MULTIPLE DATA SOURCE FOR SURVEY AND MODELLING OF VERY COMPLEX ARCHITECTURE.

F. Fassi*, C. Achille, L. Fregonese, C. Monti

Politecnico di Milano, BEST Department, Milano, Italy
(francesco.fassi, cristiana.achille, luigi.fregonese, carlo.monti)@polimi.it

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ABSTRACT:

In this paper we would like to present a possible operating way to survey and model a very complex architecture, integrating different kinds of instrumentation and modeling methods. In particular we would like to convoy the attention on a possible measure and data elaboration procedure that allows collecting and post-elaborating data in a short time in order to both extract classical architectural products, such as sections and profiles, and to build complete and accurate 3D models. The necessity is to structure multi-data source procedure buds inside a five years project (still in progress) with the goal to survey and three-dimensionally model the Main Spire of Milan Cathedral. It is a very complex "object" and, for this reason, it can be considered a very challanging and useful test field for the new 3D survey technologies and, in particular, for the various "real-based" modeling methodologies. In the paper are described the survey workflow and the relative elaboration steps, focusing on the problems and justifying the key choices.

1. INTRODUCTION

1.1 The study case

Figure 1. On the left, a global view of the Milan's cathedral with its main spire, object of the research. On the right, the base of the dome cladding taken by an UAV helicopter.

The five years research project has its aim in surveying and modelling the major spire of Milan Cathedral. The project is commissioned by the Veneranda Fabbrica* in order to renew old drawings (made at the beginning of XX sec) and measurements of the main spire in function of the forthcoming extensive restoration works to be completed for the International Expo in 2015. The main aim is to know the state of health and the geometry of the spire in order to prepare and support all the restoration operations. Classical plans and elevations, plus an accurate 3D model, are required for future visualization, informative purposes and as a support for the restoration work, the strength measurements and the deformational analysis. For our research activities, the job is an interesting test of comparison for different kinds of survey methodologies and it will be the pretext to identify an "operating way" to model such a huge and complex structure using different measurement sensors and to elaborate the result integrating together all the different acquired data.

* The Veneranda Fabbrica is a complex pyramidal organ, with different operational sectors, all of them functionally related to the life of the Duomo, both in the monument's conservative dimension and in the liturgical-pastoral expression, which depends on it. In particular, the Fabbrica provides for the restoration and the preservation of the stone manufactures and for the maintenance and the renovation of the systems, furnishings and machinery.

1.2 Milan Main Spire

Built in 1774, four centuries after the start of construction of the Cathedral, by Benedetto Croce , the term "Main Spire" identifies the unitary block that overtops the main vault of the Cathedral and it is divided into four main parts:the structure of the octagonal lantern, containing the dome;

- the architectural complex apparatus, composed of four "Gugliotti" and sixteen small spires;
- 8 flying buttresses;
- the large central spire, that reaches the height of 108.50 meters.

The spire itself may also be considered composed of four distinct parts:

1. the octagonal base, which is 9 meters high, rests directly upon the lantern and it is connected with eight flying buttresses to the side walls, that rise from the lantern;
2. the octagonal prismatic pipe, which is 19.40 meters high, surrounded by eight columns. Between these columns and the central pipe rotates the spiral staircase that leads to the last landing terrace called "Belvedere";
3. the finely decorated terminal pyramid with its 9.77 meters of height;
4. the Madonna statue, made of gilded copper (about 5 meters high) universally known as the "Madonnina".

The total height of the spire, including the statue, is about 43 meters and it rises towards the sky reaching a quote of about 65 meters above the floor of the Duomo.
As everything else in the Milan's cathedral, also the "Main Spire" is made of Candoglia Marble.

