UAS photogrammetry and SLAM for the HBIM model of the Montanaro Belltower

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ABSTRACT

Uncrewed Aerial Systems (UAS) are nowadays a consolidated technique for the 3D metric documentation of Built Heritage. Nevertheless, a complete survey of complex heritage assets still requires the integration of different techniques, using a multisensor and multiscale approach. The research presented in this contribution relates a documentation experience achieved on a complex heritage asset, from multisensor data acquisition, through data processing and validation to the phase of 3D modeling and HBIM creation.

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1. Introduction and case study

The documentation of Built Heritage is a complex task that requires to be carefully planned and executed (Letellier, 2015; Patias, 2007; Remondino & Stylianidis, 2016). The developments of Uncrewed Aerial Systems (UAS) over the last decade allowed to speed up and simplify the overall documentation process in different fields of applications and specifically also in the one of Built Heritage. A rich scientific literature is available regarding the different approaches that can be adopted with these platforms and the operative guidelines for implementing data acquisition and processing (e.g., Adami et al., 2019; Chiabrando et al., 2017; Nex & Remondino, 2014; Remondino et al., 2012; Russo et al., 2018). Nevertheless, a complete survey of complex heritage assets still requires the integration of different techniques, using a multisensor and multiscale approach (Achille et al., 2018; Georgopoulos, 2018; Remondino & Stylianidis, 2016).

Furthermore, while the acquisition and processing phases are generally managed with consolidated strategies, the phase of 3D models generation and data interpretation still presents some major challenges. This aspect is particularly evident in Heritage Building Information Modeling (HBIM) workflows where the data collected and processed need to be further interpreted, validated, modeled, and enriched (e.g., Banfi, 2020; Brumana et al., 2013; Yang et al., 2020). This phase presents a series of challenges that need to be faced, new solutions that need to be researched, and new approaches yet to be validated and studied.

The research presented in this paper relates a comprehensive and thorough experience completed on a complex heritage asset: the Santa Marta Belltower designed by Bernardo Antonio Vittone between 1769-1772 A.C. for the municipality of Montanaro (Figure 1), a little town close to Torino (Northwest of Italy). This asset was designed and built together with other structures with which it forms a unique heritage palimpsest. The belltower is indeed the fulcrum of the architectural composition, while the other structures are: the town hall, the brotherhood of S. Marta, and the parish church. This project represents the integration between the secular community and the sacred space in the XVIII century municipality of Montanaro (Battaglio, 2000) and was carefully designed by the architect (Figure 2). The belltower is approximately 48 m high; it becomes slender in the progression toward the top and has a peculiar internal spiral stairway made of stone. Considering that this asset should be part of a new requalification project in the next years, a complete metric documentation of the tower and the surroundings was necessary.

2. Data acquisition, processing, and validation

A detailed 3D model of the belltower was completed combining different techniques: in particular UAS photogrammetry was used for the exterior part of the belltower while Simultaneous Localization And Mapping (SLAM) based solutions were adopted for the

On the cover: aerial view (from south) of the Santa Marta Belltower and the buildings around.

interior. All the different acquisitions were referred to the same coordinate system thanks to a set of ground control points measured with traditional topographic techniques (Global Navigation Satellite System -GNSS and Total Station surveys) that were used also for evaluating the accuracy of the different processing approaches. The final products of the documentation project were requested to meet the nominal map scale accuracy of 1:100 (precision under 0.02 m with an accuracy of 0.04 m). The topographic network was constituted of a total number of 8 vertices (five in the square facing the tower and three in some intermediate floor in the indoor). All the vertices were measured by mean of Total Station and, moreover, two of the vertices outside the belltower were measured with GNSS static

