to preserve them from failure and collapse.
So it's of great importance to measure and document their geometry, mostly before, during and after meaningful actions regarding structural consolidation and rehabilitation.
The capability to investigate and document in a short time a state of deformation (settlements, rotations, and so on) plays a crucial role in monitoring the level of *safety* of a building.
The present active devices for fast metric acquisition without contact (for instance, *laser technologies*), go nowadays side by side to the more traditional *surveying* and close-range *photogrammetry*: all these techniques are highly suited to allow more and more automatic evaluations.
In fact, it's possible to explore surfaces, detect (in real time) changes in design attitude (like alignment and/or parallelism, verticality and horizontality) and prevent risk conditions **[**Gomes Pereira, Morgado, Pereira, 2004**].**
All the collected information is useful to document building conditions, evaluate its changing along time and develop spatial simulation about its structure (Finite Elements Analysis, and so on).
Therefore, laser technology provides a good support to the increasing demand for better assessment of geometric and structural quality under construction and for fast comparison with respect to the pre-selected standards (for instance, the assembling steps of structural elements in prefabrication industry).

2. 2D-3D REPRESENTATION

Building knowledge, useful both for its maintenance and safety, can be well supported by a spatial model, thanks to its better capability of communication, design representation and employment inside GIS environments.
3D visualization, if compared to 2D one, provides a more complete and effective tool for building investigation, which can start from each point of view, both for planimetric data (plan and horizontal profiles) and altimetric ones (vertical sections), and for wall geometry.
The investigation approach depends not only on the geometric features of the object, but also on the way of representation; this one can be limited to 2D vector CAD drawings (elevations, profiles and sections), or it can add 2D raster descriptions (facades rectifications and orthoimages) and 3D representation with photo-texture mapping (Figure 1).
Geometric data acquisition develops a building model in an absolute reference system: this is achieved thanks to technologies based on *pre-selected points* measurement, such as surveying and photogrammetry, or related to *random points*, as performed by laser scanning.
Usually, acquisition regards a spatial sequence of *object-point*, mostly without intrinsic control and with precision related to the sensor quality and resolution (linear and angular), such as in surveying measurements, in off-line photogrammetric systems and in laser scanner technologies; on-line photogrammetric systems (stereo-vision) also allow *object-lines* extraction from images.

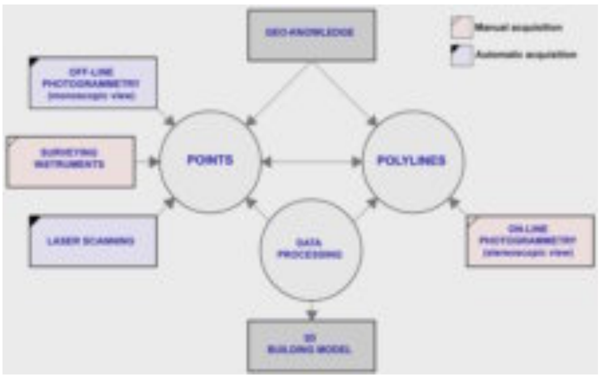

Figure 1. Geo-technologies for building knowledge

Point density and model precision are strictly related: only a quite high point-density can well describe objects and provide a proper referencing.
For instance, in the U. K., *English Heritage* sets, in its specifications for laser acquisition [Barber, Mills, Bryan, 2004],

the confidence level of the model quality by the following equation:

$$q = 1 - p/d \quad (1)$$

where: p - object grid step (linear resolution)
d - minimum dimension of recognizable details.

So, for a linear resolution of 10 mm and a minimum element dimension of 25 mm, the value of q = 0.6 = 60% is acquired, i.e. a 60% probability that particulars can be recognized.
It's obvious that random point acquisition, such as in automated technologies (motorized total station, laser scanner, photogrammetry based on correlation techniques), enhances surface description versus edge detection which is typical of the stereoscopic approach in photogrammetry [Berti, Bonora, Costantino, Ostuni, Sacerdote, Tucci, 2005].

