3D METRIC DOCUMENTATION USING GEOMATIC METHODS. Integrated and multi-sensor 3D metric survey

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3 3D metric documentation using geomatic methods

Abstract: The digitization projects of architectural heritage are a field of research continuously evolving and updating in parallel to technological innovations that allow to progressively boosting the challenges and requirements of the geometric and semantic richness of related digital models. Today, the XX century heritage typically necessitates urgent and attentive conservation plans that require multidisciplinary research and profound investigation of new and tailored approaches providing a clear indication of best practices and recommendations for correct 3D documentation, and for information management by suitable digital systems.

The multi-sensor approach is organized by combining different range and image-based techniques in order to generate a multi-scale 3D model. The use of UAV (Uncrewed Aerial Vehicle) photogrammetric approach was conceived for the documentation of the articulated complex in the outdoor spaces (concerning extrados surface). In the indoor environments, the hierarchy of documentation requires the use of different techniques: static LiDAR used for the main halls structural elements, was flanked by Mobile Mapping System (MMS) by SLAM-based portable technologies in case of non-straightforward accessibility of enclosed spaces, galleries, and underground rooms.

The first paragraph extensively describes the methods adopted, the specific characteristics of their application according to the diverse needs that the articulated spaces of the Turin Exhibition Center required; the second paragraph develops a careful study on the analysis of the generating geometries of the constructive elements of halls B and C by analyzing the reality-based models obtained in relation to Nervi's project drawings, while the last paragraph deals with the anomalies that multi-sensor models, dense and highly metrically accurate, allow to analyze.

3a Integrated and multi-sensor 3D metric survey

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3a.1 Aims and strategies of the digitization project

The 3D survey of the Nervi's pavilions of the Turin Exhibition Center was carried out by adopting procedures that are not entirely standard. The methods and systems used are parts of those pieces that make up the mosaic of investigations connected to each other and aimed at the common purpose of protecting architectural heritage[1]. The metric documentation that consists of the 3D survey and modelling is part of the overall conservation project, and must necessarily be harmonized with the historical reconnaissance, the study and analysis of materials and construction techniques, the structural and seismic assessment and with the monitoring of the structural health.

One of the important concerns is that the quality of modelling products deriving from digitisation process is not intrinsic to the models, that is, the processes that led to obtaining them are not automatically recorded. In this sense, an EU project called VIGIE is underway, aimed at a "Study on quality in 3D digitisation of tangible Cultural Heritage: mapping parameters, formats, standards, benchmarks, methodologies, and guidelines"[2]. The set of the aforementioned instances are the basis of the reasoning behind the modelling and enriched archiving of information as regards both the digitisation process and other interdisciplinary investigations.

This chapter, therefore, reports the innovative 3D survey technologies used and the consequent multi-scale and multi-content results of 3D modelling up to the prefiguration of systems to manage enriched 3D models, structured with the support of metadata[3]. The digitisation processes set out in this way, especially when the object of interest consists of exceptional architectural structures that are relevant to the constructive innovation that had led to their creation, do not simply aim at reproducing a geometric model that is faithful in shape to the original, but also at really generating a *Digital Twin*[4]. In recent years, Geomatics has structured a consolidated set of methods and measurement systems for a 3D survey and modelling of large architectural complexes[5]:

- *3D range-based and image-based survey methods* i.e. photogrammetric techniques, applied from different terrestrial and airborne points of view using not only UAV, but also hybrid systems, such as MMSs that allow quick and differently accurate scans by exploiting sensor movement.
- *Continuous control of error propagation* (by adopting accuracy control strategies for each phase of the process, and making use of statistical criteria to evaluate the quality of the processing results and the resulting 2D / 3D products)
- *3D modelling strategies and fusion of techniques.* The continuous development of automation that has characterized space information technologies offers a good set of techniques for merging techniques. Fusion of methods or techniques means being able not only to combine and integrate the results of photogrammetric and laser scanning processing, but also to make their contributions collaborative, reaching different, more specialized results than are the sum of the parts.

In the field of architectural structures, such as those of the vaulted systems made by Nervi, it is necessary to consider that structural engineering investigations certainly require not only high accuracy point clouds and 3D models, but also a simultaneous balanced density of information and an adequate level of detail[6] (Figure 3a1.1).

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[1] ICOMOS. 2017.

[2] EU VIGIE project: https://digital-strategy.ec.europa.eu/en/funding/study-quality-3d-digitisation-tangible-cultural-heritage.
IMMOVABLE SUCCESS STORIES / CASE STUDIES; The Pierluigi Nervi Halls project of digitization, pp. 46-47.

[3] See also Chapter 8, paragraph 1

[4] Chapter 8, paragraph 1.

[5] Some examples are: Grussenmeyer et al. 2011. Munumer & Lerma 2015.

[6] Abbate, Invernizzi & Spanò 2020. Ottoni, Freddi, & Zerbi 2017.

In other words, the following objectives need to be carefully harmonized:

General configuration of the building

- Precise geometry of the structural elements
- Multidisciplinary information content

Requirements to be met (3D metric survey):

- rapid acquisition and accuracies, level of detail, reliabilities adequate to the degrees of analysis and representatio
- seamless positioning problem has been pursued using new strategies: most prominent is SLAM (Simultaneous Localization and Mapping)

Multi-scale, multi-content and multi-sensor models: crucial role in the framework of architectural documentation.

- generai vision of the structure and the possibility of investigations at different levels of detail, especially where the structural degradation is investigateci
- possibility to derive lightweight models for subsequent processing or predictions of the structural behaviour

3a1.1.a, b, c. (Above) A summary of requirements of the 3D metric survey; (centre) an oblique image from the drone employed; (below) A south gallery view, and a view of Hall B with the overall encumbrances relating to the temporary exhibitions, removed after the 3D survey.

One of the most important aspects is the possible future use of the data, in order to obtain user-oriented models, which is a fundamental value for their usability. Finalizing multi-sensor, multiscale, and multi-content models aims to support different purposes: a global knowledge of the spaces and the morphological characterization of the structural elements, which will, therefore, be suitable for the identification of architectural values and will support the detection of the mechanical deterioration of the elements and surface degradation. The use of the results is possible when the characteristics of the final products, such as resolution, level of schematization and final file formats, also meet the needs of users, articulated for different purposes as listed before.

3a.2 Rapid Mapping

Many of the adopted methods are known as rapid mapping technologies, as the acquisition phase has been highly automated. An important point is that the sensors can be mounted on UAVs, in order to be able to collect aerial images that enable building roofs to be documented, as in the case of the Turin Exhibition Center.

A number of photogrammetric applications were also clearly taken from the ground, when the radiometric values of the investigated surfaces were considered particularly important, and the radiometric information derived from laser scans was, therefore, deemed insufficient[7].

Parallel to traditional laser scanning technologies, managed by static positioning, for some years now we have been able to rely on mobile mapping systems based on SLAM (Simultaneous Localization and Mapping) technology, which exploit the characteristics of the environment: the system simultaneously locates the sensor and measures the scenarios in which acquisition takes place[8].

The new, SLAM-based positioning solutions, implemented in some recent, portable systems for indoor/outdoor mapping, are progressively developing and are supported by geometric feature extraction algorithms even when traveling through complex, uneven environments. In parallel, the possibility to exploit the advances in digital photogrammetry algorithms for image matching and dense reconstruction using action-cam, compact, and fisheye cameras enable investigation solutions to be deployed even in complex environments that are at first sight impossible to map using a photogrammetric approach.

During acquisition, the raw laser profiles continuously captured into time-windowed segments are rapidly and progressively re-projected in the real-time 3D reconstruction of spaces while the operator is walking. This depends on the best correspondence to surface characterization, using an ICP-like approach for profile matching, with a global accuracy of the final, processed point cloud identified by a representation scale of 1:100-1:200.

The SLAM-based clouds that can be obtained are less precise and less dense than traditional scanners. However, the advantage is that the methods can be applied to confined, indoor and underground spaces. That means we can use these scanners even without the help of the contribution of GPS / GNSS positioning systems. As will be further explained, a system supported by a hand-held scanner for the internal service spaces and a more sophisticated hybrid system using a traditional scanner coupled to a profilometer, both mounted on a mobile trolley, were used at the Turin Exhibition Center[9]. Figure 3a 2.1 shows a sample of the instrumentation used for the 3D survey of the Turin Exhibition Center halls.

3a 2.1: Technologies used: GNSS (Global Navigation Satellite System) receivers, total stations for traditional topographic measurements, cameras mounted on multi-copter drones, laser scanners for static acquisitions and for adopting a mobile mapping configuration.

The innovation of digitization systems. SWIFT Mobile Mapping Systems

The extensive, complex 3D survey activities, such as those required to document the immense spaces enclosed by Nervi's futuristic, vaulted structures of the mid-50s, often constitute opportunities to experiment and test new sensors. In the case of the Turin Exhibition Center, the possibility of collaboration with the international company Faro Technologies arose. This made it possible to evaluate the brand-new Swift system, introduced on the market in 2021, to validate its potential in a digitisation scenario for the conservation of an important example of 20th-century ferrocement heritage.

The capabilities of FARO Technologies' Swift system are mainly based on the integrated nature of its sensors. It consists of three different connected components (Figure 3a 2.2):

- a static 3D laser scanner of the S series (also working autonomously).
- the so-called ScanPlan is equipped with a horizontal laser profilometer, through which the SLAM-based positioning function operates.
- the Smartphone connects and manages the two sensors in Wi-Fi mode.

All components are anchored to a light, stable trolley, pushed by the operator walking during the survey (Figure 3a 2.2). The ScanPlan sensor featured an operating range of up to 20 m

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[7] Sammartano et al. 2021.