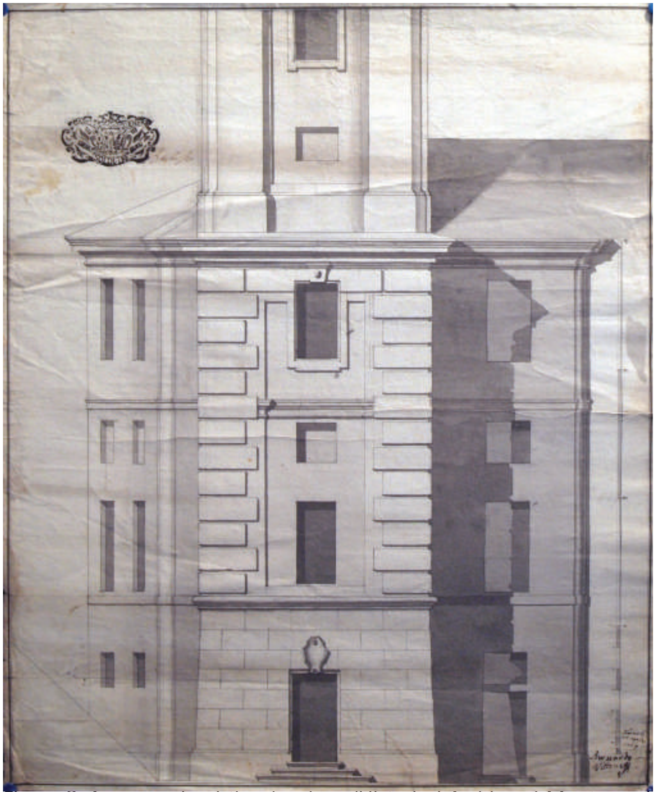


Figure 2. An example of the drawings (Historical Archive of Montanaro) carried out by B. A. Vittone: the main façade (1769-1772).

technique, to georeference the network with respect to WGS84 Datum (UTM Zone 32N coordinates). Secondly, UAS acquisitions were performed to achieve a complete 3D reconstruction of the exterior part of the belltower. The UAS deployed in the field was a DJI Phantom 4 Pro[1] and, considering the urban conformation of the area and the proximity of other buildings it was decided to perform manual flights, to guarantee a better control of the platform during the operation. Images were acquired starting from the ground to the upper limit of the tower and to ensure the desired Ground Sample Distance (GSD) of 3 mm, a mean distance of 5 meters was maintained between sensor and object. For each façade both nadiral and oblique images (with respect to the façade average plane) were acquired for a total number of 543 images (Figure 3). This acquisition solution was preferred to the Point of Interest (PoI) flight scheme for two main reasons: i) to avoid flying over the nearby building and ii) to guarantee a lower acquisition distance from the tower with a consequent lower GSD and higher detail. To document the interior part of the tower a rangebased approach was used exploiting the SLAM algorithm

Figure 3. UAS acquisition scheme (left) and examples of acquired images (right).

