Integrated Modeling and Monitoring of the Medieval Bridge Azzone Visconti

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Abstract
This paper presents the modeling and monitoring work related to the mediaeval bridge Azzone Visconti in Lecco (the “old bridge”). Metric information was acquired with different instruments and techniques for an integrated digital documentation that combines observations with variable precision: ±0.1 mm for the analysis of small vertical movements and subcentimeter precision for the geometrical reconstruction.

The complexity of the bridge, with irregular constructive elements and different materials, required a detailed geometrical survey with laser scanning and photogrammetric techniques for the generation of plans and sections along with an accurate 3D parametric representation based on Building Information Modeling. A strategy based on NURBS curves and surfaces was implemented to overcome the lack of BIM libraries for historical constructions. Modeling was carried out at a metric scale 1:50 by assembling BIM objects following the logic of construction of the bridge. A semi-automated strategy that incorporates point clouds was developed to use information gathered by other data sources, such as historical analysis, destructive and non-destructive testing, and existing documentation.

The monitoring project aimed at revealing vertical movements during loading tests. The measurement phase was carried out with a high-precision geometric leveling network made up of 47 benchmarks, resulting in redundant measurements adjusted via least squares techniques.

The combined use of (i) photogrammetry and laser scanning for the 3D modeling project and (ii) geometric leveling for the analysis of vertical displacements allowed one to capture the metric information needed not only for specialists in the field of surveying, monitoring and modeling, but also for the other specialists (architects, engineers, etc.) involved in the project.

1 INTRODUCTION

Nowadays, several instruments and techniques can be exploited for surveying, modeling and monitoring applications. Usually, a single measurement technique is not sufficient to cope with the complexity of large projects requiring accurate and detailed metric reconstructions [1]. Different algorithms and data processing methods were developed to automate the modeling pipeline and reduce the manual effort of specialists, i.e. interactive
measurements. However, in the case of complex scenes a strong user’s interaction is still needed because of the lack of automated solution able to interpret and understand the facility and its logic of construction (how the object is actually built). A deep analysis of the logic of construction is a fundamental requirement in projects in which the model is not only a graphical reconstruction for visualization purposes.

The growing interest in Building Information Modeling (BIM) requires not only geometric models, but also 3D parametric models with relationships between objects. Here, 3D reconstructions that go beyond the typical “pure models” generated with direct modeling techniques [2] are required.

The US National Building Information Model Standard Project Committee (2014) defines BIM as “a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition”.

BIM is therefore an innovative solution for the field of construction, where there is an increasing demand for efficient and smart strategies for the different stages of a project (design, construction, operation, maintenance, renovation, and demolition). Several private and public clients are adopting BIM to improve collaboration and reduce inefficiency. The European Public Procurement Directive (2014) is just another indicator of the interest in BIM technology. In fact, the directive provides a clear indication towards the use of BIM in public works (Article 22.4): “For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar”.

As mentioned, BIM relies on a 3D model made up of objects with a rich set of attributes stored in a database. BIM objects are defined as parametric objects with relationships to other parametric objects. The 3D model is not only a graphic representation of the construction, but also an advance computer technology to manage information for the automatic generation of drawings (sections, plans, etc.) and reports, design analysis, schedule simulation, thermal and structural simulation, facilities management, and much more [3].

BIM is also a great opportunity for experts in the field of 3D reconstruction such as photogrammetrists, surveyors, computer vision specialists, and software developers. Although as-designed BIM (i.e. BIM generated in the design phase of a facility) has reached a sufficient maturity for practical purposes, as-built BIM generation (i.e. BIM of existing facilities generated from a preliminary survey after the construction process, is still a challenging task in projects where it is difficult to capture, interpret and represent as-built conditions using a complete BIM workflow [4].