[8] Bosse Zlot & Flick 2012. Riisgaard & Blas. 2005. Sammartano & Spanò 2018.

[9] Swift system by FARO Technologies, see paragraph 3.1.3.

in the first release, but this has recently been raised to 60 m, and detects the characteristics of the environment on a plane used by the SLAM function to estimate the trajectory during mapping. The performance of the LiDAR distance measurement depends on the capabilities of the S-series scanner (the S350 long-range is the one tested in this circumstance, i.e., the scanner is capable of detecting points at 350m).

The FARO Swift system certainly intends to target the application field of digitization projects of extended environments featuring standard building elements of large complexes (airports, hospitals, office blocks). Here the historical, 20th century structure legacies were used as a test dataset: the architectures characterized by enormous vaulted systems, such as the 20th century spatial ferrocement, structures can be efficiently digitized with these systems[10]. The system operates in three scanning modes: a. continuous mobile scanning; b. the so-called anchor scans, which are implemented along the trajectory by conducting a very short scan in static mode, and which are useful when problematic points, such as long corridors, doorway crossings between different rooms, curved lines etc. are present in the scanning environment, but which can also be used as low-resolution static scans and co-registered separately; and lastly, ordinary static scans, the only scans that can be activated to acquire images and attribute radiometric values to the cloud. However, their role is also aimed at post-processing, for a better evaluation of positioning and levelling control problems.

These innovations make the system very versatile with respect to the different purposes of digitization and can better adapt to the different articulations of the surveyed object, although obviously they are unsuitable for climbing stairs and inclined planes. These are the main features that distinguish this from other consolidated solutions used, for example, to survey the Flaminio stadium[11] or even in museum environments[12].

One of the first lessons learned in the context of the Turin Exhibition Center survey is that it is necessary to carefully evaluate the balance between scan duration and consequent file size, which affects subsequent processing times[13].

3a 2.2. a, b: The SWIFT system of Faro Technologies: (above) the main components (S series laser scanner, ScanPlan with profilometer that uses SLAM technology to determine the trajectory and the mobile phone that connects the different components); (below) the system is in action in Hall 3 of the Turin Exhibition Center.

3a.3 3D metric survey planning

Articulated architectural structures, such as the Turin Exhibition Center complex, today require urgent conservation plans, thanks to construction work and to the stratification of the uses that generally characterize them. These plans have to be particularly attentive to overall knowledge and to contrast degradation by pointing in the direction of protection and adaptive reuse.

For this reason, the project of the 3D survey of the complex of Nervi's Halls B and C required the provision of acquisition and modelling methods compliant with best practices and recommendations for correct 3D documentation. Based on these requirements, and especially in compliance of the survey outcomes both in terms of metric accuracy and of the multiscale level of detail of the information collected, the various development phases of the survey project were planned to achieve a precise definition of the overall geometry of the building. They also aimed to provide results with useful semantic contents to study the consistency of the ferrocement elements of the vaulted system. with the overall purpose of evaluating the structural health.

It is, in fact, important to consider that the quality of modelling products is not intrinsic to the models, but depends on the processes that led to their acquisition and on the related reciprocal relationships.

For all these reasons, it can be said that the 3D survey of P. Nervi's halls has made it possible not only to address methodological issues that can be used in similar contexts, but also to tackle the task of the digitization process in order to define the outdoor and indoor configuration of the rooms.

In short, it is possible to identify the main objectives which the survey project addressed:

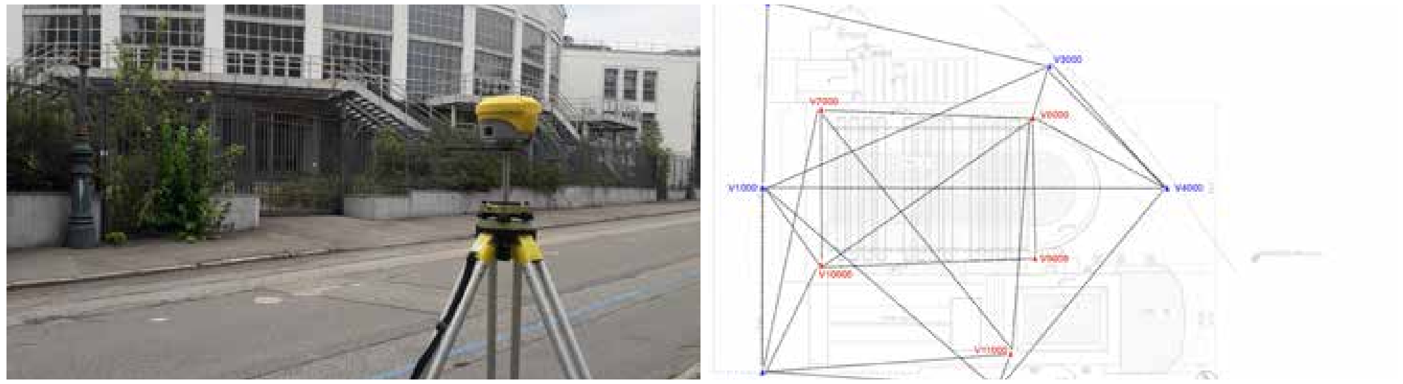
1. The definition of the *overall configuration of the envelope* of the spatial architectural structure, focusing on the thickness of the ferrocement elements and studying the intrados-extrados problem;

2. The *recognition, segmentation and modelling* of the elements involved in the structural analysis;

3. The organization and archiving of the dataset's complex and *multidisciplinary diagnostic investigation tests*, which generate a more complete and in-depth information context if their spatial relationship is enhanced.

4. The generation of the *enriched model* is carried out with the aim of seeking the appropriate balance between the information density that characterizes the model of the architectural complex and its structural elements, their level of detail, correctly harmonized for different purposes.

Operationally, the 3D survey was organized into three phases, each bearing specific objectives, also in terms of accuracy and level of detail to be achieved.



3a 3.1: Diagram of the main topographical network and GNSS measurement phase.

Phase I: Topographical control network

The main control network, usually aimed at the metric survey of architectural heritage not only to obtain the reference of all the measurements and the relevant drawings to a single reference system, but also to control the propagation of errors in order to guarantee the required tolerances, was carefully designed in the case of the Turin Exhibition Center to also be able to study the extrados/intrados problem and consequently define the thicknesses of the structural elements.

The topographic network (Figure 3a 3.1), deployed around the building complex, on its roofs, and inside, was measured, calculated and adjusted in order to meet the requirements of the accuracy of the final survey conforming to the scale of 1:50 - 1: 100. Therefore, the required accuracy of the coordinates of the vertices was approximately ± 5mm.

Phase II: 3D survey of the envelope, the roofs, and the architectural complex

The outdoor survey of the complex and its surroundings was planned by prefiguring the use of UAV photogrammetry, especially in order to obtain detailed documentation of the roofs and related systems (Figure 3a 3.2). The problems of organizing a UAV flight in an urban area were addressedwith the help of the traffic police, and a topographic survey was carried out to constitute the photogrammetric support with the prediction of the accuracy of the topographic coordinates of the control points. approximately 1 cm.

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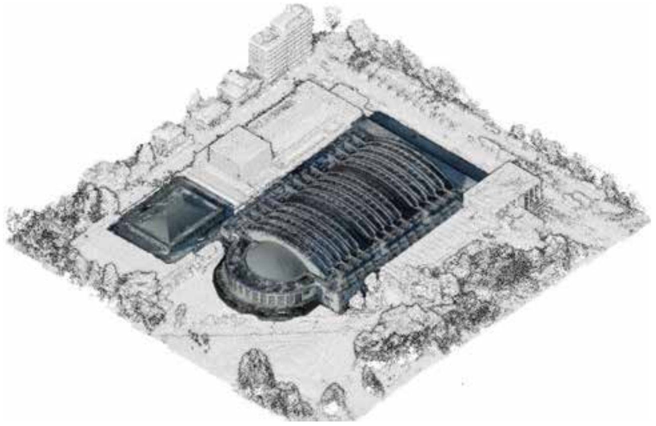
10 Bonfanti et al. 2021.

11 Ippolito Diacodimitri & Ferrari 2020.

12 Tucci et al. 2020.

13 Bonfanti et al. 2021



3a 3.2: Area of interest of the roofs of Halls B and C.

Phase III: 3D survey of the interiors of Halls B and C.

As far as the interiors are concerned (Figure 3a 3.3 and Figure 3a 3.4), the most appropriate methods of a detailed survey were chosen, prefigured in an integrated form or, as it is commonly defined, with a multi-sensor approach, all featuring rapid acquisition capabilities. These were 3D scanning systems, close-range photogrammetry applications, Mobile Mapping Systems from hybrid technologies, and hand-held scanners based on SLAM technology. These detailed survey methods, combined together in a hierarchical way, are all accompanied by topographic surveys of control points, also featuring coordinate accuracies of the points of approximately 1 cm.

The data processing (recordings of the clouds and generation of point clouds from Structure from Motion - SfM techniques of digital photogrammetry), was planned and organized to provide a detailed representation of the shape in the form of integrated point clouds and completed, where necessary, from digital orthophotos, characterized by metric accuracies between 2 and 4 cm. (With the meaning of the reciprocal position of each point with respect to any other, which is found in any level of the building).

From these first results of the 3D survey, we expect to derive both the continuous shape models in the direction of the constitution of a digital twin model in the HBIM environment and the 2D vector drawings typical of the architectural description. The latter is certainly useful for supporting detailed metric calculations and, in the configuration that integrates digital orthophotos, allows in-depth analysis of the state of conservation of the wall faces.