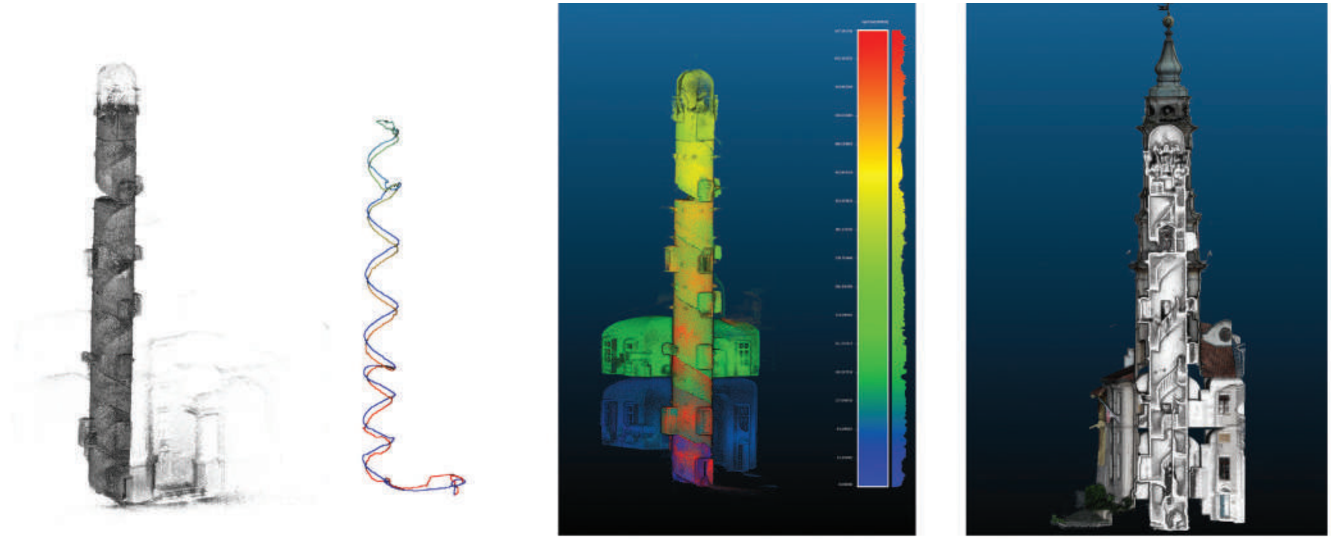
within the ZEB Revo RT[2]. This approach is sustained by a recently new technology that however has proved to be suitable also for heritage documentation under certain conditions (Barba et al., 2021; Chiabrando et al., 2018; Malinverni et al., 2018; Sammartano & Spanò, 2018). During fieldwork, the operative and wellknown procedures for acquiring data with this system were followed (Riisgaard & Blas, 2004), and specifically, closedloop acquisitions were achieved. The acquisition with the Zeb Revo RT started and ended outside the belltower entrance and the operator reached the higher accessible area inside the belltower, a total number of four scans was acquired. The acquisitions with TLS were not conceived to cover all the volume of the belltower, and thus only few scans were achieved to serve as ground reference. A Faro Focus3D X 330 TLS was used for data acquisition and a total of eighteen scans were acquired covering part of the exterior of the tower and part of the indoor areas. The processing and the final products derived from the acquisitions were metrically and geometrically validated following two approaches: the use of Ground Control Points (GCPs) and Check Points (CPs) and the comparison with a Terrestrial Laser Scanner (TLS) dataset that can be considered a more consolidated technique and can thus be used as a ground reference.

Both artificial papercoded targets and natural features were used as GCPs and CPs and were measured by mean of a Total Station in the interior and exterior part of the belltower. The points measured on the exterior were mainly used for the UAS data processing and validation, while the ones in the interior were crucial to ensure a reliable connection between indoor and outdoor and to control the interior acquisitions. In the exterior part, it was possible to measure 67 points while 32 were measured in the interior. Concerning data processing, it was decided to follow consolidated strategies for all the different acquired data. Images acquired during the photogrammetric flights were processed in a commercial solution (Agisoft Metashape) exploiting the standard pipeline: from image matching, via the Bundle Block Adjustment (BBA), metric validation through GCPs and CPs (Table 1), point cloud densification, and generation of added value products such as Digital Surface Models (DSM) and orthophotos. Due to the high number of

Table 1. Main processing results of the photogrammetric processing.

Images	N° GCPs	3D RMSe GCPs (m)	N° CPs	3D RMSe CPs (m)	GSD (m)
543	27	0.009	8	0.008	0.003

Figure 4. Example of the quality of the 3D models generated by the UAS photogrammetric processing on a portion of the belltower.



One of the point cloud acquired with the ZEB Revo RT (left) and acquisition path (right)

Scalar field representation of ZEB Revo RT point cloud (acquisiton time)

UAS and SLAM point cloud coregistered

Figure 5. Workflow of the on the field survey (left), schema of the GNSS network and the position of the ground marker used for the photogrammetric UAV processing (center)). Topographic measurements total station (right).