3. TECHNOLOGIES FOR METRIC ANALYSIS

Different devices for detail acquisition (lines and points) are classified according to their precision level, sensor resolution and repeatability (stability along time), relationship between measurement process, environmental parameters and speed of acquisition.
Among these procedures, surveying laser techniques (reflectorless) provide a meaningful way to locate points (even if not accessible) over buildings walls, define structural edges, extract sections and detect settlements.
The acquisition process (based on time of flight, phase difference measurement or both) is conditioned by surface reflectivity (light or dark colour), roughness and irregularity, by beam angle of incidence, wavelength, divergence and spot size on the wall [Hoeglund, Large, 2005].
Photogrammetry still plays a relevant role for building description, thanks to the quality of plotting and work time. Its products are vector representations, but it's also possible to get orthoimages and 3D models.
Photogrammetric image keeps all geometric and thematic information that can be useful for further needs; both analogue and digital plotter provide vector output in close-range photogrammetry.
Digital plotters are classified according to their capability to provide stereoscopic vision (on-line systems) or mono-vision (off-line systems): the last one works in a semi-automated way, while searching homologous points for their spatial determination.
More recently, the new laser scanner technique is getting great interest for its relevant simplicity and speed.
This process is based on spatial point clouds acquisition; they have to be well oriented and overlapped, so as to avoid perspective occlusions and reduce too small angular points of view.
Laser scanner output, after raw data processing (noise filtering and point decimation in areas of simple geometry), consists of point or surface models, suitable to provide spatial description and suggestive video-sequences.
Till now, it is not simple to extract *vector edges* from point clouds, as requested for façades description: this way, close-range photogrammetry, with no doubt, provides better results [Gomes Pereira, Morgado, Pereira, 2004; Ikeuchi, Nakazawa, Nishino, Sagawa, Oishi, Unten, 2003].
Instead, section definition, from point clouds, can be easily made in a semi-automatic way, thanks to proper software [Colombo, 2003].

On the market it is possible to find many laser scanner devices, with different technical features and precision; their manufacturers provide basic tools for acquisition process, while specific packages are generally needed for post-processing.
These software procedures are available in a proprietary environment or as an AutoCAD plug-in: some are more specialized for point clouds collection and for point model reconstruction, other, instead, are devoted to surface modelling and photo-texture mapping.
Point cloud connection (*registration*) can be managed either with the support of signalized control points (plane or spherical targets) or by solving a matching process (*feature based*) between overlapped clouds, like the one requested for images in off-line photogrammetry.

4. SURVEY APPLICATION

The described on-going application regards the Cathedral of Santa Maria Maggiore in Bergamo Alta (Figure 2); the monument (built in 1137) represents the *votive chapel* of the city and one of the most important building, belonging to the commune age, which includes the Colleoni Chapel (Figure 2), wanted by the same famous commander as his funerary chapel. In the Church, it is worth-while quoting the famous Lotto's marquetries and the composer Donizetti's grave.
The inner geometry of the Church is nearly like a little bit lengthened Greek cross, with three naves and a presbytery; the exteriors are irregular and without architectural homogeneity.

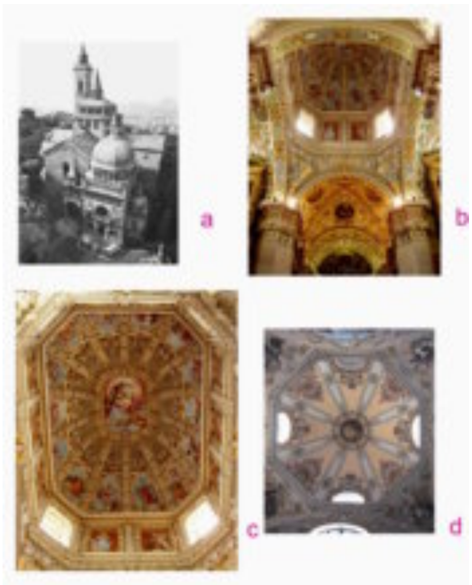

Figure 2. Basilica and Colleoni Chapel outside (a) and inside (b), with the two domes (c, d)