3a 3.3.a, b, c: Interior environments object of the 3D detailed survey methods using traditional laser scanning techniques, a hybrid technique from the Swift mobile system and terrestrial photogrammetry for the structural elements and related diagnosis.

3a 3.4. a, b, c: For underground environments, it was necessary to use traditional 3D scans, but in general, all the service areas and stairs were detected by means of mobile scans from hand-held scanners.

3a.4 Topographical control network

The topographic control network, as mentioned, enables the entire complex of 3D measurements to be calculated in a single reference system, so the propagation of the error can be organized and controlled according to the hierarchical order of the different levels of both the architectural complex and the external-internal relationship. (Figure 3a 4.1)

The topographical vertices of the main network were permanently marked on the ground, placed around the Turin Exhibition Center complex and on the roofs, and measured with GPS / GNSS (Global Positioning System / Global Navigation Satellite System) technique in static mode with 1s sampling for 45 minutes / 1 hour of stationing.

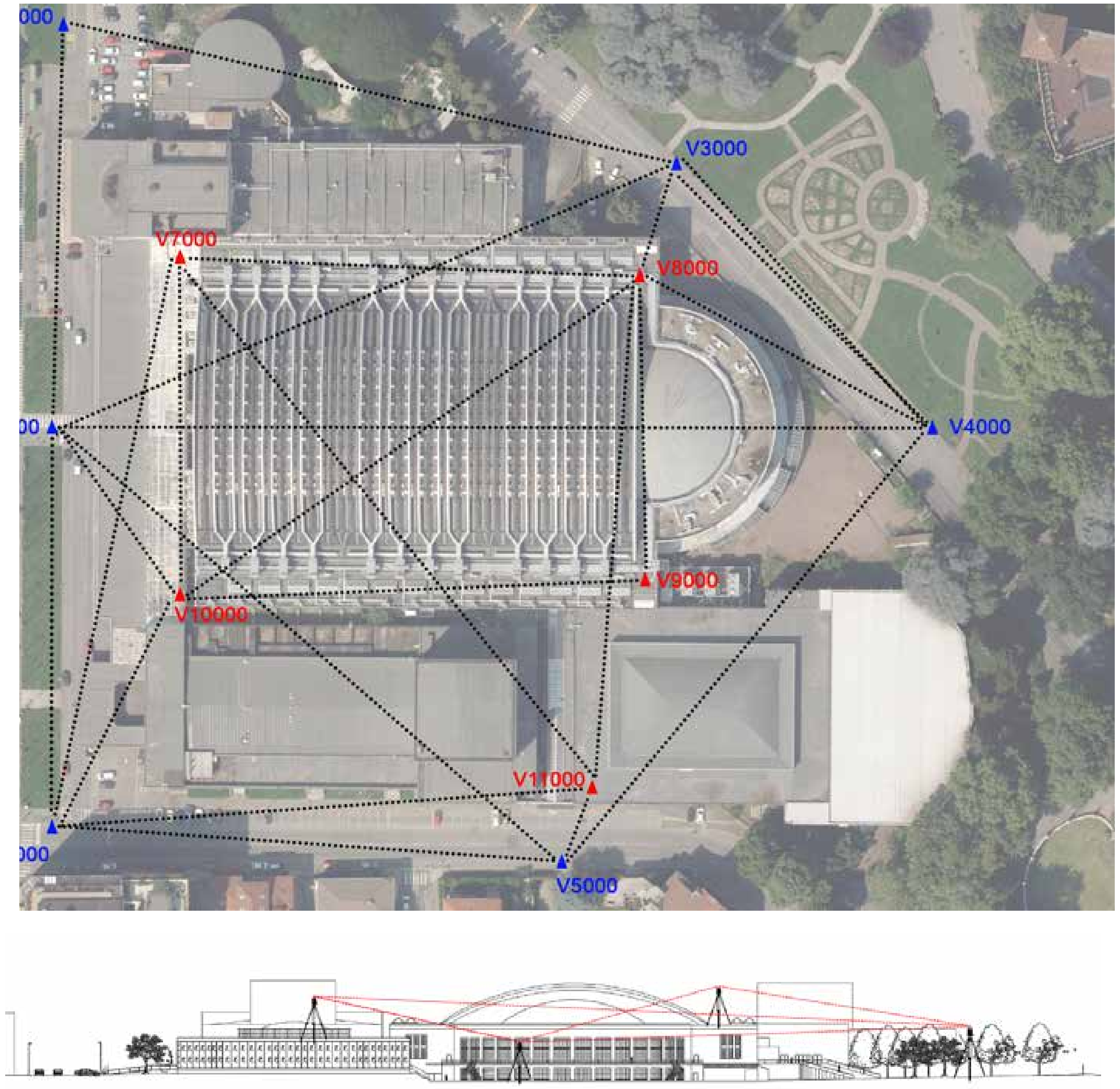
3a. 4.1: Phases of topographic control network and detailed 3D metric survey in progress.

The topographic network was developed with the Leica Geo Office (LGO) software using the permanent stations of Turin, Savigliano, and Crescentino, adopting the reference system WGS84-ETRF2000; the entire elaboration of the survey of the Turin Exhibition Center complex is, therefore, *GEOREFERENCED*. The ellipsoidal heights were converted into orthometric elevations using the ConveRgo software and using the IGM GK2 grids.

The calculation and adjustment of the network of vertices were performed using the least-squares compensation procedure, which estimates not only their metric quality, but also the coordinates of the vertices; the average accuracy of the vertices was found to be approximately 5 mm (Table 1).

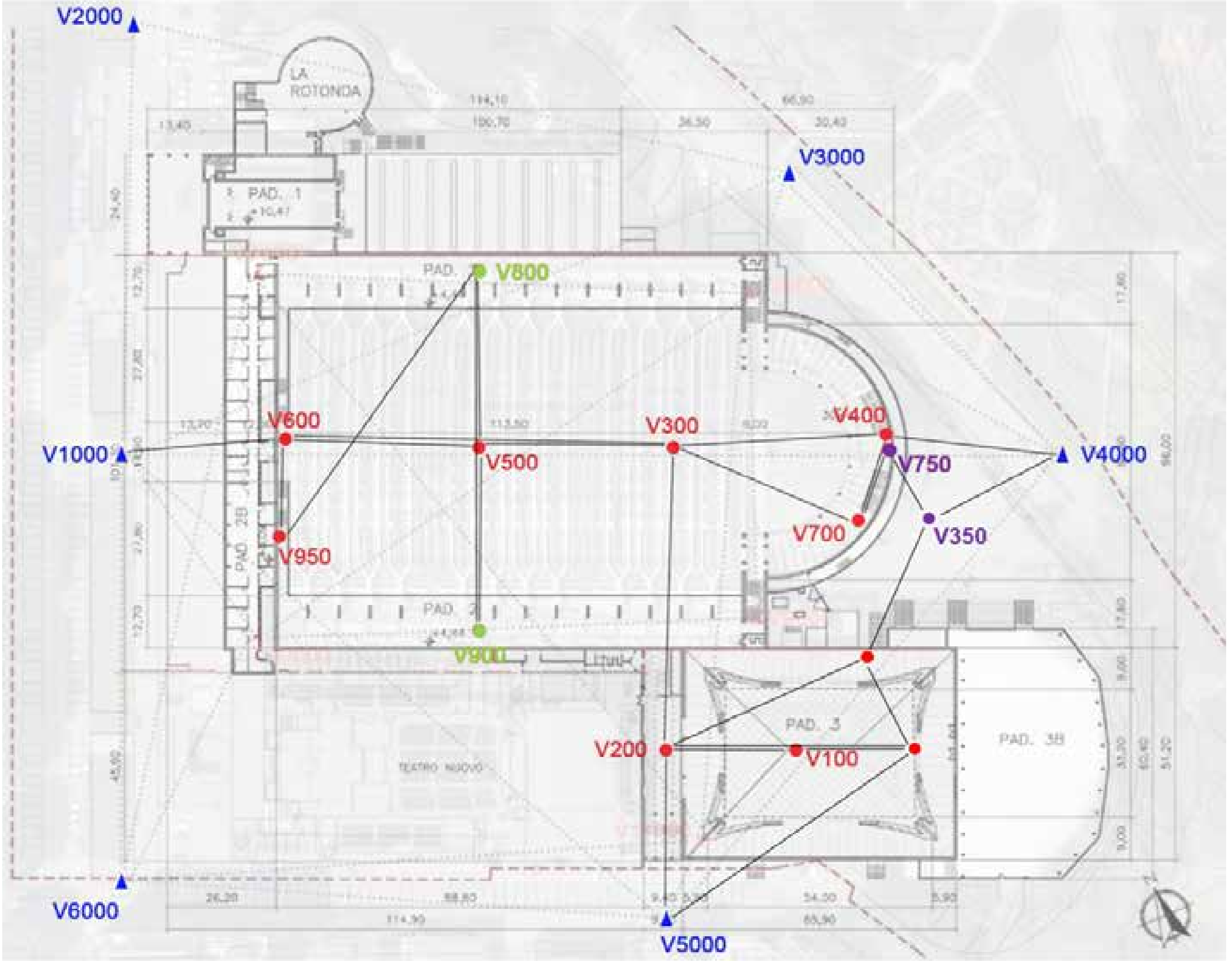
3a. 4. TA. Table 1: Medium values of Standard coordinate deviation [m]