For these reasons, an accurate geometric survey of a complex facility is not a trivial task. A proper data acquisition plan is needed to answer the following questions:

• which instrument? do we need multiple techniques? how can we combine different data?
• do we need a stable reference system? are measurements taken at different epochs necessary?
• what about metric accuracy? metric scale?
• which level of detail?
• data acquisition time? data processing time? costs?
• ...

and much more. This means that the goal of the survey should be clear right from the start of the project in order to satisfy the requests of the customer. Then, the expert operator has to find a good compromise between instruments and techniques, data processing algorithms and
CPU time, data visualization methods and storage formats, etc.

This paper presents the modeling and monitoring results for the bridge Azzone Visconti, which is a mediaeval bridge located in the city of Lecco (Italy) (Figure 1). Several analyses were carried out to assess the stability and safety of the bridge, as well as the state of conservation of materials and structures. This paper illustrates the geometrical work carried out to provide detailed metric information from different data acquisition technologies and methods. In particular, during the project the following measurement techniques were exploited:

1) a geodetic network to provide a stable reference system;
2) laser scanning technology to acquire dense point clouds for an accurate 3D reconstruction of the bridge;
3) digital photogrammetry to integrate laser scanning point clouds and provide photorealistic metric products;
4) geometric leveling to determine the vertical movements of the bridge during load tests.

The goal was the generation of an accurate BIM of the bridge, as well as 2D project boards including photorealism (orthophoto) and more traditional vector drawings (CAD). Results on the inspection of vertical movements during loading tests are also described. Metric information was therefore acquired with different instruments and techniques for an integrated survey that combines observations with variable precision: ±0.1 mm for the analysis of small vertical movements during loading tests and subcentimeter precision for the geometrical reconstruction of the shape.

Figure 1: The bridge Azzone Visconti in Lecco.

2 DATA ACQUISITION AND PROCESSING

2.1 Geodetic network

A geodetic network can be extremely useful to create a stable reference system in large projects. The network is usually physically materialized by means of nails in the ground, retro-reflective targets, or prisms on top of stable nails. A total station, a set of tripods, and some reflectors are the equipment for data acquisition. Measurements are adjusted with standard least squares techniques.

The geodetic network has also another important function: if additional metric information (e.g. images and laser scans) has to be included into the project, the use of a geodetic network allows a reduction of error propagation. For instance, if multiple laser scans with an irregular
distribution in space (e.g. scans at different floors, outside and inside, etc.) are added with basic scan-to-scan correspondence (e.g. spherical targets), a progressive registration error is expected because of error propagation. The use of a geodetic network allows one to include some additional points with known coordinates. This can significantly improve the registration of additional data because error propagation can be controlled. This means that the geodetic network is useful (i) to establish a stable reference system, (ii) to check the accuracy of other measurements, and (iii) to control the deformation of an image- or scan-based survey: additional measurements can be incorporated into adjustment processes as pseudo-observations not only to solve for the “datum problem”, but also to reduce network deformations.

The geometric survey of the bridge started with the measurement of a rigid geodetic network (Figure 2) with a total station Leica TS30. The network is made up of 6 stations and the measurement phase took one day. In all, 834 observations and 264 unknowns gave 570 degrees of freedom. Least Squares adjustment provided an average point precision of about ±1.5 mm.

If the final survey needs georeferencing (i.e. Cartesian or geographic coordinates) some GNSS receivers allow the measurement of the geographic coordinates of some specific points with a precision better than ±1 cm (if static techniques for data acquisition and processing are employed). On the other hand, the survey of the bridge did not require georeferencing, except for information about the elevation above sea level, which was useful to compare existing drawings with new project boards. Starting from the geographic coordinates of two points measured via GNSS survey (latitude, longitude, ellipsoidal height) the orthometric height was obtained by estimating geoid undulation. Because of the limited size of the bridge (less 150 m), geoid undulation was assumed as a constant value and all Z coordinates were corrected with a constant.