5. THE SURVEYING NETWORK

The lack of a geodetic network, suitable to reference the building, demanded its design and measure.
Survey scales (level of detail) are fixed to 1:50 for plans, sections and decorated walls, 1:100 for 3D model and façades, and 1:200 for 3D modelling inside Internet.
The plano-altimetric network has been designed and measured as a redundant surveying scheme (*r.m.s. = ± 5 mm*); all the

vertices were located, so as to last in time, graphically documented and calculated in Gauss-Boaga and UTM-WGS84 reference systems [Colombo, Marana, 2005].
The surveying network has been adjusted in a local reference system, projecting all distances onto a local plane at the mean orthometric height (so, the linear deformation of map projection is not applied): this choice allows keeping the true dimension of the building, with coordinate differences, in point position, of about 3 cm.
The 1:200 representation scale (detail points) has a predefined *tolerance* (given by 0.4 mm · denominator of scale) of 80 mm, the 1:100 scale of 40 mm and the 1:50 of 20 mm.
During network adjustment, the tolerance was set equal to 10 mm, half of that established for 1:50 scale. Later, thanks to some *tie points*, known in both reference systems, vertices have been translated in height and roto-translated in planimetry into the Italian (Roma40) and the international (WGS84) datums.

6. PROFILES AND DETAIL MEASUREMENT

The wall thickness acquisition, which is still in progress, needs the survey of the building internal and external profiles.
After the interiors acquisition (horizontal profile at 1.50 m over the floor level), through a motorized total station (with and without reflector), it was planned a point position testing by *trilateration* method with hand-held rangefinders.
Trilateration has proved to detect possible random errors (related to laser spot dimension, uncertain morphologies, and so on) in reflectorless measurement and to fulfil survey lack in detail (pillar section, doors, niches, mouldings, permanent church ornaments and zones with low visibility).
Motorized polar survey and trilateration process are, in this case, two independent methods of similar precision: so, the admissible difference Δ, between two positions for the same point, can be expressed as $\Delta = \sigma_{population} \cdot \sqrt{2}$ and, for this application, the value is $\Delta = \pm$ (1-2) $\sqrt{2}$ cm.
When the shift threshold is lesser than 1 cm, it was decided to select the position acquired via total station.
The external profile of the building has been instrumentally surveyed starting from the network, reconstructing the geometry of the ground line: this is due to altimetric irregularities and reduced working spaces for the areas surrounding the building.
This profile has been integrated with additional acquisition, at different height, so as to better describe the wall thickness of the building structure.
Vertical sections (longitudinal and transversal) are an important geometric tool to know a building shape and its dimension: motorized laser instruments, with reflectorless and/or scanning devices, allow an *easier* and *faster* graphical representation.
In the study over the Basilica of Bergamo, a significant number of vertical sections has been surveyed according to the directions of the main axes of the naves and of the transept.
Along these alignments, there have been signalized and determined 15 vertices devoted to automated sections acquisition over the vaults and the dome.
Data acquisition is supported by software, setting the zenital sector of interest (starting point-ending point) and also the angular or linear step between two following points.
This way, there have been measured nine vertical profiles on the Basilica interiors (Figure 3), suitable to describe the building morphology, and two profiles on the Colleoni Chapel; a number of different stations, from one to five, has been used for each profile to avoid perspective occlusions. In the same figure, it's possible to see, described with different colours, the height levels of the building floor (light colours for *lower* level areas and dark colours for higher ones).

After some preliminary tests, a constant angular step Δα equal to 0.2000 gon was selected; according to detail distances, this choice assures an interval between following points equal to 6-12 cm.

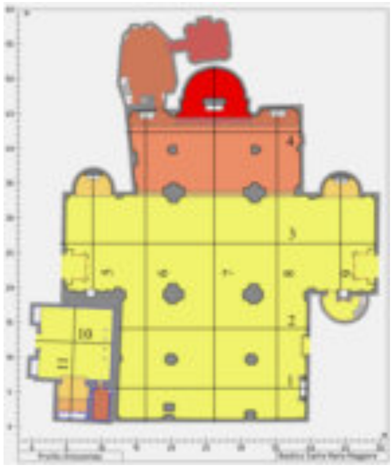

Figure 3. Internal plan of the Building, with tracks of measured profiles (transversal: 1, 2, 3, 4, 10; longitudinal: 5, 6, 7, 8, 9, 11)

It is possible to write the *linear step* between two detail points as:

$$\Delta S = r\,\Delta\alpha. \qquad (2)$$

If Δα is considered as a constant, it is the distance r from the station, with its variability, which sets the acquisition interval ΔS.
By differentiating the previous equation, it is possible to write:

$$d\Delta S / \Delta S = dr / r + d\Delta\alpha / \Delta\alpha. \qquad (3)$$

If it is acceptable to assume $d\Delta S / \Delta S \leq 10^{-1}$, i.e. a 10% relative variability of the interval, it follows $dr / r \leq 10^{-1}$, which means an admissible variability of the station-point distance within 10%.
Detail points show anomalies (*shadow zones*) due to the station position and morphology of the corresponding surfaces of the building; measurement from different stations is necessary to overcome these problems and to acquire a hardly complete vertical profile (Figure 4).