RMSE [m]		
X	Y	Z
0.0039	0.0048	0.0027



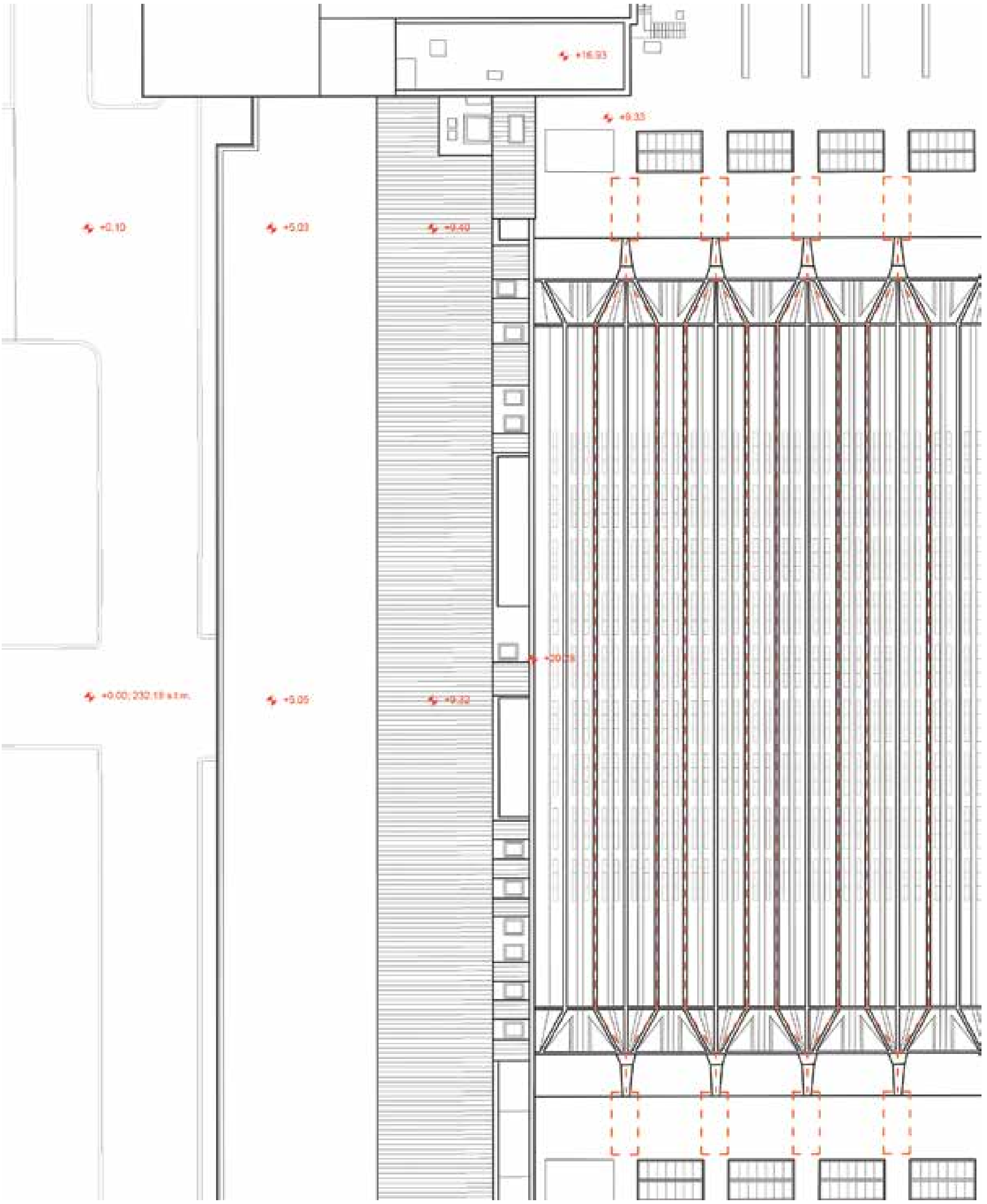
3a 4.2. a, b: Topographic network distributed outside the buildings (in blue) and on the roof (in red). The environmental section of the complex shows the baselines of the topographic network in a practical 3D configuration.

The topographic refinement network led the topographical vertices inside the building, to refer the detailed surveys to the single reference system. The internal network was obviously measured with the classic technique by means of a total station, to determine a certain number of directions measured in connection with the main network. Repeated conjugate measurements were performed at least 3 times; the vertices network was also calculated and adjusted using the least-squares compensation procedure via the MicroSurvey STAR * NET software, which estimates not only their accuracy, but also the coordinates of the vertices.



3a 4.3: Topographic control network inside the buildings (in red) connected to the external network (in blue). In green, the vertices in the galleries, in purple, the basement and courtyard level.

For easier processing of the point clouds, the coordinates of the network of vertices inside the pavilions were truncated (large translation with respect to the georeferenced coordinates). The elevation referencing of the vertices was further converted by assigning the conventional elevation of 0.0 to a point around the vertex 1000, near the main entrance on Corso Massimo D'Azeglio of the Turin Exhibition Center complex (Figure 3a 4.4). The drawing files then report the elevations referring to this conventional origin.

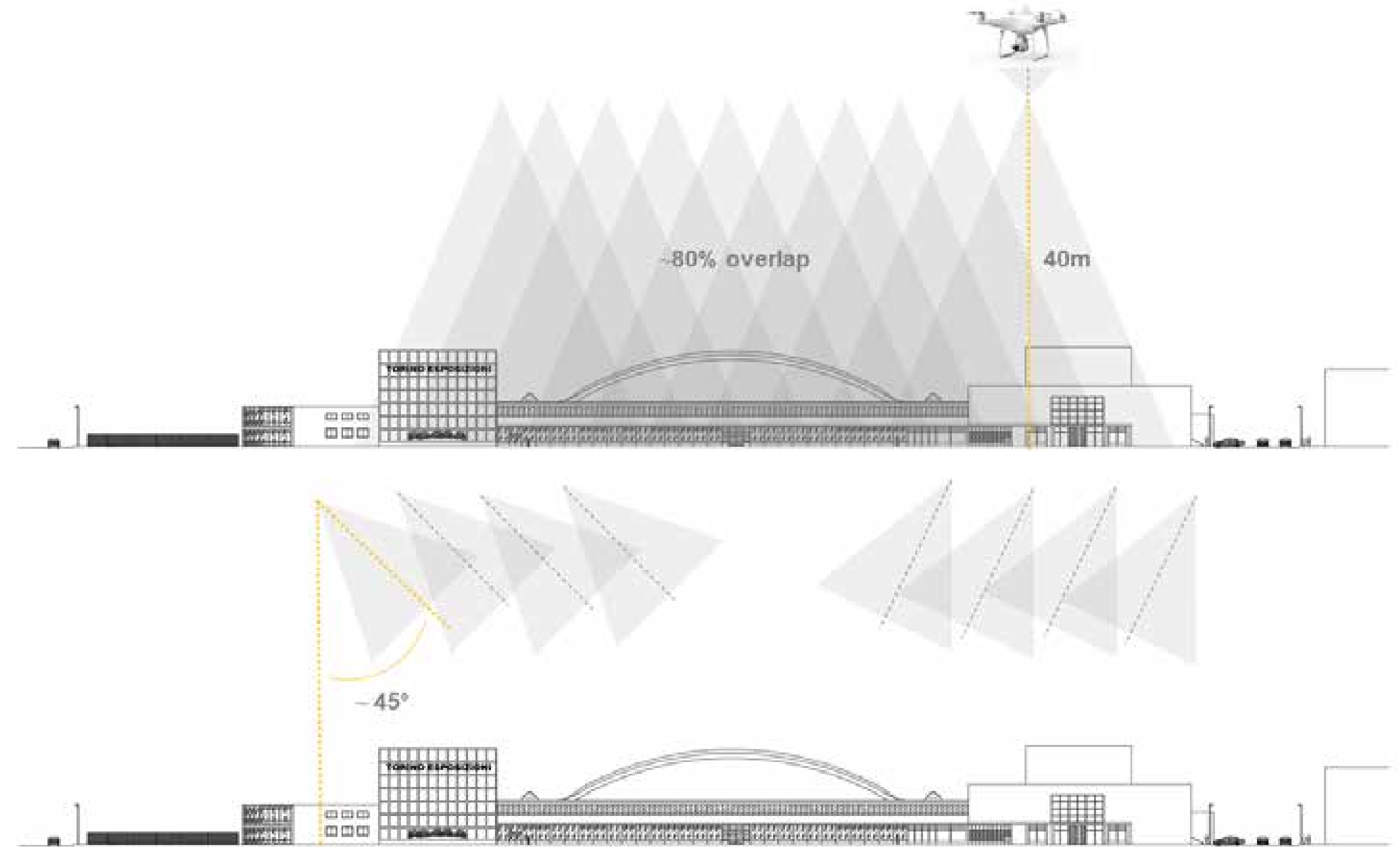


3a 4.4: Position of the conventional zero point near the entrance (vertex 1000), in an extract of panel 2, roof plan.

3a.5 UAV Photogrammetric survey

The UAV photogrammetric survey of the architectural complex and of the roofs was preceded by the distribution and measurement of control points on the ground and on the roofs, using permanent markers on horizontal surfaces or natural points on surfaces in any case-oriented, in order to optimize the bundle adjustment of image blocks taken from UAV flights. In order to measure the control points, the classic technique of a total station was preferred to the satellite topographic technique, with directions determined starting from the vertices of the topographic network. This solution was adopted to increase the accuracy of the photogrammetric survey from UAVs and to meet the goal of estimating the mutual spatial relationship of the extrados and extrados of the vaults with greater precision. The photogrammetric acquisition was performed using a Phantom 4 RTK drone (Figure 3a 5.1) equipped with an FC6310R camera (equipped with a 1'' 20 MP CMOS sensor with a focal length of 8.8 mm / 24 mm 35 mm equivalent format).