images and the reduced sensorobject distance, it was possible to generate a high detailed 3D model, as shown in Figure 4. The TLS dataset was processed using its dedicated solution: the Faro SCENE software and two different approaches were followed for the outdoor and indoor dataset. The outdoor scans were firstly registered using an Iterative Closest Points (ICP) algorithm and then georeferenced using the ground control points measured during the fieldwork. For the indoor dataset, the control points were used for both the registration and georeferencing phase, due to the different and more complex geometry of the scan positions influenced by the environmental constraints. The accuracy of the targetbased registration was 1 cm for the outdoor dataset and 0.5 cm for the indoor dataset. The first step of the ZEB Revo RT processing (Figure 5) foresees an optimization of the acquired point cloud thanks to the SLAM-based algorithms and is then followed by a registration of the SLAM point cloud in the same reference system of the other acquisitions. The first step is performed in GeoSLAM hub and the operator's possibility of processing customization is quite limited.

In the second step inside GeoSLAM hub, the different point clouds are roughly aligned and then registered by the software via the "merge" function. During this second step the SLAM scans were then coregistered with the TLS dataset using an ICP registration in the open-source solution CloudCompare[3]. The RMSE (Root mean square error) resulted from this operation was approximately around 4 cm. A more detailed description of the acquisition and processing phases can be found in (Teppati Losè, Chiabrando, & Tonolo, 2021; Teppati Losè, Chiabrando, Novelli, et al., 2021) while more information about some tests connected to Spherical Photogrammetry approaches completed using the belltower as test sites can be found in (Teppati Losè, Chiabrando, & Tonolo, 2021).

3. From point clouds to HBIM

Two main products were generated starting from the point cloud derived from the metric survey: traditional 2D drawings and a first HBIM model. The creation of an HBIM "as-built" model represents a further step of the documentation project of the belltower.

As is well known, the use of this type of data (point clouds) in the BIM software solutions is still not fully implemented and different challenges need to be addressed when adopting this approach, especially when dealing with a complex architectural object.

Different solutions were tested in the BIM software used (Autodesk Revit), both using built-in tools and external plugins or software.

The first approach tested for the creation of the HBIM model consisted in a more consolidated solution, that started with the import of the point cloud in the Autodesk Revit software and the subdivision of the belltower in different main portions. For each of the eight portions created a series of sections was then extracted to serve as the geometrical base for the creation of the main volumes constituting the belltower. Thereafter, the sections were manually vectorialized and served as core elements to create the main volumes of the belltower (Figure 6). After this first phase of modeling, each face of the new volumes created was converted into wall elements, and information derived from the joint use of indoor and outdoor data was applied (e.g., thickness, stratigraphy, etc.). Concluded this initial modelling phase, it was necessary to refine the details of the belltower (decorative elements, windows, niches, etc.) that needed to be individually modeled exploiting different tools provided by Revit (e.g. cutting geometry using solids) and using as reference the different point clouds. It was particularly challenging to model the molding and the decorative bands for which three different strategies were tested: i) sweeping a 2D profile along a path, ii)using AutoCAD and Rhinoceros to create more complex NURBS and, iii) increasing the number of sections on the element to be modeled (Figure 7).