2. THE SURVEY

The survey secures the return of the geometric-morphological knowledge of the complex object in a three-dimensional way, underlining both the structural and the decorative plan. The metric texture mapping will be completed by the acquired images, obtained through a rigorous photogrammetric process. The survey process relies on the integration of global and local techniques that can ensure a 360° coverage of the monumental complex. It is designed for the nominal medium scale of 1:20, reserving the scale of 1:50 for the less accessible portions that do not affect the general purpose of the task. (Monti, 2009) The choice is to use all the survey methodologies that can provide an accurate "3D virtual image" of the object: topography, laser scanner and close range photogrammetry are used to integrate the different data together in order to complete the whole object model and, in particular, to recursively check the single results and overcome limitations , different difficulties and misdeeds of each single methodology.
For a better operativity, the whole object is divided in different macro-areas surveyed and modelled separately:

- the intrados of the main vault,
- the extrados of the vault,
- the base of the dome cladding with the 8 flying buttress,
- the inner low level staircase,
- the first Terrace (First Belvedere),
- the inner high level staircase,
- the second Terrace (Second Belvedere).

Even though every part is measured and modelled separately, every single element is georeferenced together in a topographic network anchored to the four roofs.

2.1 Topographic survey

The object geometry is quite complex, rich of decorations and with many narrow spaces. In this case it is very difficult to choose the right measuring methodologies. In particular the classical topographic architectural approach results to be a truly arduous work. Nonetheless the topographic measurements remain essential to georeference all the data together, check the results throughout the several elaboration steps and try out the final results.
A relative complex topographic net is materialized with 4 rigid measurement rings: one at the quote of the cathedral roofs, one on the dome cladding, one the first Belvedere and one on the last Belvedere. All these measurements are blocked and connected with the iper-determined high precision measurements previously taken inside the central dome for the static control of the whole structure. Besides the usual target coordinate measurements, some deep direct architectonical measurements are conducted from the materialized base stations, in order to check the accuracy of the model elaborations and to complete some parts that cannot be surveyed in other ways. The topographic measurement phase present some difficulties, due to the behavior of the laser total station distancemeter on the marble surface -this subject will be more accurately described in the next paragraph-, as for now we bypassed the problem applying "mobile targets" during the acquisition.

2.2 Laser scanner acquisition.

A complete laser scanner survey obviously seems to be the right and natural choice to obtain the whole 3D point model of the object with the aim to extract, from the enormous amount of data, the relevant desired information. The instrument at our disposal is the Leica HDS6000, a Phase Shift Scanner with a very fast acquisition time (500000 point/sec). This is an ideal characteristic for the survey of such a "huge object" both for the scanner acquisition speed and for the extremely high resolution reached. In this case the Candoglia Marble does not lend itself easily to be surveyed because of its crystalline structure. (Godin, 2001) This type of scanner presents a lot of problems, due to the raw marble surface, especially in the places where the objects are too close to the instruments. In particular a serious penetration of the laser beam in the heterogeneous material causes grooves in the data and systematic evident errors in the distance measurements. In some cases, as for example on the high part of the marble staircase, we got errors of 3-4 centimetres. The problem can be partially overcome by reducing the laser power.

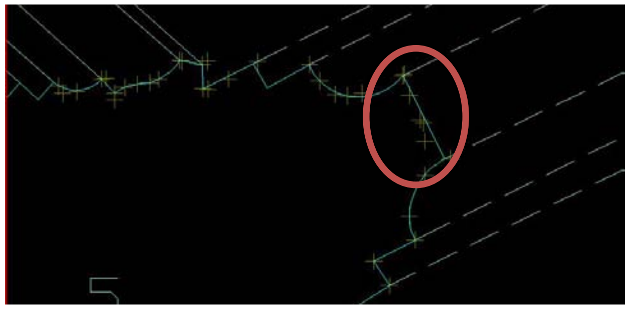

Figure 2. Detail of topographic measurements made as a sample survey to check the accuracy of the extracted horizontal sections. In the red circle it is possible to see some measurements with evident errors (more than 1cm) due to the behaviour of the laser distancemeter on marble.