3a 5.1: Phantom 4 RTK.



3a 5.2: Phases of accurate flight planning in an urban area subject to restrictions that impose the position of the drone within the vertical volume of the building.

The aerial survey affected the entire the Turin Exhibition Center complex and the immediately adjacent areas, covering an area of approximately 0.07 km^2. The average flight altitude was around 60 m, with an estimated *Ground Sample Distance* (GSD) of approximately 1.5 cm. Several flights were planned in order to acquire both nadiral images (in order to cover the surfaces relating to the roofs) and images inclined at 45° (to tighten the calculation and to improve the identification of the vaulted surfaces of the roofs). 1922 images were acquired (image resolution: 5472 x 3648 pixels), of which 850 nadiral and 1072 oblique (Figure 3a 5.2).

The digital images acquired following the methods illustrated above were subsequently processed using the photogrammetric software based on Agisoft Metashape SfM (Structure-from-Motion) algorithms. The workflow followed was the following:

I. Relative orientation of the images by extraction of tie-points (Figure 3a 5.4)

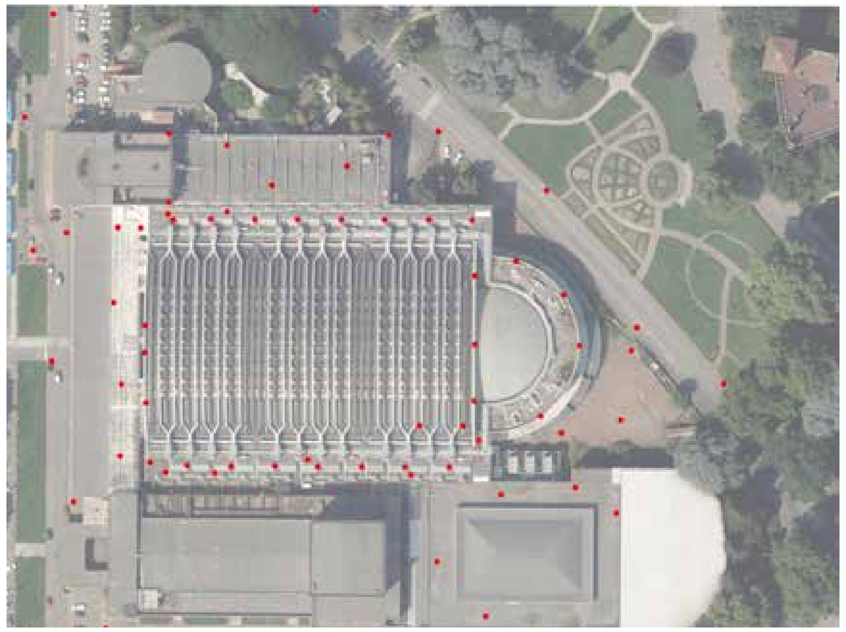
II. Extraction of tie-points

III. Georeferencing and bundle adjustment using the set of control points acquired as reported previously.
In total, 39 points were used as GCPs (Ground Control Points) and 25 points as CPs (Control Points) (Figure 3a 5.3). The accuracy (RMSE) observed on GCPs and CPs is shown in Table 2.

IV. Generation of a dense cloud (3a 5.5)

V. Generation of a DSM (3a 5.6 left)

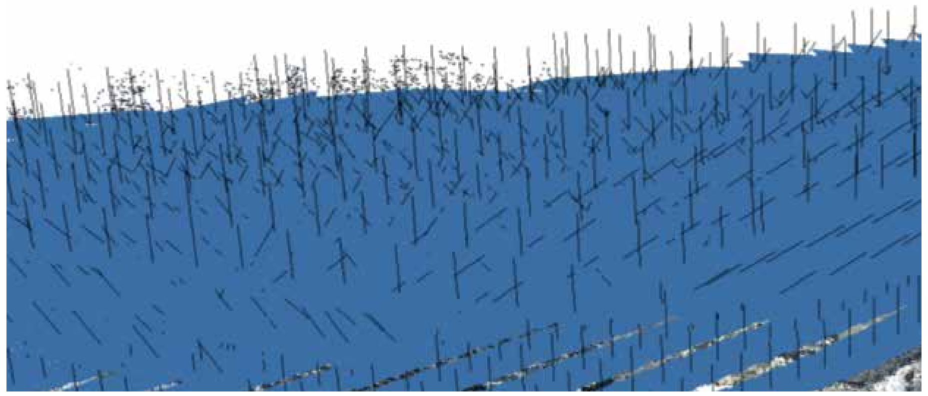
VI. Generation of an orthophoto (3a 5.6 right)



3a .5.3: Distribution of control points for UAV photogrammetric survey

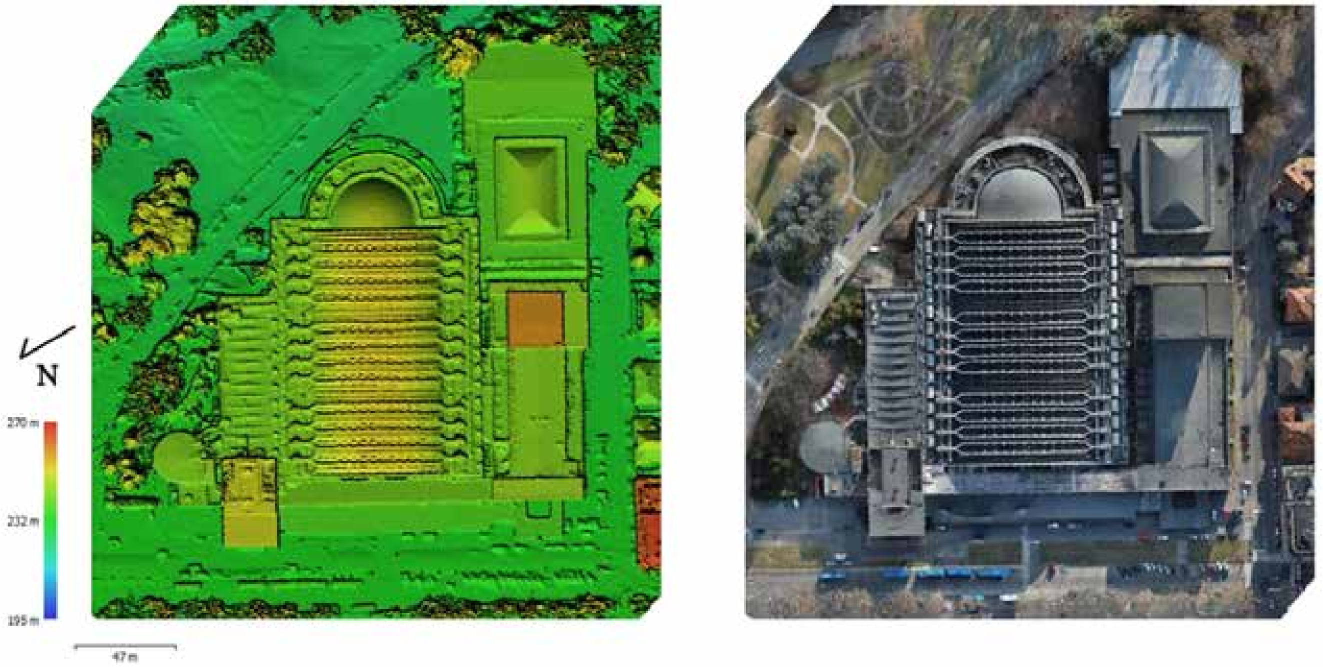
3a .5: TA Table 2: Accuracy observed on control points (GCPs and CPs).

	RMSE [m]			
	X [m]	Y [m]	Z [m]	XYZ [m]
GCPs (39)	0.017	0.014	0.009	0.024
CPs (25)	0.021	0.016	0.013	0.030



3a 5.4: Oriented images and tie-point cloud.

3a 5.5: Dense cloud.



3a 5.6: Metric products achieved using the photogrammetric technique. Left, DSM. Right, orthomosaic.

3a.6 Laser Scanning survey

As regards the interior spaces, a complete terrestrial laser scanning survey was planned and conducted inside both Hall B and Hall C, with the aim of acquiring the greatest number of surfaces and geometries to document the interior of the spaces measured as completely as possible. The laser scanner used was of the phase shift type, model Faro Focus3D X330 (Figure 3a 6.1). It is possible to read the technical specifications of the instrument used in Table 3.