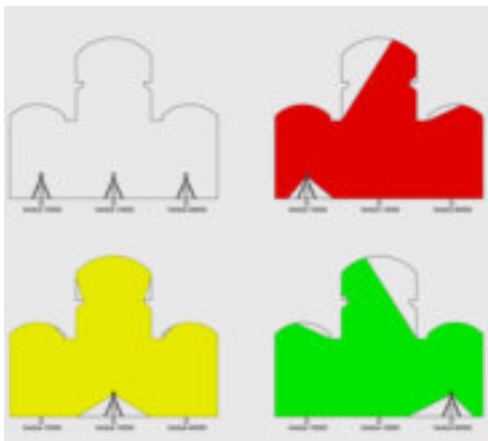

Figure 4. Example of profile acquisition

It has been also observed that the structure complexity (decorations, different prominences and recesses) and relevant dimension need further acquisition also at levels higher than the floor.
As an example, figure 5 describes the building main sections profiles, which involve the octagonal irregular dome of the church, whose geometry is due to the XVI century design of the architect Francesco Maria Richini.
Anyway, each section representation is composed not only by the measured profile, but also by the details proper of the *background*. So, a complete description of a section can be obtained, for instance, by the aid of digital photogrammetry, performing rectification of images, their mosaicking and superimposition onto the section plane; on the contrary, if the background surface is irregular, this representation has to be carried out by laser scanning; this way, a set of point clouds are collected, connected together and ortho-projected over the section plane.

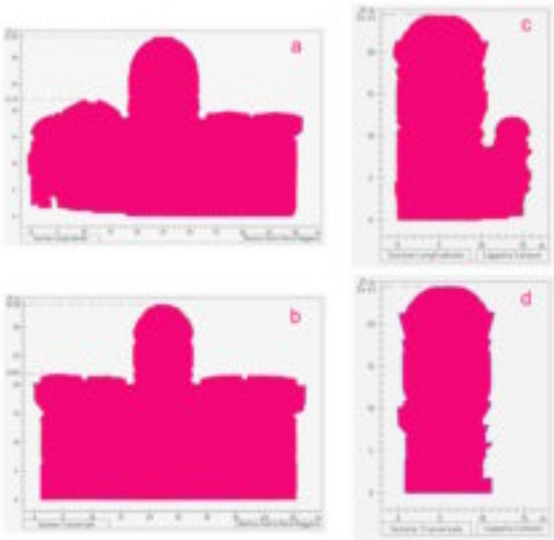

Figure 5. Main profiles, longitudinal and transversal, of the Basilica (a, b) and of the Colleoni Chapel (c, d)

All the horizontal and vertical profiles were automatically registered in a building wireframe model (Figure 6), useful for a first volume investigation.