We have also tested a TOF scanner, but with the same results: the situation in narrow places doesn't change. The scanner behaviour on the marble surface and the geometry of the "object" hints to choose another methodology to survey and model the spire. In fact modelling the laser data, that per se is not always a simple operation, results to be more complicated, inaccurate and sometimes even impossible. For example, a perfect registration of the several point clouds becomes impossible using surface matching algorithms. It can only be done topographically using measured targets.
However, the choice was to complete the scanning measurement, using them as macro-reference and crosscheck for the model (built in other ways) and as base to georeference together all the single modelled pieces. In fact, beyond the described problems and the general low accuracy in comparison of the expected laser capabilities, the single georeferenced scans are a good way to understand the complex geometry of the place and the misunderstandings during the difficult modelling phase. Another motivation to complete the scanning survey is the future planned visualization purposes where the scan low accuracy doesn't play a critical role.
In the images below it is possible to notice how the high point density allows a "tri-dimensional reading" of the object geometry in all its details. The following images are screenshots from the visualization window of PointoolsView, A relative new software that seems to be the best visualization package on the market today. It enables to visualize a huge number of points, coloured with the reflectance or RGB value, to take distance measurements, to extract points coordinates and to attach notes and external links to the models. Thanks to these simple operations and to the power of loading high resolution scans, a raw point cloud can already be a usable and useful virtual model without any post-elaboration or modelling requirements (excluding the necessary clouds registration). In

particular, the possibility to take measurements and load any 3D models format makes it possible that a "simple viewer" can already be a fast and sufficient way to understand the complexity of the geometry, and to provide an optimal instrument to perform simple analyses and virtual direct surveys on the model. The high resolution permits to directly use the raw points cloud for valid and immediate 3D visualization purposes or for operations where no extreme accuracy is required. As this is valid for architectonical and also for archaeological studies, the architectonic and restoration design cannot completely substitute the modelling phase and the accurate extraction of forms and geometries in the classical CAD format.
Flying through movies and stereographic visualization (also possible with PointoolView software) have been prepared and are planned for future demonstration, divulgation and for "museum entertainment".

Figure 3. A global visualization of the point clouds of the internal vault, the extrados and the spire with the dome cladding using PointoolsView. In these cases 1.6 billions of points are displayed and easily navigated.

2.3 Close Range Photogrammetry

For the described laser scanner issues and the difficulties with traditional method of architectonical topographic survey, photogrammetry is the natural choice. This approach leaves available oriented images useful for: i) a precise texture mapping, ii) rectified images for the description of the restoration operation and the classification of the material deteriorations and in particular iii) to create the 3D base model of the objects. In this case the difficulties remains in the orientation of a huge amount of photos and in the complete managing of all the oriented blocks. Moreover, the narrowness of the place creates lots of difficulties both in the acquisition phase, while planning and executing the right capture geometry, and in the photogrammetric image adjustment. In fact, choosing the right images to be oriented and getting an accurate results, both in the adjustment and in the image modelling phase, is a hard, manual and time consuming work. The main issue is to have the availability of more than two images for a single object with an optimal relative angle, due to the narrowness of the place. This provides a serious uncertainty in the XZ placement of the extracted 3D points. To minimize the problem, a good quantity of topographic control points had to be acquired to perform a better orientation, to make stronger blocks and to have a sufficient available number of check points in order to evaluate the accuracy of the final 3D restitution.

Figure 4. Some screen shots that show the registered point clouds of the dome cladding base.

For the photogrammetric survey we use a Canon 5D Mark II camera with a 35mm lens. The camera is calibrated on site simultaneously with the ongoing photogrammetric survey.

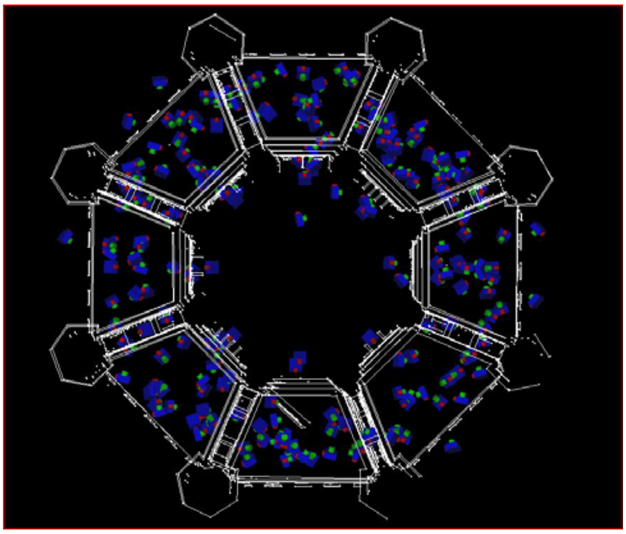

Figure 5. The plan view of the photogrammetric free block with the raw model of the first Belvedere.