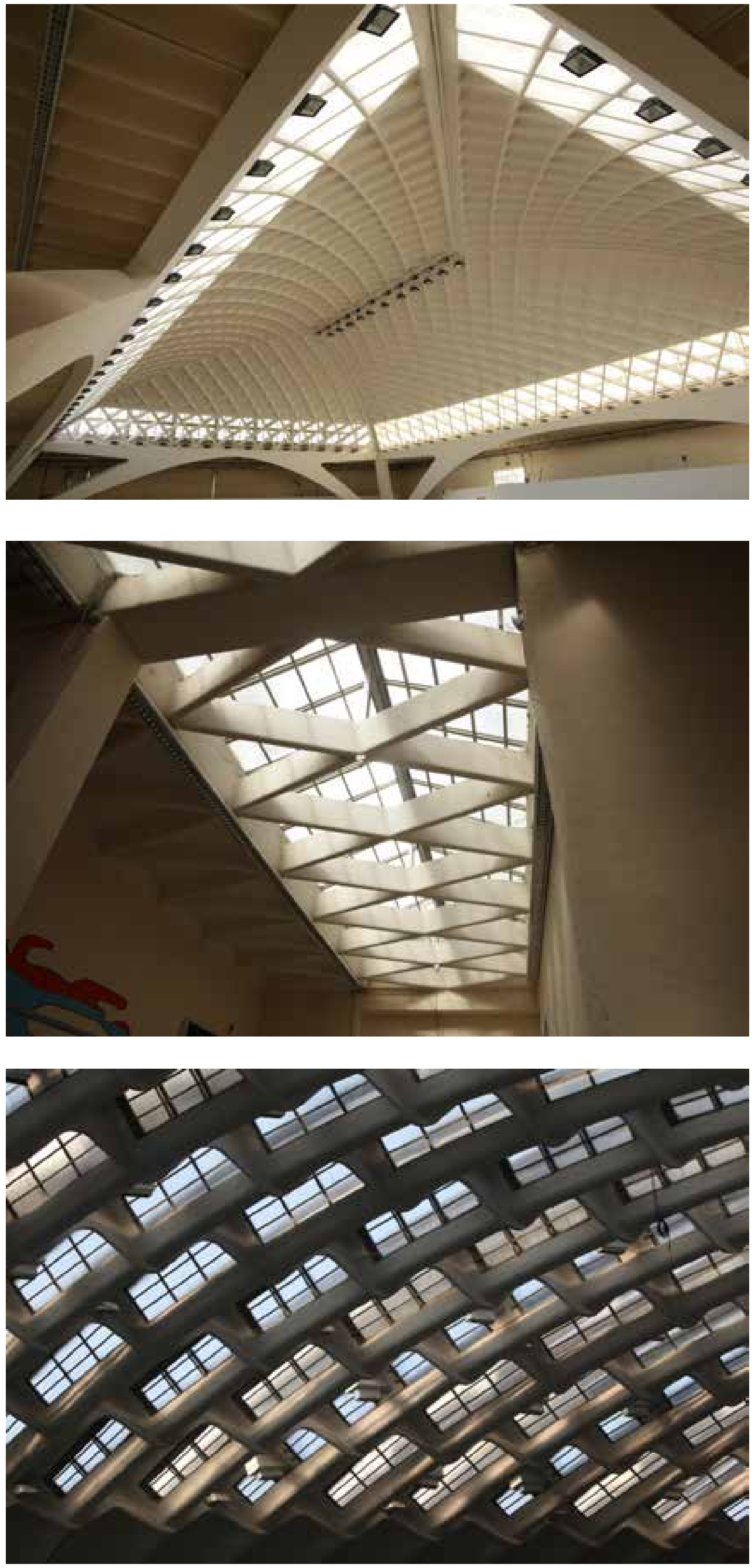
The position planning of the station acquisition was carried out in order to optimize the reciprocal coverings between contiguous scans and, therefore, to minimize the number of scans required to obtain the complete covering of the two halls. Therefore, the occlusion areas, blind areas, and areas characterized by an increase in terms of noise (due to various factors including, for example, the presence of glass surfaces) were taken into account. (Figure 3a 6.2)

The acquisitions and the subsequent data processing phases aimed at a correct recording of the scans were carried out as reported in the following paragraphs.

3a 6.1: Laser scanner Faro Focus^{3D} X330

3a 6. TA Table 3: Technical specifications of the laser scanner used during the survey.

Laser scanner	X 330/S120
Field of view (Hz and V)	305/360°
Accuracy	± 2 mm @ 10 m
Acquisition speed	up to 976,000 pt/s
Camera	RGB



3a 6.2. a, b, c: Example of views of challenging architectural/structural elements of Halls B and C.

Hall B

58 static scans with a planned density of points >100,000 pt / m^2 were acquired in Hall B. The acquisitions were divided as follows:

- N° 7 scans in the area adjacent to the entrance.
- N° 4 scans in the central area of the hall.
- N° 6 scans in the northern loggia.
- N° 10 scans located in the exedra area.
- N° 10 scans in the area adjacent to the connecting stairs between the exedra and the basement.
- N° 21 scans in the basement.

The registration of the scans took place with a two-phase process according to a consolidated workflow, which consisted of a preliminary registration using the ICP algorithm (*Iterative Closest Point*). The average error observed at the end of this procedure, understood as the average distance between the points of the recorded scans, was approximately 3 mm. The second step consisted of the registration by means of control points (measured by total station: in this way both points materialized in the form of high radiometric contrast checkerboard targets, and uniquely recognizable natural points were measured). In total, 28 control points were used: the average error at the end of this second registration procedure was observed to be approximately 5 mm.

Considering the high number of points (equal to over two billion points), at the end of the registration procedures, we then proceeded to apply a filter to the overall cloud to eliminate redundant or noisy points and any outliers. An algorithm to radiometrically equalize the colour of the clouds of adjacent points, with the aim of homogenizing the RGB value of the adjacent scans at the end of these processes, the point cloud derived from the LiDAR survey is composed of approximately 193 million points.

In the case of Hall B, the static Lidar cloud was generated at crucial points of the arched structure, entrance and exedra. In the main hall, the Swift cloud from MMS, co-registered at a later stage in the global reference system, was used (see next Par.) (Figure 3a 6.3)

3a 6.3: LiDAR cloud of Hall B.

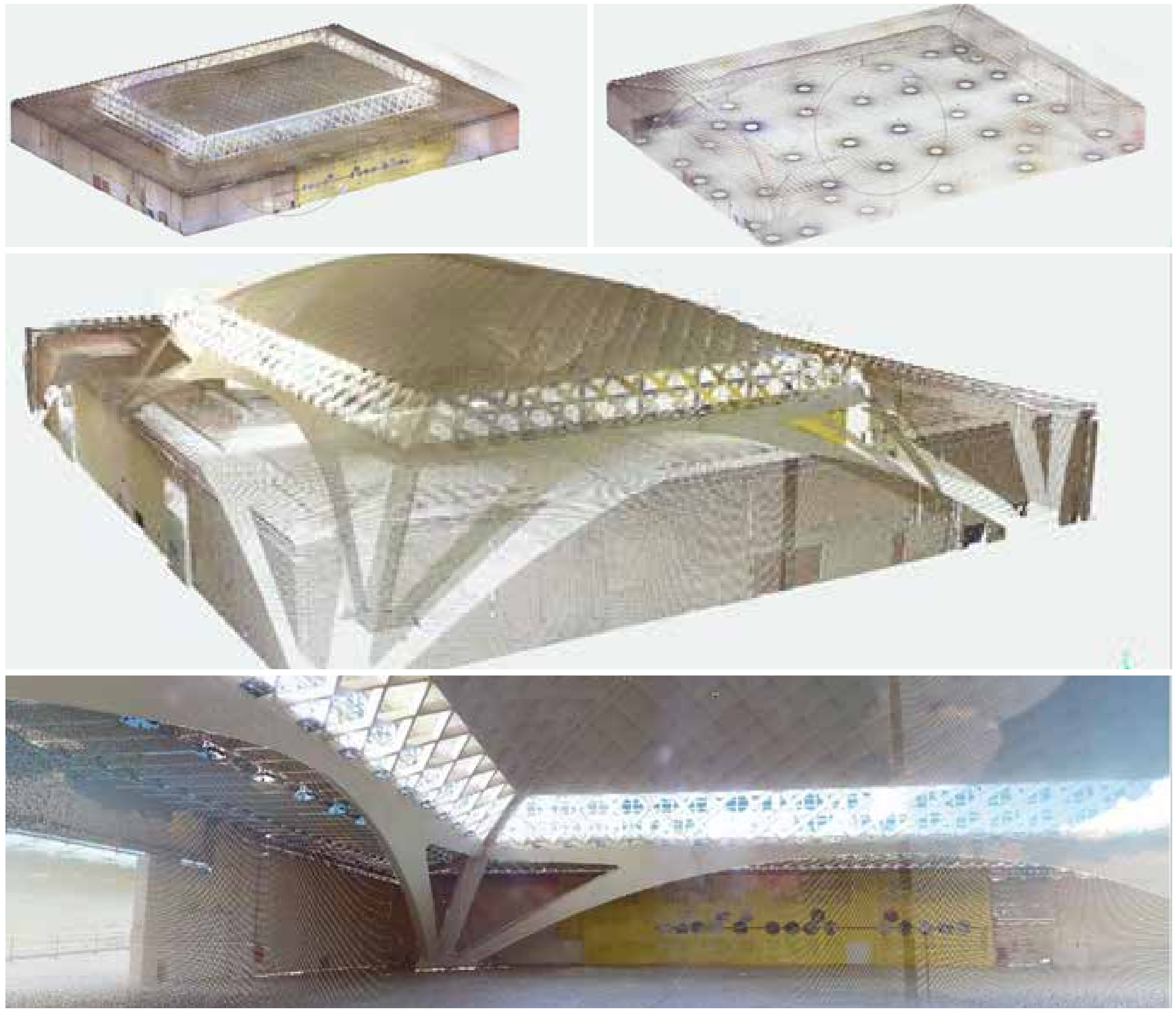
Hall C

52 static scans were acquired within Hall C, with a planned density of points of > 100,000 pt / m^2. The acquisitions were divided as follows:

- N ° 44 in the hall area.
- N ° 8 in the corridor adjacent to the hall.

In this case also, the point clouds were registered following the previously illustrated, operational workflow. During the first phase (recording using the ICP algorithm), the average error observed was approximately 2 mm. Subsequently, registration was carried out using control points (the metric control was also carried out by means of topographic measurements with a total station). 39 control points were used (again both resulted in points in the form of a checkerboard target with high radiometric contrast and uniquely recognizable natural points were used): the average error at the end of the target-based registration was observed to be approximately 7 mm.