![Figure 2: Geodetic network for the bridge.](image)

### 2.2 Photogrammetry and Laser scanning

A laser scanning survey made up of different scans taken from different station points was carried out to capture the irregular shape of the bridge. The complexity and the size of the bridge required 77 scans registered with the use of the geodetic network. The instrument used
is a Faro Focus 3D and the final point cloud is made up of 2.5 billion points. The instrument was placed in different positions, including the road and the riverbanks. The survey of the vaults required the creation of a mobile metal structure that allowed one to capture the intrados of the vaults (Fig. 3).

The network provided a robust reference system to remove deformation during scan registration. Scans were registered with an average precision of ±3 mm by using chessboard targets measured with the total station and additional scan-to-scan correspondence (spherical targets).

The laser scanning survey was then integrated with more than 500 images captured from a boat. Photogrammetry was used to generate accurate orthophotos of the elevations (South and North), the columns and the vaulted surfaces (intrados). Images were oriented via bundle adjustment, then orthophotos were generated by reprojecting multiple images on the 3D model. The last step was the projection of the textured model on a plane. Orthophotos were useful to analyze the object because they provide a photorealistic visualization. They were used in different stages of the project, for instance for planning the location of destructive and destructive analysis and a complete stratigraphic analysis. These analyses were carried out by different specialists involved in the project. In all, 35 orthophotos were generated with a scale 1:20 (Fig. 4).
3  MODELING VIA IMAGES AND LASER SCANS: FROM PLANS AND SECTIONS TO 3D PARAMETRIC BIM

Photogrammetry and laser scanning are measurement techniques able to capture the complexity of the objects thanks to the huge number of surveyed points. On the other hand, the direct use of raw models (i.e., those directly obtained without further processing) generated in a fully automated way (such as point clouds or heavy meshes) is not useful for a construction/restoration project. Starting from raw products, typical 2D and 3D representations used in the construction industry have to be generated. Plans and sections were created beforehand to fulfill the requirements of some specialists involved in the project, then BIM was used to obtain a 3D model with parametric functions and attributes.

The generation of plans and sections was carried out by setting specific cutting planes, that are commonly called slices. Horizontal slices provide the points of the original cloud inside a specific range \([Z-t, Z+t]\), in which the thickness \(t\) is usually set to 0.5\(±1\) cm. In other words, if the acquired point clouds have a good distribution around the object, the extraction of the slice provides a preliminary discrete representation of plans. The final plan can be obtained by connecting points with polylines. Obviously, this provides only the reconstruction for the chosen cutting plane and other elements have to be integrated, such as those visible for projection, e.g., those below the cutting plane. The same procedure can be carried out with vertical cutting planes, obtaining vertical sections. This part of the work still requires manual measurements performed by an expert operator for the lack of automated algorithms able to analyze the complexity of the objects, which is not only a geometrical problem, but it requires preliminary knowledge on materials, state of conservation, connection between elements, etc. This means that the logic of construction of the object (how the bridge is actually built) is an important factor which cannot be neglected in real construction projects, where the goal is not a 3D model for basic visualization purposes.

Fig. 5 and 6 show some of the plans and sections generated via manual reconstruction. In all, the project includes 2 elevations, 4 plans, and 21 sections.

![Figure 5: A global visualization of plans and sections.](image-url)
One of the aims of the project was the use of Building Information Modeling, that is becoming an essential task for construction projects. The goal is the creation of an interoperable BIM for the different specialists (engineers, architects, etc.) involved in the project. For this reason, the survey included a historical analysis, the identification of materials, technological aspects, stratigraphic analysis, and information from other inspections such as destructive and non-destructive inspections. This was useful for the generation of plans and sections, but it becomes fundamental for a BIM project. Indeed, laser scanning and photogrammetric techniques can reveal the external layer of construction elements, whereas a BIM is made up of objects with an internal structure.