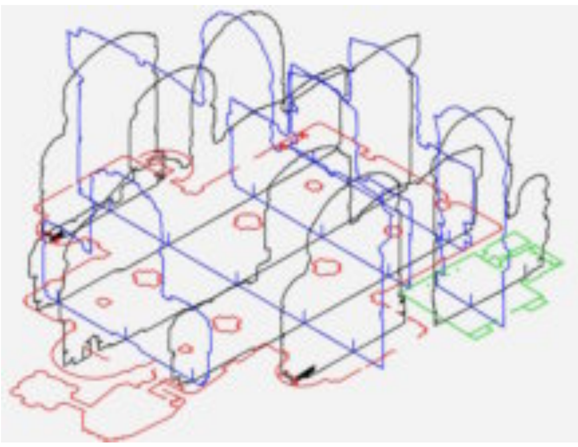

Figure 6. Wireframe 3D model, with horizontal and vertical profiles

7. AN ANALYSIS INVOLVING THE BASILICA DOME

A geometrical analysis has been performed over the Basilica dome, utilizing the main longitudinal and transversal profiles (figure 4- a, b).
Setting a three-dimensional reference system (the origin is set at the intersection of the longitudinal and transversal building axes), with the x and y axes over the floor plane (respectively, along the longitudinal and transversal direction) and the z axe in orthogonal direction, the longitudinal section belongs to a plane parallel to the (x, z) one and translated of a quantity nearly equal to y = 2.2 m; on the other side, the transversal section lies in a plane parallel to the (y, z) one and is translated of about x = -2.2 m.
Analyzing the collected points, the maximum height results, for the longitudinal section, in the point of abscissa x = -2.176 m and z = 33.915 m; for the transversal section, instead, the point has ordinate y = 2.186 m and z = 33.923 m. This way, it's possible to realize that the two sections have a common maximum which correspond to the vertex of coordinates $x \cong -2.18$ m, $y \cong 2.19$ m (as expected) and has a value of $z \cong 33.92$ m.
Both profiles have been interpolated, with MatLab software, selecting *robust estimate* methods: the process used polynomials of different degrees and stopped at the 4th one, to prevent instability. Looking at figure 7, it is possible to see at sight how the architectural behaviour of the two dome sections (blue crosses) is well described by the two interpolant polynomials (red line).

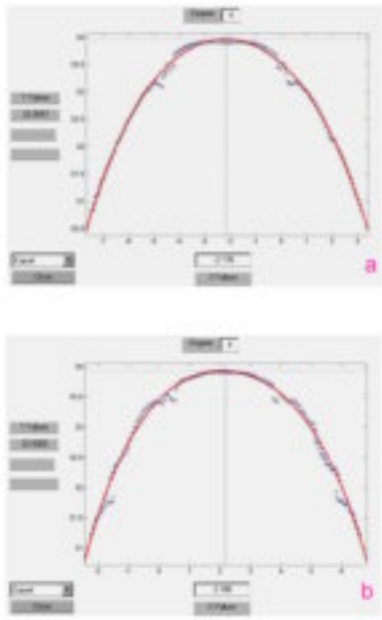

Figure 7. Robust interpolation of the longitudinal (a) and transversal (b) profiles measured on the Basilica dome

8. LASER SCANNING APPROACH

In the last four years, some tests have already been executed, over the building, to survey different structural elements (Northern protirum, Basilica apse, Colleoni façade), by means of laser scanning and image mapping techniques. The aim was to compare different scanning devices and post-processing

software, in order to select the best tools to create a 3D model describing the whole structure of the church and of the Colleoni Chapel.
The performed experiences involved at first Riegl devices and then Cyra technologies, for data acquisition, and packages such as Polyworks Modeler (InnovMetric), RapidForm (INUS technology), Cyclone (Cyra) and Reconstructor (Inn.Tec.), for post-processing.
In particular, Leica HDS2500, a re-branded Cyrax 2500, has been the final choice for surveying the dome intrados: in fact, the combination of high accuracy and field versatility makes this scanner ideal when tripod mounting is not practical and field-of-view requirements are less stringent.
A complete description of a complex 3D object, as the Basilica dome, can be obtained only scanning it from multiple points of view, also at a different height level, in order to avoid or reduce *geometrical shadows*; at the same time, it is possible to acquire range images with a more regular point distribution when scanning directions are almost perpendicular to the selected object surface.
In the case study here described, the decorated intrados (fresco paint and stucco relief) of the dome has been surveyed from 17 points of view, providing 9 range images from the floor level, in order to survey the whole transept, and 8 from the four corner windows at the tambour level, to complete the description of the zones above the trabeation (Figure 8 a, c).

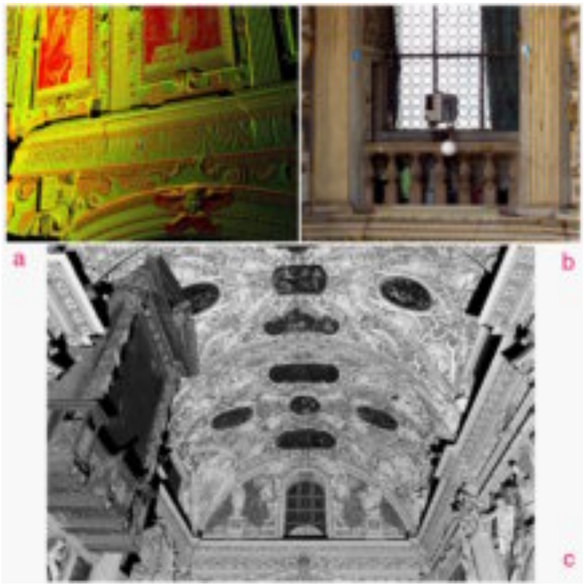

Figure 8. A range image related to transept (c), a cloud acquired at the tambour level (a) and Leica HDS2500 with planar targets and spheres (b)