Moreover, the same procedure for filtering the points and radiometric equalization described in the previous paragraph was conducted.

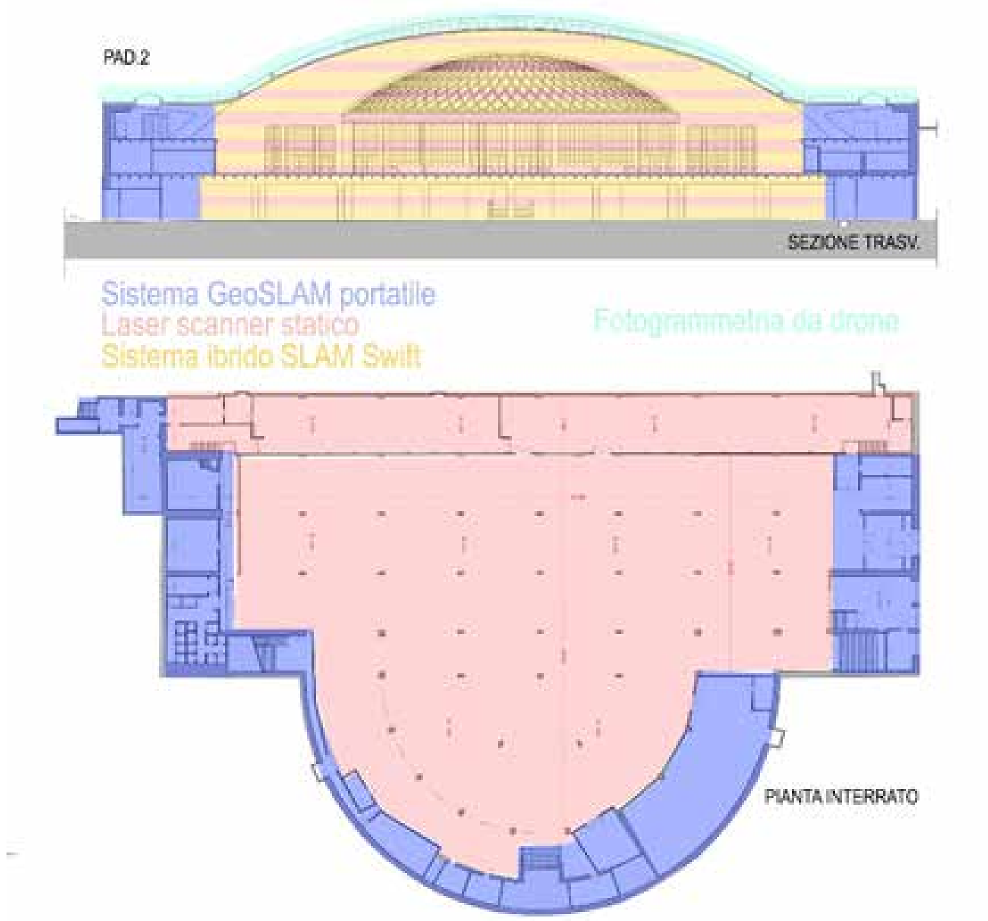


3a 6.4. a, b, c, d: (above left) LiDAR cloud of Hall C. (Above right), LiDAR cloud of Hall C with the positions of the laser scanner stations highlighted. (Below), a general view of the point cloud and a zoomed view of the entrance area.

3a 6.5: A projected section of the LiDAR point cloud of Hall C.

3a.7 Completion of the survey by MMS integration

The configuration of the environments, their accessibility, and the reasons linked to the effectiveness of some of the measurement phases made it possible to experiment, as previously mentioned, with 3D mapping systems to complete the main environments mapped traditionally with a static scanner, locally more accurate and certainly and globally more expensive in terms of resources. We verified and validated these techniques as being well suited to the complexity of the hall spaces and their competitiveness made it possible to speed up data acquisition times. More specifically, the areas of Hall B delimited by temporary plasterboard walls below the galleries and above the north gallery, which incorporate the structures of the large, inclined arches (or pillar-arches) in their attachment to the ground, were mapped together with the rooms in the basement using a series of trajectory scans performed with the SLAM system (Figure 3a 7.1).

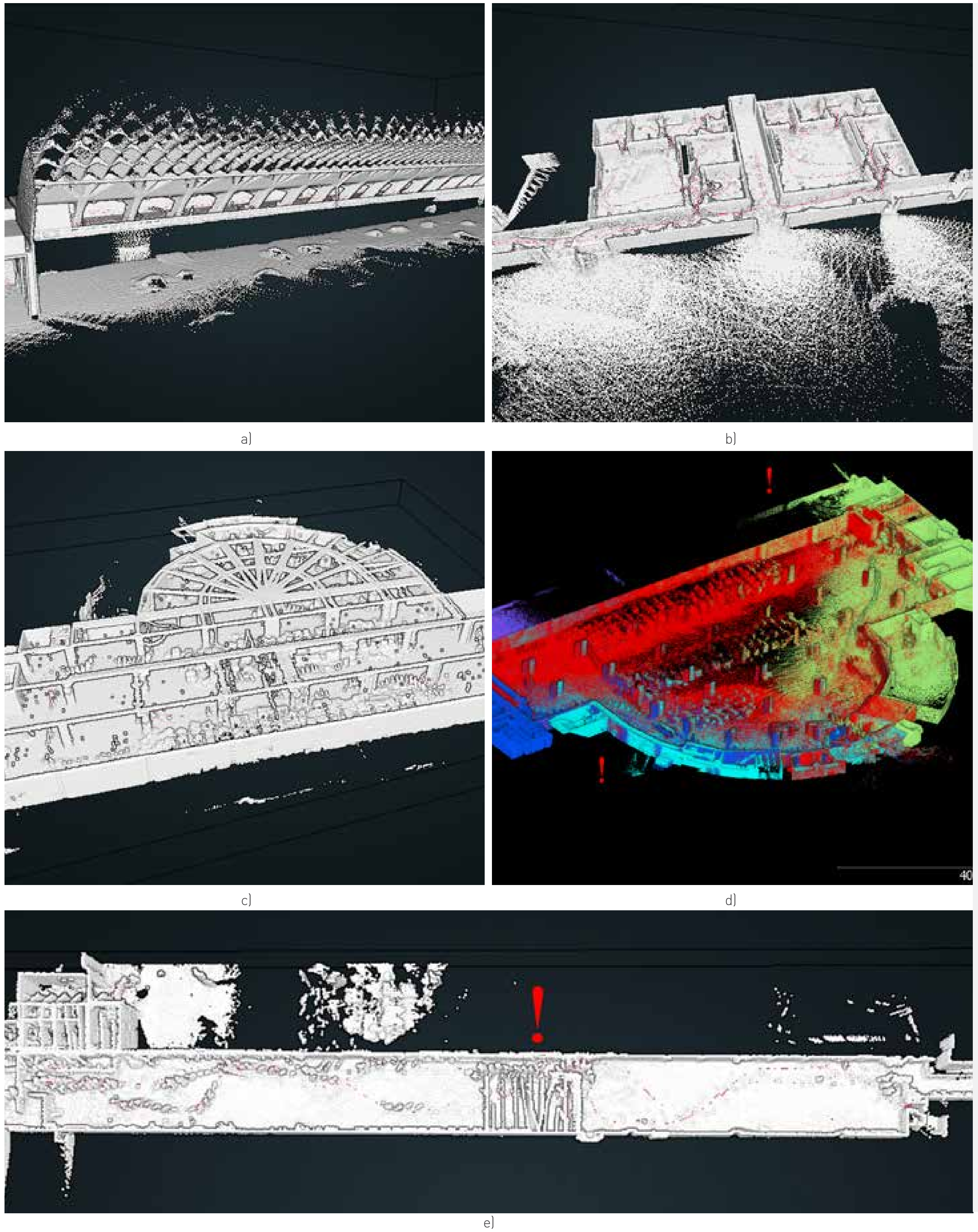


3a 7.1: Areas of Hall B and coverage of the integrated techniques used.

3a.8 ZEB Revo RT by GeoSLAM

The portable system ZEB Revo by GeoSLAM was mainly tested in Hall B. It was possible to complete the complex and extensive mapping not only of the upper and lower temporary spaces of the galleries consisting of plasterboard partitions, but also of part of the articulated areas of the basement, with a considerable saving in terms of time and operational resources used (Figure 3a 7.2).

The acquisitions featured closed trajectories returning with the closing of the acquisition at the starting point. The scanning operations exploited the operator's movement and the features of the environment: the SLAM algorithm was able to determine the trajectory of the projection centre, on the basis of which it was possible to calculate the cloud acquired during the trip using ICP algorithms. Some of the trajectories worked on the upper floor in the two galleries and in the underground space are shown (Figure 3a 7.2).