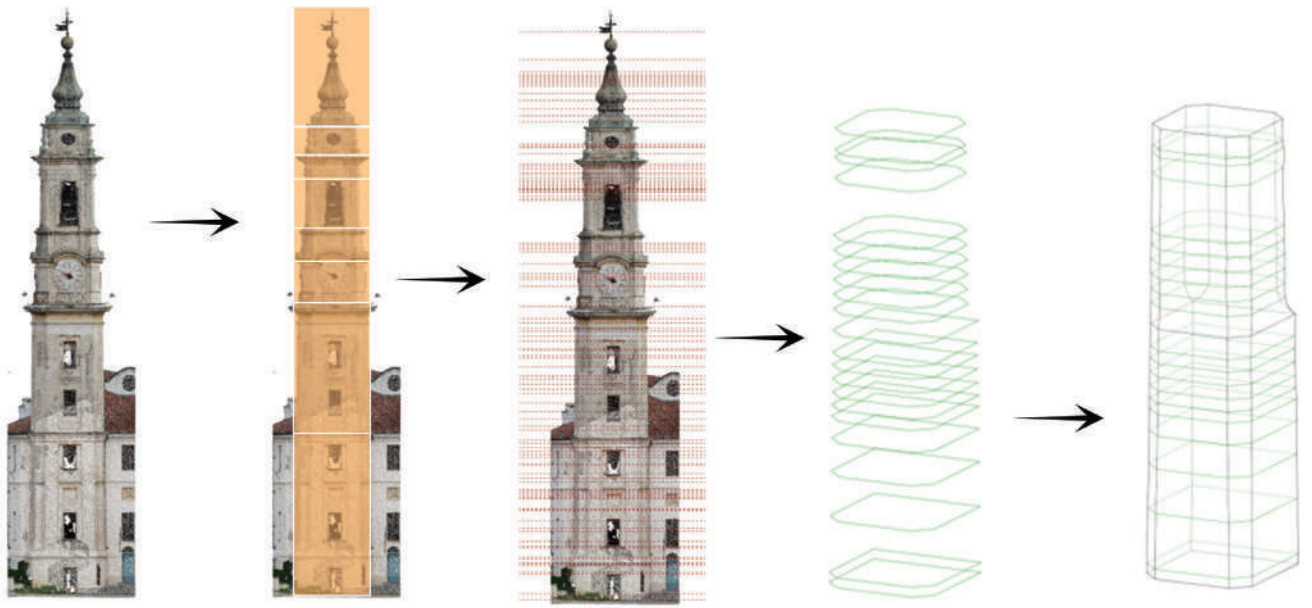


Figure 6. Standard approach from point cloud to solid geometry.

Furthermore, considering that some decorative elements are repeated on the four facades it was possible to create specific families inside Revit and to customize all the related parameters.
A final step of this process was connected with the enrichment of the HBIM models with a series of information. Data derived from historical sources and in situ inspections concerning the wall stratigraphy and materials were added to the model. Moreover, extracts of the orthoimages of each facade were connected as image parameters where it was necessary to underline specific features such as state of decay, missing elements, etc. The generated HBIM model was finally validated using an M2C (Model to Cloud) analysis thanks to the plugin FARO As-Built for Revit; results from this analysis are reported in Figure 8. It needs to be reported that the plugin failed to analyze the portions modeled inside Rhinoceros and thus further analyses are needed on these elements. The image reports the analyses conducted using the point clouds as a ground