Another aspect that was taken into consideration is the lack of BIM software able to provide a parametric representation of complex and irregular shapes, such as those of the bridge. This problem was overcome with the procedure proposed by [5], that allows the creation of parametric objects with NURBS curves and surfaces. The creation of the BIM was carried out by considering the requirements of BIM technology. The model is not only a virtual representation of the construction. It is an essential part of the project, where the different elements of the building become advanced objects with parametric functions. Elements can be modified without redrawing and are structured in a database. Objects have relationships to other objects, as well as attributes [6]. Building information modelling was carried out by dividing the different structural objects. Chronological, material, and
stratigraphic aspects were also taken into account. The final BIM (Fig. 6) is available in Autodesk Revit and A360 (for mobile devices).

Figure 7: The final BIM of the bridge in Autodesk Revit and A360.
4 MONITORING VIA GEOMETRIC LEVELING

Geometric levelling has a primary role in structure monitoring. It is based on the creation of a horizontal line of sight by means of a level equipped with a pendulum or a compensator. Levelling rods must have a regular graduation to obtain the scale of the levelled differences. According to the basic principle of levelling, the difference between two readings is the height difference. The process is repeated to obtain the height difference between backsight and foresight, so that the total height difference between widely separated points can be measured by combining the height differences of intermediate points.

In the case of the bridge, the use of an optical level with the parallel plate glass micrometers gave the opportunity to improve reading precision. Rods with 5-mm graduations were employed, for which the collimation of the nearest reading with an adjustment screw is directly connected to the displacement measured by a micrometer. This provides readings with a precision of ±0.05 mm, that are then estimated to ±0.005 mm.

The monitoring project of the bridge was carried out with 47 benchmarks. A benchmark is considered fixed if it is connected to the structure so that it follows its movement. The design of an appropriate measurement scheme coupled with precise measurements allows the determination of heights (and height variations for data taken at different epochs) with sub-millimeter precision. The design of optimal acquisition nets has a direct impact on the precision: series of closed loops with common points must be preferred to (i) improve the accuracy and (ii) to obtain an immediate check based on misclosures.

The final scheme for the bridge is illustrated in Fig. 8. The adjustment of the network can be carried out via least squares. The observation equations \( H_i - H_j = \Delta_{ij} \) give a design matrix \( A \) made up of zeros and ±1. The problem is in the form \( Ax = b + v \), where \( b \) contains the observations, and \( v \) is the residual vector. The solution is \( x = (A^TWA)^{-1}A^Tb \), where \( W \) is a weight matrix (identity matrix for the network of the bridge). Finally, the covariance matrix of parameters can be estimated as \( C_{xx} = \sigma_0^2(A^TWA)^{-1} \). The precision of heights (after least squares adjustment) was about ±0.15 mm for the different tests carried with different load conditions by means of a heavy truck. The network was measured at different epochs to determine vertical displacements with a simple difference of \( H \) coordinates. Points 10000, 2000 and 3000 were assumed as fixed benchmark because they are outside the bridge.

Figure 7: The leveling network with points on both sides of the bridge.

5 CONCLUSIONS

This paper presented the geometrical survey and the monitoring project carried out for the documentation and conservation project of the bridge Azzone Visconti (Lecco, Italy). The complexity of the mediaeval bridge, with irregular shapes and different materials, required the use of the most advanced measurement techniques: photogrammetry and laser scanning to
capture large point clouds that reveal the actual shape of the bridge, and geometric leveling to measure the vertical displacement during loading tests (precision of about ±0.15 mm). The use of a total station was fundamental to obtain a stable reference system in which all measurements are registered. The precision of the instrument coupled with a strong network geometry with several intersections allowed one to reach a precision of ±1.5 mm after least squares adjustment. Laser scans were registered with a procedure that exploits both scan-to-scan and scan-to-network correspondences, obtaining a precision of about ±3 mm. Finally, images were oriented with some ground control points for datum definition, obtaining residuals better than 10 mm for strips covering the whole length of the bridge. The obtained precisions were more than sufficient for the creation of accurate project boards at a scale 1:50, as well as a detailed BIM.

REFERENCES


