PARAMETRIC MODELING APPLIED IN WOODEN TRUSSES 3D RENDERING

○ Riccardo Gulli＊[1]
Davide Prati＊[2]

Keywords. : Generative algorithms; 3D modeling; cultural heritage; Terrestrial Laser Scanning.

1. Introduction

The analysis of the wooden roofing structures, historical trusses in particular, is present in scientific literature in many contributions, both in the disciplinary field of building science and construction technology, and in that of practical technology and restoration. Nevertheless, few studies systematically investigated the real behavior of these construction systems counting on experience and diagnosis in the field (Tampone, 1996) (Barbisan and Laner, 2000). This is justified by various factors, obviously including the fact that roofing structures are hidden and difficult to access, not attracting the attention of technicians and researchers, unless in case of severe problems of deterioration or obvious damage with consequences on people's safety. The roof is the area of the building most prone to deterioration and fire and is characterized by strong transformations and large substitutions over time.

The theme is therefore downgraded to an issue of minor importance for restoration, since the matter of study is no longer authentic or otherwise difficult to date. The interest is preserved only if these structures are left exposed and decorated or if they support valuable ceilings, for example frescoed surfaces. One of the main reasons for this lack of attention, however, lies in the fact that wooden roofs are typically indeterminate structures, whose safety depends mostly on the materials' quality and on the characteristics of knots and joints. In other words, it pertains to the art of building, to the practice of carpentry and for this reason it eludes scientific and analytical interpretations, if not at the cost of large approximations.

The study proposed here is based on an accurate geometric and material survey of all constructive elements and proposes the application of generative algorithms aiming at reconstructing a three-dimensional model of historical wooden trusses starting from a laser scanner survey. On the one hand, the analysis aims to give importance to this kind of constructive elements, neglected in the literature, identifying also new functional types, on the other it is used as an effective investigation protocol, with high diagnostic capability due to the wide use of technologies.

2. State of the art

Studies on wide span roofing, especially trusses, are usually based on important textbooks (Émy, 1841); many classifications proposed in literature are the outcome of nineteenth-century technical sensitivity, that used to force complex and partly structurally undetermined systems into simplified and calculable schemes. In the recent past, some historians of architecture and construction used to identify structural systems types within these constructive systems, highlighting their behavior based on strongly simplified theoretical hypotheses (Munafò, 2002) (Valeriani, 2006). Most of the technical solutions identified for possible consolidation, safeguarding and conservation policies, have often been based on these simplified hypotheses and on preliminary analyzes carried out with hurried surveys. The intervention logic was based most of the times on the idea of forcing the behavior of these structures into well-known or typical schemes.

Regardless of current approach to the problem of preservation of historical roofing structures, the research assumption is that digital technologies for surveying allow extrapolating new and original considerations that would be almost impossible following traditional methods of investigation, based on direct observation or on simplified architectural survey. If use of TLS for surveying complex architectural surfaces is not new and is matter of many researches in restoration field, rarer, or even absent, is its use applied to the study of hidden spatial structures such as wooden roofing. The outline hypothesis was to exploit the large amount of geometric data, which can be acquired by the TLS device as 3D point clouds, in order to read wooden trusses in detail and then gather specific and comparative information on their static behavior and on their conservation status.

Shaping of wooden trusses follows a very precise and often ignored construction practice, linked to the possibility of raising all elements up until the base of the roof, to readjust them, assembling them through other ancillary supports and fix them together using metal brackets. Nowadays the joining system of wooden elements has completely changed with the introduction of metal plates and the possibility of numerically verifying each part of the artifact; then retracing the original logic of the junctions is a de facto non-trivial procedure. Palladian trusses, for example, are notoriously distinguished in classical and composed ones, but within these categories there are many diversifications. These depend on a series of factors: different ways of assembling the linear elements to form longer tie rods or rafters with larger cross section, more or less accentuated stiffness of the knots, due to the carving of notches and to fastenings, presence of more or less brackets and other characteristic details (Lamborghini, 2014) (Zamperini, 2015, 2013).

Large and detailed geometric information provides very interesting data to perform an accurate 3D rendering of each truss into a single roofing but also to evaluate even slight differences in the static schemes of different wooden trusses used to cover different roofs.