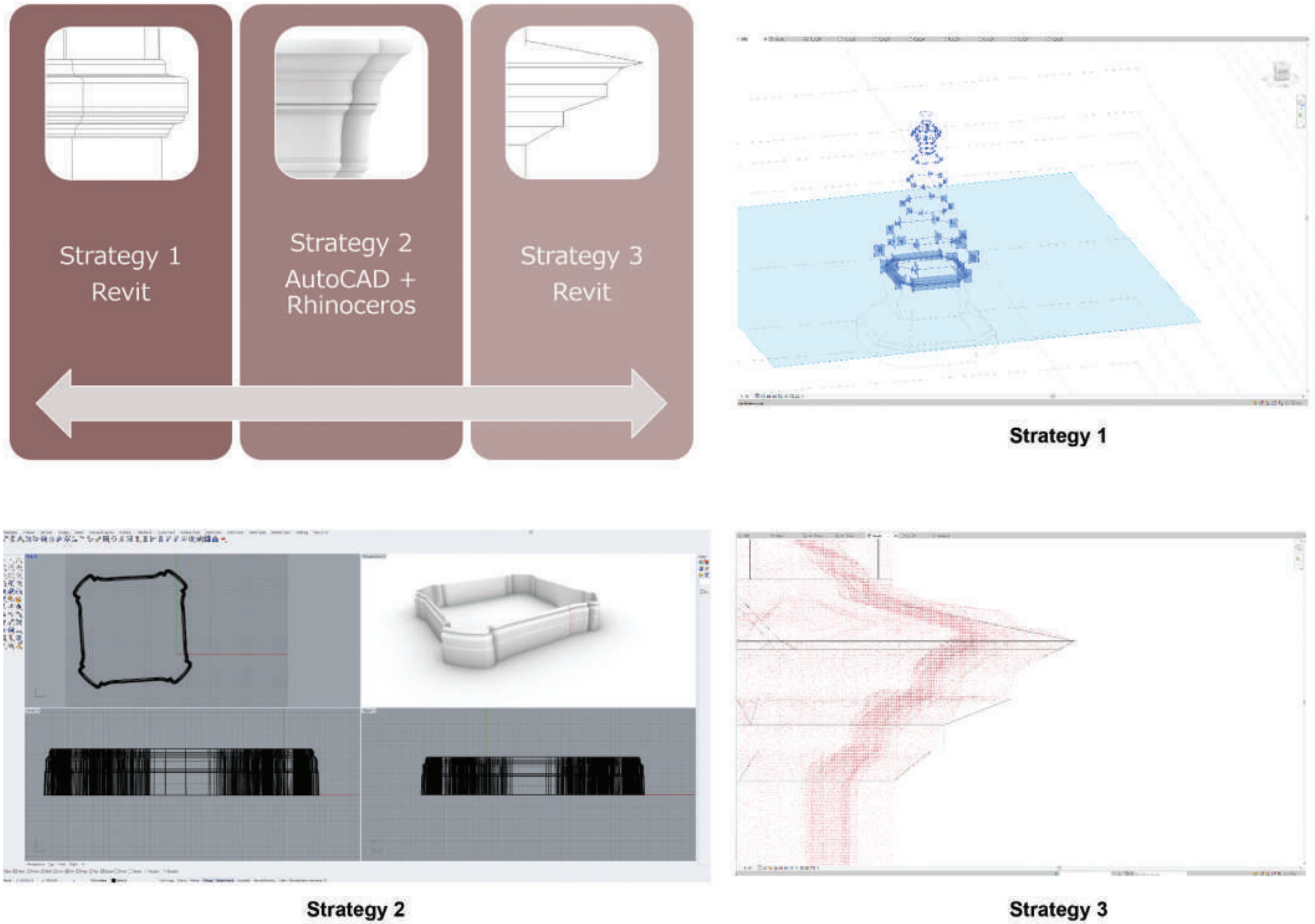


Figure 7. Example of the different modeling approaches tested.

reference and shows the deviation of the HBIM model. As is possible to notice results can be considered satisfying, especially for a complex asset like the Santa Marta Belltower and are in a range of few centimeters. Results are under 2 cm in areas constituted from the more simple geometries of the belltower, while a bigger deviation can be observed in the more complex parts where the modelling phase was more challenging (mainly in the higher moldings of the structure).

4. Conclusion and further perspectives

The documentation project of the Santa Marta Belltower allowed tailoring several issues connected with the different phases of the documentation work,