The result is an ideal calibration , because it is done with the right operative camera setup needed for the survey. (Remondino, 2006) The full-frame sensor of 21Mpixel lets usacquire images with great resolution.
Untill now we have acquired and oriented approximately 600 photos, using about 1000 tie points and 100 between control and check points acquired topographically. According to our experience, in this case it is a better solution to orient the entire block of images of the identified macro areas. Even though this brings to a more complicated and hard block adjustment computation, it is possible to get better results in terms of mean accuracy. To divide the diverse macro areas in mini-blocks is surely an easier job, but it requires more photos, more control point acquisitions, and it also imposes to orient the same photos several times. Moreover, in this process the models, extracted from two contiguous micro-areas, have topological and connection problems that are very difficult to evaluate and correct in post-processing. On the other hand, the elaboration of a unique photo-block for the entire macro-areas spreads the errors in the whole block, offering at the end a better mean-accuracy.

3. THE MULTI DATA SOURCE MODELLING APPROACH

Taking into account what has been previously discussed, it is clear how the photogrammetric and the laser approaches have different specifications, different qualities and different negative aspects. The idea of integrating the methodologies may seem very obvious. The different sensors can be combined so that a methodology can come in aid of the other one, simplifying a process or increasing the final accuracy.
The task main idea is to follow a process of survey and elaboration that should be unique for both the 3D reconstruction purpose and the 2D restitution. Generally, two different approaches can be followed to achieve the two distinct aims. Topography and manual measurements are normally used for the construction of 2D drawings. That lets us collect information only of the parts that are sufficient to reconstruct sections and profiles. On the other side, 3D models are generally produced from 2D sections with a classical operation of extrusion. For relative simple objects, image modelling or extraction of 3D information from the laser scanner points cloud are becoming nowadays also a standard procedure. Normally this kind of restitution is made for visualization purposes and is generally more inaccurate than the classical architectonical products ordinarily used for professional purposes.
Our aim is to conduct a multi data source approach in order to concentrate the efforts on the construction of an accurate 3D model following only one of the two approaches, the 3D approach, and to consequently extract the necessary 2D information directly from the 3D.
This has three different benefits: i) the efforts during the survey phase are minimized; ii) it is possible to extract every future 2D information from the 3D model (while the vice versa is impossible) ; iii) it can suggest to the customer a new way to work and design moving from a traditional two-dimensional to a innovative three-dimensional logic, still not rooted nowadays in the professional daily activities. To achieve this result, it is evident how the 3D model should be really precise and that a good elaboration workflow is required in order to check the accuracy during the various modelling steps.
Inside this logic, the integration of different data set and the employment of a number of different sensors provides many advantages:

- Redundant information: when multiple sensors perceive the same feature of the environment, the redundant information can be exploited to reduce the uncertainty about feature status and increase the reliability in case of a sensor failure or in a situation where a sensor cannot work in optimal conditions, as it happened in this case with the laser scanner.
- Complementary information: multiple sensors may perceive different features of the environment at different scale, this consequently allows to measure and virtually re-build even complex features (which could not be sensed by each sensor independently).
- Increased robustness: the final elaboration of a single sensor can be used to control the product of another one or it can be integrated in another process to increase the final accuracy.
- Speeding up the acquisitional phase: the complexity and the dimension of the spire and in particular the site intrinsic difficulties, in relation to the placement and the positioning of the object, impose to chose the right methodologies in order to simplify the survey and overcome the acquisition problems. (Fassi, 2009)