Some points were signalized over the surveyed surfaces with targets (*planar, tilt and turn* and *spherical*): a few of these have been used as control points for cloud registration purposes and quality assurance, others (determined with a reflector-less total station) allowed the spatial transformation (geo-referencing) of the whole point-model in a previously defined reference system. Therefore, both planar targets, automatically identified and extracted during the acquisition phase by Cyclone software (from Leica Geosystems), and polystyrene spheres were adopted (Figure 8 b). An interactive software procedure has been arranged to recognize spherical targets: their position is at first manually selected on the range image and then a *script file* was developed to refine the acquisition through a higher resolution scan of a small area surrounding each of them. A best fitting estimate, applied to spherical targets provided a set of tie points (*the sphere centres*), well defined in every range image: in fact, these isotropic targets are more independent from the scanner position (for instance, planar targets, if nearly aligned with scanning direction, could be wrongly detected).
In every cloud related to the dome, it was possible to recognize automatically from 4 to 8 reference points.
Laser scanner survey can be considered as a first step to reconstruct a 3D surface model of a building; different kinds of data processing have to be applied, both in automatic ways and in interactive ones:

- pre-cleaning data,
- filtering noise data,
- data segmentation,
- data reduction,
- surface triangulation,
- surface editing.

A wide photographic documentation has been taken for the interiors of S. M. Maggiore with a digital calibrated camera (D1 by Nikon), in order to collect both metric and non-metric images useful as photo-textures for the Virtual Reality model reconstruction [Tucci, Algostino, Bonora, Chiabrando, 2003].
The referenced point model represents a detailed archive of geometric information about a case study; profiles and sections of the object can be easily extracted, according to any different spatial plane. On the contrary, instrumental profile acquisition needs a preliminary cutting-plane location, at the accuracy requested for representation.
This way, longitudinal and transversal vertical sections (with their orthographic *background*) of the S. M. Maggiore dome were defined as shown in figure 9 (a, b); the transversal profile is detailed in figure 9 c. Figure 9 (a, b) represents a partial point model, reconstructed only with clouds acquired at the floor level: in fact, black areas above the cornice represent missing information which can be overcome with scanning performed at the tambour level.

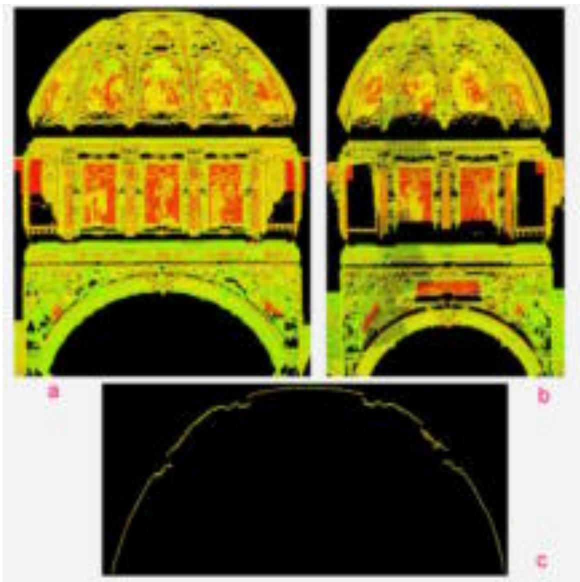

Figure 9. Longitudinal (a) and transversal (b) sections of the S. M. Maggiore dome, together with the transversal profile (c)

At this time, some more work has to be developed and it's possible to identify the following steps:

- processing of all the acquired data to reconstruct a 3D model of the dome with photo-textures [Georgopoulos, Ioannidis, Daskalopoulos, Demiridi, 2004].
- analysis of the building geometry, with a careful comparison (according to accuracy, time consuming and cost parameters) between profiles acquired by different techniques, i.e. motorized total station profiling and laser scanning point model extraction [Tucci, Bonora, Sacerdote, Costantino, Ostuni, 2004].

However, in addition to 3D models, 2D sections really represent a very important tool to investigate historical buildings and a synthetic and exhaustive way for architectural description.

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