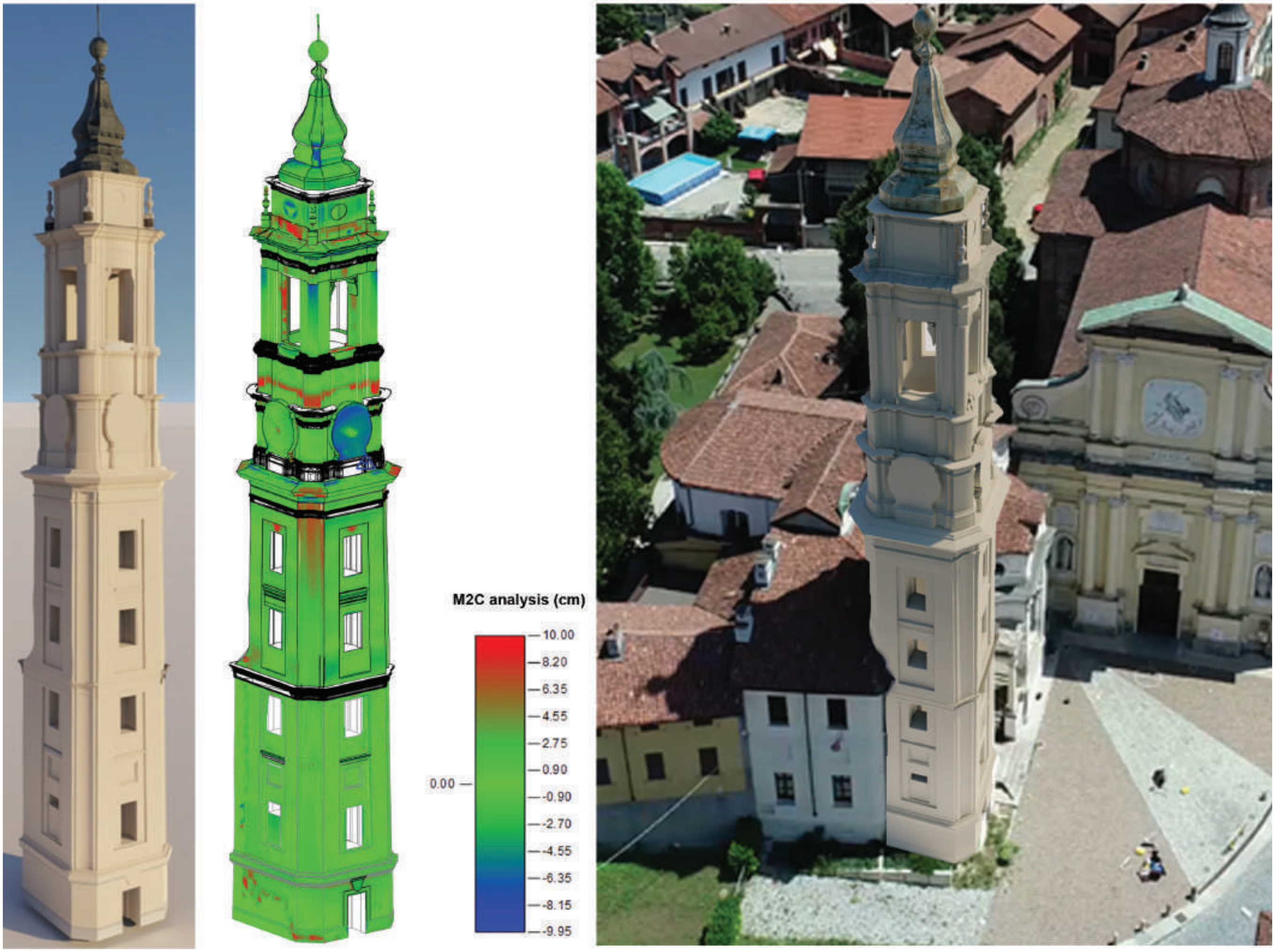


Figure 8. The final HBIM model and the results of the M2C analysis.

exploiting all the survey pipeline from survey design, via data acquisition, processing and validation, to the generation of addedvalue products including the HBIM model. In this contribution, the focus was on the modelling phase. After data acquisition and processing, for the creation of an as-built parametric model. It is clear from the experience conducted and from the result presented that, despite the advancement of the last years, this phase is still the most time-consuming and the one that requires a high effort from the involved operators. Automatization is still missing, or at least is at its initial phase of development, and the use of point clouds in the modelling requires expertise and experience. Different strategies have been tested for the management of survey products in the phase of 3D modelling, both inside the Revit software, both using external solutions or ad hoc plugins. Nevertheless, every strategy has its own pros and cons and needs to be selected mainly considering the characteristics of the asset. This is particularly evident when dealing with Built Heritage which lacks the possibility of standardization and still requires the research of new solutions for enhancing this phase of work. A contribution in this sense can be provided by the recent development of AI (Artificial Intelligence) approaches applied to Cultural Heritage, which is a hot research topic continuously evolving.

Notes

1 https://www.dji.com/uk/phantom-4-pro/info#specs

2 https://geoslam.com/solutions/zeb-revo-rt/

3 https://www.cloudcompare.org/

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