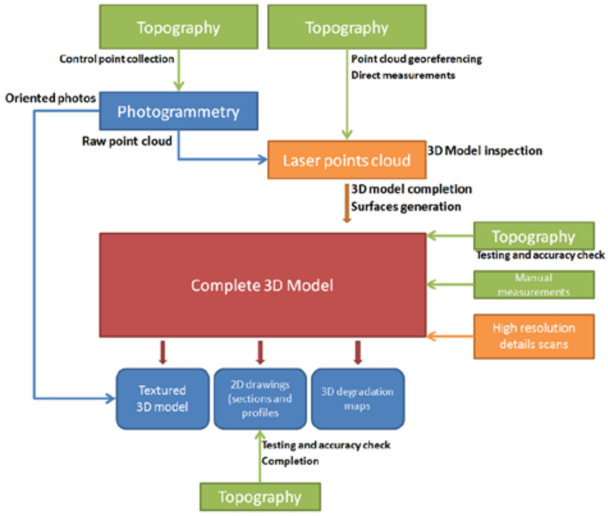

Figure 6. Summary schema of the projected modelling workflow

3.1 The first step: photogrammetric image modelling

The modelling phase begins from an approximate, but relatively complete, model based on the images. In particular, only those parts that can be called “linear based objects” are modelled photogrammetrically using the Photomodeler scanner.
This model is checked and corrected using sample topographic measurements (check points and profile points). The laser scanner data are also used to find gross errors, to check the global georeference and complete the model in a real 3D modelling space. At the end the model is integrated with manual geometric survey measurement for the smaller details or for the hidden zones that cannot be reached by any other instruments. Decorations and more complex “surface type objects” are scanned and acquired with small and dedicated sensors, such as for example triangulation scanners or structured light scanners, and are then integrated in the global model.
An additional difficulty is that the 3D virtual object is built considering all the single parts that compose its complexity: every constructive element is modelled individually, only then inserted in the global totality of the object and are topologically integrated with the other parts.
The image modelling approach provides an optimal level of “visual interpretation”, because it allows the extracting of

information that can be only acquired from images. On the other hand, the modelling capabilities of the photogrammetric software do not offer optimal 3D modelling and visualizating tools. Thus the model obtained from this first step is called "raw model", because it needs to be completed and built following the standard of the tree-dimensional modelling. Moreover, the accuracy of the photogrammetric models needs to be checked. It can be done using laser scans that provide a fast visual verification in order to find out macro-mistakes. Following: analytic comparison analysis tools (only applicable in the areas where laser data do not present the previous described problematic).

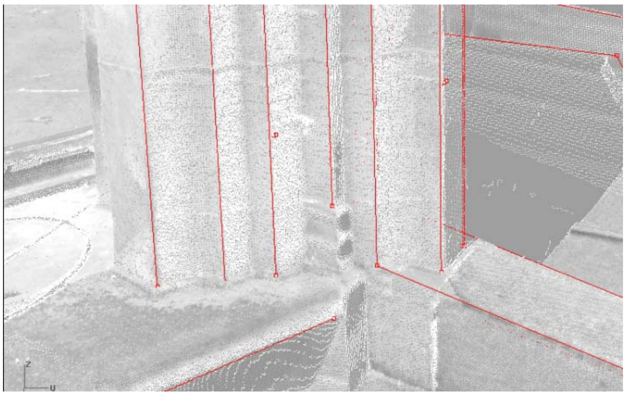

Figure 7. The model created with photogrammetric modelling superimposed on the laser cloud in Rhino. In this case it is possible to notice an evident good accuracy in the model. In Rhino is then possible to complete the model and create surfaces.