3. The case study selection

Since many religious buildings, built between the 16th and 18th centuries, have been pinpointed in Bologna territory with pitched roofs made using wooden trusses, an investigation protocol has been set up in order to systematize the analysis of these roofing systems. This protocol was tested on the Cathedral of San Pietro, the church of San Salvatore Maggiore, the church of San Giovanni in Monte, the Basilica of San Petronio and the Basilica of San Domenico. This choice was due to the fact that these religious buildings were built almost in the same years and are all dimensionally significant.

The protocol includes an **acquisition** step followed by the digital **rendering** of the acquired data. This last step provides many **outputs** (photos, drawings, graphs and models) that constitute the operative tools to define and correctly interpret the behavior of the constructive systems studied. **Results** interpretation therefore allows us to suggest the most coherent design solutions, disengaging them, where necessary, from usual and standardized techniques (Prati et al., 2016).

Although some significant results were obtained applying the described method, several critical issues were found, mainly regarding the step in which simplified 3D models were generated (**rendering**). Vectorization of orthophotos strongly depends on the operator and has a low degree of repeatability and precision. Given the size of these artifacts, moreover, it is not possible to resort to the automatic generation of meshes, since the point clouds are largely incomplete and extremely articulated.

To overcome these difficulties, it was considered suitable to review and improve this rendering step within the research protocol. In order to develop and test this new approach in 3D model generation, the case study of San Domenico was chosen among those already investigated. In this way it was possible to compare the obtained results, so as to evaluate any improvements in terms of precision and accuracy, in relation to time spent and process automation (Kalyan et al., 2016) (Bello Caballero et al., 2017).

The choir roofing structures' circumscription and their easy accessibility allowed to carry out a good TLS survey campaign[1]. These trusses, with a wide span of more than 16 meters, have a configuration of Palladian queen post truss with side queen posts that build up the joint with the straining beam. The under-rafter stops at the level of the straining beam while the upper-rafter continues up to the ridge ending in a small central connecting king post. Their simplicity, authenticity but also their remarkable construction quality and the historical importance of the entire building, suggested to choosing these elements to try the new model generation method.

4. The 3D model generation procedure

In the previous method, it was necessary to perform "vectorizing" operations of frontal orthophotos of each truss, from which to draw 2D drawings and 3D models (Figure 1).

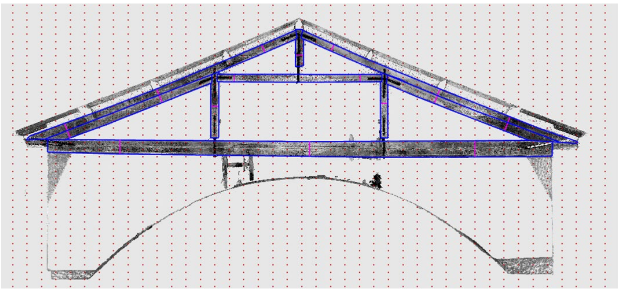

Figure 1. Point cloud of the Chorus of San Domenico church.

To avoid operating with excessive approximations, it was decided to transform the point cloud into 3D models using parametric modeling tools such as generative algorithms. These algorithms, once created for a single truss, allow to automatically generating 3D models of all trusses, changing only input parameters. This procedure allows saving a considerable amount of time and eliminates many of the inaccuracies identified by adopting the previous vectorization method.

After extracting from the project point cloud only the portion representing the truss object of study, a few clipping boxes are created in strategic positions close to the knots. Size and orientation of clipping boxes varies according to the sectioned beam, remaining as orthogonal as possible to each beam itself (Figure 2).

Figure 2. Red rectangles indicate the clipping boxes used for the sectioning of a truss point cloud.

These sections are exported as orthophotos in a 3D modeling software, Rhinoceros. Exporting takes place at the original coordinates of the section without the need to create additional reference systems or to make further alignments. This task is done entirely by keeping fixed the global point cloud's reference system (Figure 3).

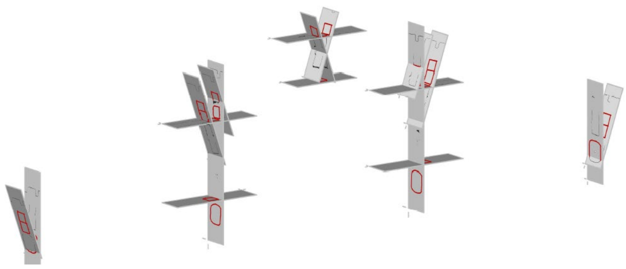

Figure 3. Orthophotos of the clipping boxes exported in 3D modelling software.