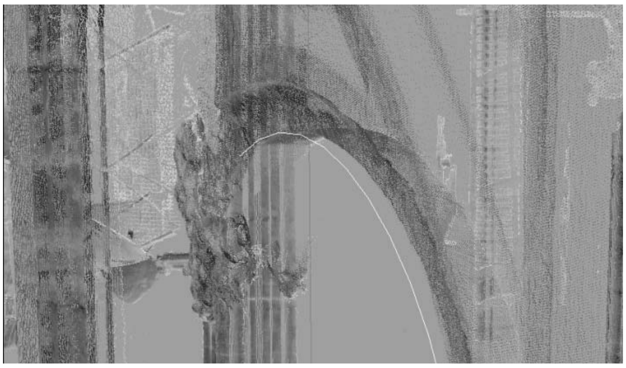

Figure 8. In the image it is possible to see some errors that can be found out comparing model and laser cloud. It is immediately possible to recognize the white arc modelling errors. In the photogrammetric procedure the lack of good angled images produces inaccuracy in the XY plan, as this case shows for the white curve. In the same images it can be also noticed how the laser surface present "a false raw surface". The entity of the problem should be evaluated case by case. Here the laser cloud can be used as reference to correct the modelling mistake just the same.

3.2 The second step: laser scanner check and modelling

The preliminary 3D model extracted thanks to image restitution is imported in Rhino, a well known modelling software that can create, edit, analyze, document, render, animate, and translate curves, NURBS surfaces and solids.

Since many free-form modellers are not accurate enough for manufacturing or engineering analysis, the modelling phase is always the most inaccurate: it results difficult to get the necessary modelling precision. Rhino is a modeller software but it is very close to the CAD logic and way of operate. Rhino, like most of the CAD products, represents position in double-precision floating-point numbers. This is the reason why Rhino is as accurate as other CAD products, as for example AutoCAD, and is, in our opinion, more accurate than any other modelling product, this not as much from modelling capabilities, but in terms of achievable accuracy. In fact,

Figure 9. Check of the final 3D model with the point cloud.

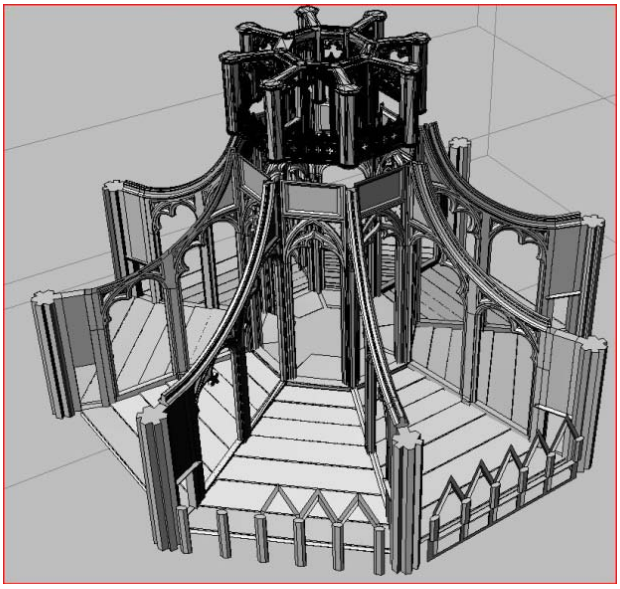

Figure 10. 3D model of the dome cladding and the first Belvedere at the moment.

Rhino provides tools for setting accuracy and units, as well as tools for controlling and evaluating continuity. Moreover there are no limits of complexity, degree, or size and it is also very easy to use and to learn. Rhino also supports polygon meshes and point clouds, but we prefer to use "Pointools for Rhino" that let us visualize inside Rhino a huge number of points with colour or intensity information using a series of shading options that are useful and indispensable to model on the point cloud in an optimal way. Importing the "photogrammetric raw model" in Rhino it is possible to check its precision directly in the 3D space using the laser scanner point cloud as a reference and even modelling the parts that could not be extracted due to the limited modelling capabilities of the photogrammetric software or due to the hidden and narrows areas that could not be reached photogrammetrically.

Moreover, after the check phase, it is possible to construct the real model generating the surfaces. In order to create a 3D degradation map, the whole 3D model is then cropped in the various blocks that compose the object. So every stone or marble block can be analysed, catalogued and labelled separately.

3.3 The third step: extraction of the 2D drawings.

With Rhino it is possible to extract 2D views automatically from 3D model, materializing every time the desired projection plan.