After exporting orthophotos of all sections, their vectorization is performed manually. This is the only non-automated operation within the present modeling method. The model generation process is defined using Grasshopper, a Rhinoceros 3D software plugin. First of all, section curves previously obtained are implemented as input parameters. This means that the final output of the entire algorithm (Figure 4) will depend exclusively on inserted curves (Rrapaj, 2018).

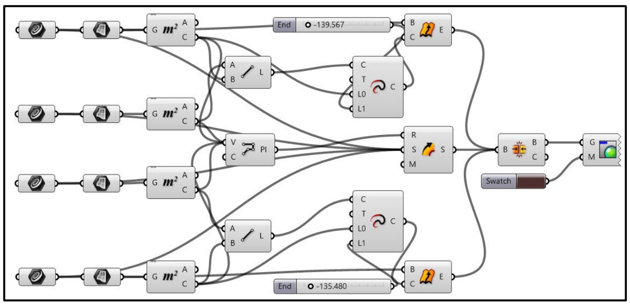

Figure 4. Modelling process of a truss element created with Grasshopper's generative algorithms.

Each box corresponds to one of the implemented operations. Starting from the left, the boxes represent the section curves that are the input parameters. Then the algorithm transforms the implemented curves into surfaces, operation represented by the next column. Once identified surfaces surrounded by input curves, the algorithm calculates their area and the center of gravity of each of them and then draws a polyline joining the newly identified barycenters (Figure 5).

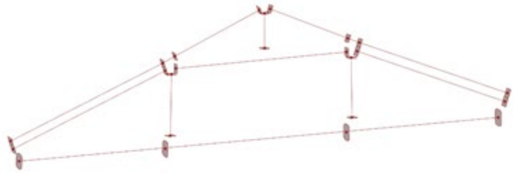

Figure 5. Definition of section's barycenter and their connections with polylines.

Finally, the algorithm extrudes all sections along these axes defined by barycenters, thus obtaining the 3D profile of each beam. To create knots, section curves are extended along their barycentric axis until they intersect another crossing beam.

The result of this process is a 3D model representing the truss rendered with a limited number of sections. Number and position of the sections used has been decided in order to have the best-fitted 3D model with the lowest number of sections. Creation of clipping boxes, orthophotos and the subsequent vectorization, in fact, represent the most time-consuming steps of the whole method. As a result, using fewer possible sections strongly affects the quickness of the proposed method (Figure 6).

Figure 6. Basic 3D model.

To verify the degree of compliance of the rendered model with the surveyed point cloud, a comparison of these two elements is carried out using a reverse engineering software, Geomagic Control X. The same software detects and reports in a chromatic scale distances between the points of the point cloud, considered as reference object, compared to the 3D model, considered as test object. Furthermore, it is possible to extract summary reports indicating the percentage of points within the nominal overlap threshold of the two compared objects.

The two highlighted columns contain the points within the threshold ± 5 mm whose deviation is considered non-significant, then treated as correctly overlapping points. Adding the point's percentage of both the negative and positive threshold the total degree of overlap between point cloud and 3D model is equal to 73.63% (Figure 7).

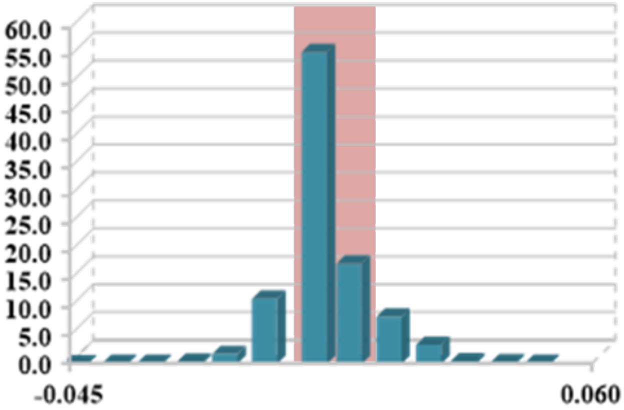

Figure 7. Graph indicating the distribution of the deviation of the point cloud from the basic model.