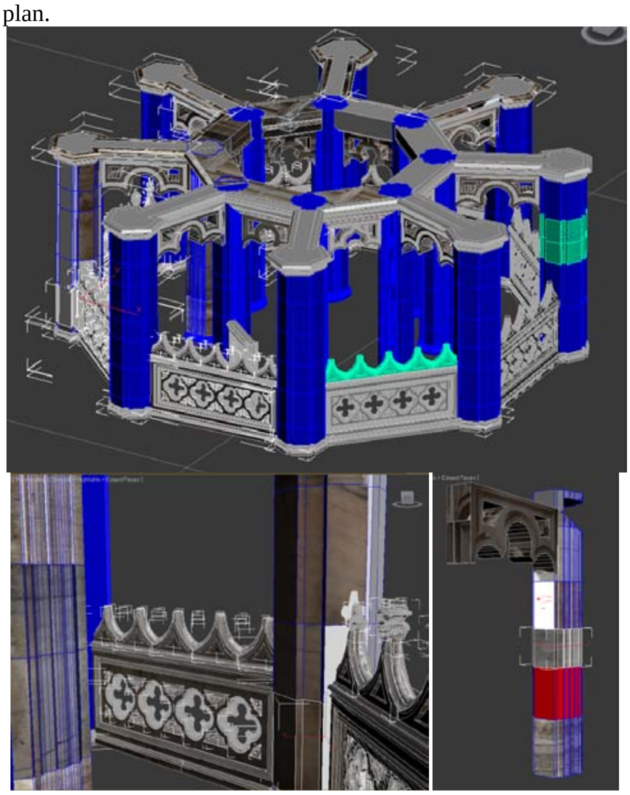

Figure 11. Every elements of the object is divided in blocks. In this way it is possible to add information to every constructive part, assemble and disassemble the entire object creating in this way a 3D degradation maps with which it is possible to elaborate an accurate conservation or restoration project , a mapping of the material and a pathological survey.

In this way it is possible to extract plans, elevations and different views. This “raw sketch” can be easily completed, settled, simplified and prepared for 2D prints. Extracting information from a complete accurate 3D model allows the extraction of all the desidered 2D information even throughout the progression of the works without being locked into forced and programmed starting survey design.

In this operation it is very important to control the accuracy and test that every measurement respects the representation scale. Yet another time again, sample topographic survey is useful to estimate and validate the data.

3.4 The fourth step: 3D model completion

The model is then integrated with the texture information using classical texture mapping procedures, or photogrammetric image re-projection for the areas where was possible to conduct a photogrammetric survey. Modelled decorations, such as statues and ornaments, can also be surveyed using high resolutions instrumentation and then added into the model. And this will be the last part of the future progression of the project.

4. CONCLUSION

This project has made it possible to test and compare different survey methodologies, meaning with “survey” both the measure and the elaboration phase. In such a complex test field as the described Milan’s Cathedral Main Spire, the usage and the integration of diverse instrumentation and modeling methodologies is absolutely essential. The aim is to turn upside-down the classical architectonical “2D thinking” that is bonded to work only with 2D logic, beginning from the survey phase until the last stage of elaboration. Since all of us were trained in the 2D surveying and engineering world this can be easily understood, but this kind of thinking is definitely holding back the overall adoption and benefits of 3D Laser Scanning and in general modeling capabilities. “*We all need to think in 3D.*” (Roe, 2010)

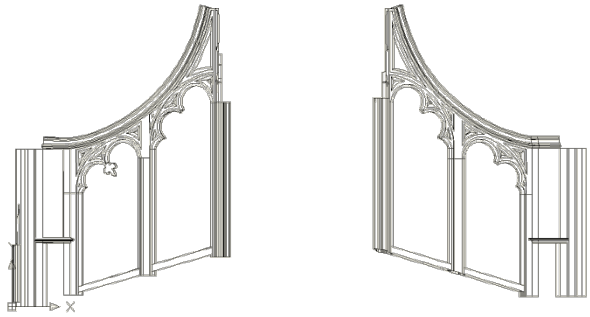

Figure 12. 2D prospect of two flying buttress extracted directly from the constructed 3D model.

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