5. Conclusions

The goal was to create a modeling procedure that was as independent as possible from the operator who performs it. The most significant result of what has been presented consists in the substitution of the manual work of rendering a 3D model with a process defined by generative algorithms. This substitution has brought a significant reduction in processing time and reduced the arbitrariness and inaccuracies due to the subjective considerations of the operator in the rendering phase. The choice to use the vectorized cross-sections as a basis for the generation of 3D models has prevented inaccuracies due to the vectorization and extrusion of the frontal orthophotos. 3D models rendered in this way respect much better the morphological and spatial characteristics of the original structural systems, reaching an approximation to the survey point cloud up to 70%.

In addition to the rendering of a relatively detailed 3D model, it has been possible to define a procedure able to generate automatically many other 3D models by simply varying input parameters that seems to be an effective procedure for all structural systems with characteristics similar to wooden trusses. By simply adding more a few more vectorized cross-sections it should be possible to reach even higher approximation between the original point cloud and the 3D model. This means the possibility to render, in a short time and with good approximation, 3D models of large objects starting from a mere point cloud, even if incomplete and not totally closed.

Good results obtained suggest applying this new method to other case studies already analyzed, in order to improve the algorithm and to make it an equally efficient method applicable on every other type of wooden trusses.

Endnotes

1. The entire TLS survey of San Domenico's roofing has been carried out with a FARO CAM2 FOCUS 3D laser scanner using a targetless approach. The survey campaign took 3 working days and it was necessary to shoot 91 scans with a resolution of 12mm/10m and a quality filter of 3x in order to get the whole roofing. The survey of the choir roofing needed 30 out of 91 scans and the alignment was performed using an interactive Cloud to Cloud registration. With a medium overlapping between scans of 22,3% it was possible to achieve an extremely accurate alignment with standard deviation between correspondent points of 2.5 mm and a maximum deviation of 3.8. The whole point cloud counts over 390 million points.

References

1) Barbisan, U., Laner, F., 2000. Capriate e tetti in legno: progetto e recupero: tipologie, esempi di dimensionamento, particolari costruttivi, criteri e tecnologie per il recupero, manti di copertura. FrancoAngeli, Milano.
2) Bello Caballero, L., Mezzino, D., Federman, A., Santana Quintero, M., 2017. From field work to deliverables. Experiences on the tin house courtyard documentation. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-2/W5, 77–81. https://doi.org/10.5194/isprs-archives-XLII-2-W5-77-2017
3) Émy, A.R., 1841. Traité de l'art de la charpenterie. Avanzo, New York.
4) Kalyan, T.S., Zadeh, P.A., Staub-French, S., Froese, T.M., 2016. Construction Quality Assessment Using 3D as-built Models Generated with Project Tango. Procedia Engineering 145, 1416–1423. https://doi.org/10.1016/j.proeng.2016.04.178
5) Munafò, P., 2002. Le capriate lignee antiche per i tetti a bassa pendenza: evoluzione, dissesti, tecniche di intervento. Alinea, Firenze.
6) Prati, D., Mochi, G., Guardigli, L., 2016. Contribution to the knowledge of wide span wooden roofing in the area of Bologna. Tema:Technology,Engineering,Materials and Architecture 2, 132–144. https://doi.org/10.17410/tema.v2i2.114
7) Rrapaj, I., 2018. Le capriate lignee dell'architettura religiosa bolognese. Contributo della modellazione parametrica nell'interpretazione degli stati deformativi. (Magistrale). Alma Mater Studiorum - Universitá di Bologna, Scuola di Ingegneria e Architettura, Bologna.
8) Tampone, G., 1996. Il restauro delle strutture di legno: il legname da costruzione, le strutture lignee e il loro studio, restauro, tecniche di esecuzione del restauro. U. Hoepli, Milano.
9) Valeriani, S., 2006. Kirchendächer in Rom: Beiträge zu Zimmermannskunst und Kirchenbau von der Spätantike bis zur Barockzeit = Capriate ecclesiae, Imhof, Petersberg.
10) Zamperini, E., 2015. Timber trusses in Italy: the progressive prevailing of open-joint over closed-joint trusses, in: Fifth International Construction History Congress. Construction History Society of America, Chicago, pp. 629–639.
11) Zamperini, E., 2013. The Study of Timber Structures Based on In Situ Investigation. Advanced Materials Research 778, 97–104. https://doi.org/10.4028/www.scientific.net/AMR.778.97

＊1 Alma Mater Studiorum – University of Bologna, Full Professor
＊2 Alma Mater Studiorum – University of Bologna, Ph.D. and Adjunct Professor