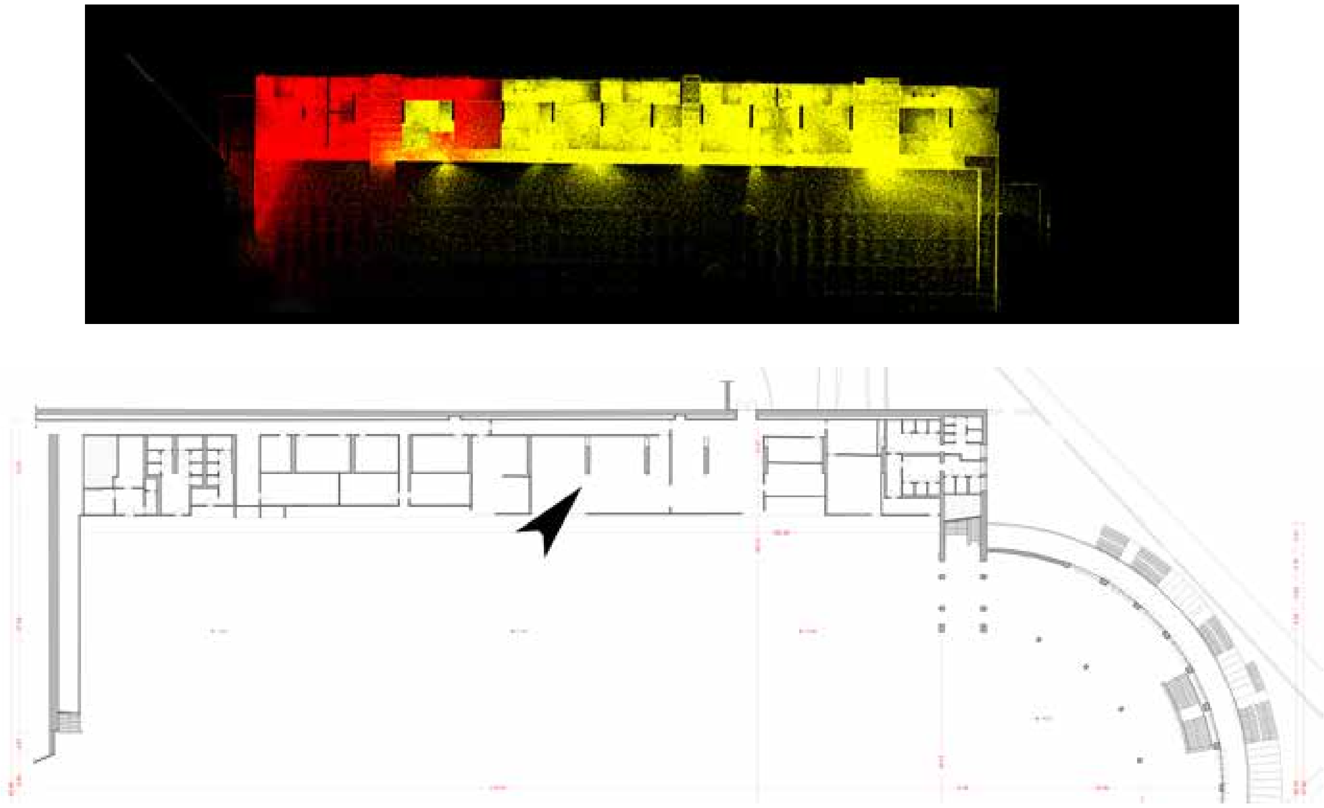


3a 7.2. a, b, c, d, e: Some working images of the clouds acquired with the GeoSLAM portable mobile system. Both the correctly acquired data and the cases in which the algorithm failed for reasons of configuration of the environment are reported. The last images show the different merged clouds in the underground environment and some misalignment problems.

The rooms on the ground floor required a division of the trajectories due to the complexity of the environments and the risk of a possible drift in the acquisition of geometries with trajectories that travelled too far. The acquisitions had an average duration of 10-20 minutes, with 15mln-25mln points per scan, depending on the route. For this reason, the north and south rooms on the ground floor and their bathrooms were acquired separately, but with overlapping areas: 3 clouds in the north side rooms and 5 clouds in the south side rooms.

The basement proved to be an environment that appears to be congruent with the typical spaces of the operation of such SLAM systems, but a series of environmental conditions made the acquisition articulated and the performance of the measurement system was compromised. Some of the causes were the dense, modular mesh of pillars at the exedra, the pervasive presence of water on the ground and on the walls due to infiltrations, and a number of reflective metal surfaces that caused noise problems, drift errors and duplications of the acquisition patterns (Figure 3a 7.2).

The 5 clouds via MMS in the basement, therefore, only concerned the accessory rooms and for this reason, the SLAM acquisition was integrated with a static scan dataset of the central entrance area.



3a 7.3: The combination of clouds from consecutive trajectories in the north rooms of the ground floor of Hall B and the corresponding architectural drawing to a scale of 1: 200. It was thus possible to recognize and measure the complete spatial configuration of the large, inclined pillars incorporated into the rooms.

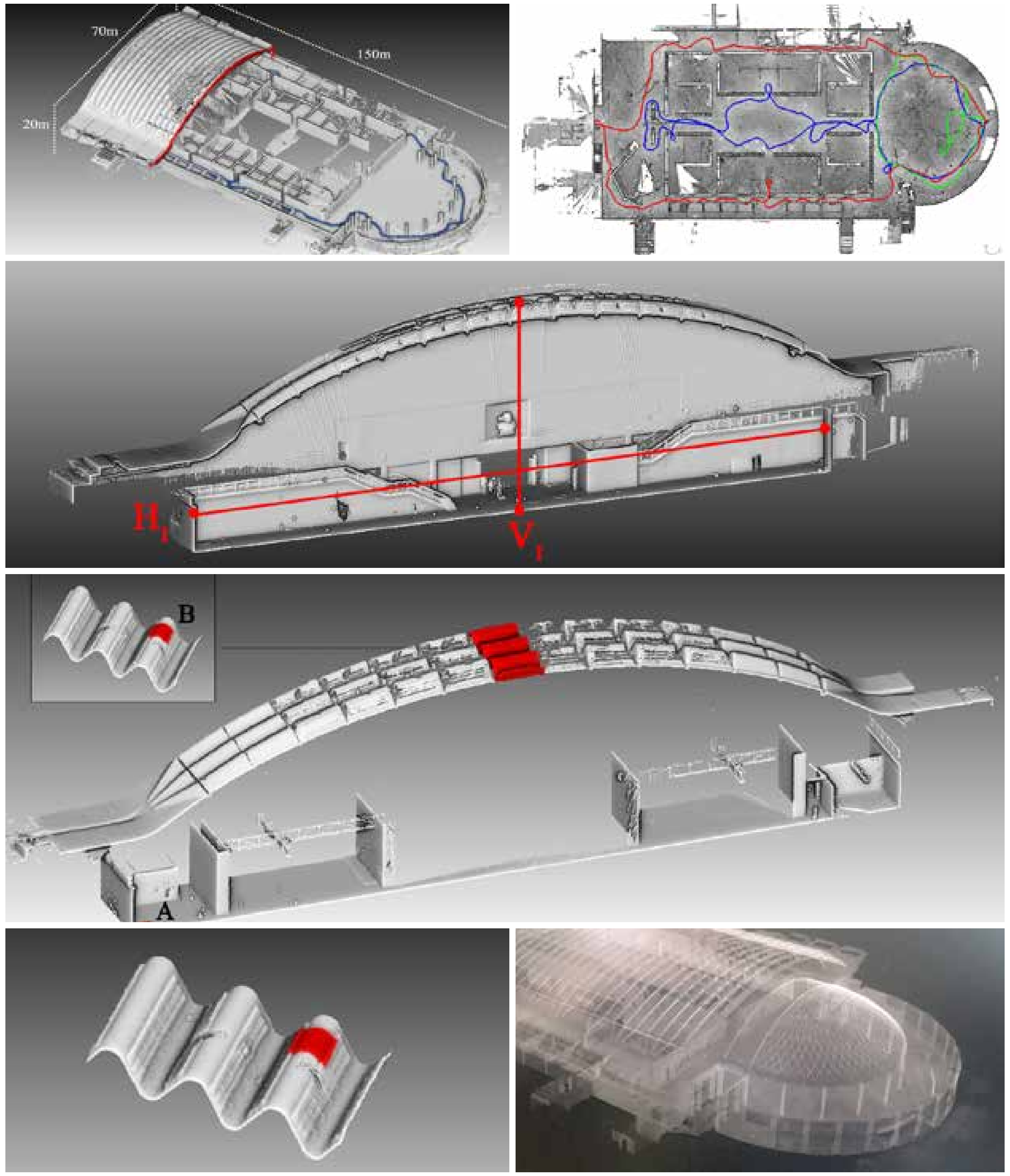
SWIFT System by FARO

The Swift system by FARO Technologies, introduced in paragraph 3a. 2, was tested in the large vaulted environment of Hall B and at the same time also in Hall C as a comparison to the more consolidated static technique. The data relating to Hall B, where the 3D cloud from Swift was used, was an integral and consistent part of the mapping and graphic rendering and restitution.

Three acquisition trajectories were established in the main open rooms of the nave, along which the operator walked at a constant, slow speed: two in the hall and one around the pillars of the exedra, in connection with the descent to the basement.

The trajectories lasted approximately 10-15 min each (Figure 3a 7.4), with routes up to 400m (red), and a point cloud of approximately 600-700mln points (red and blue). A sample of longitudinal measurements, compared with the static reference data, made it possible to globally validate the Swift system with an average residual error <1cm for shorter distances, less than 100m, and 4-5 cm for longitudinal distances > 100m.

As regards a local evaluation of the 3D data, in terms of geometric accuracy and precision, useful for treating the cloud in the process of sectioning, vectorization and modelling, different cloud samples were analysed. For example, samples a and b in Figure 3a 7.4 are approximately 53,000 pt / m^2, on the ground, and about 23,000 pt / m^2 in coverage at about 20m from the sensor, respectively. Density analysis of the data points, the flatness of the reconstructed surfaces and the noise in the distribution of the points are at very competitive values compared to the static scanner, although not with the same instrumental precision. The data, integrated with the remainder of the point model, was then used efficiently, together with the data from the static and portable SLAM data, for the interpretation and graphic rendering phase.



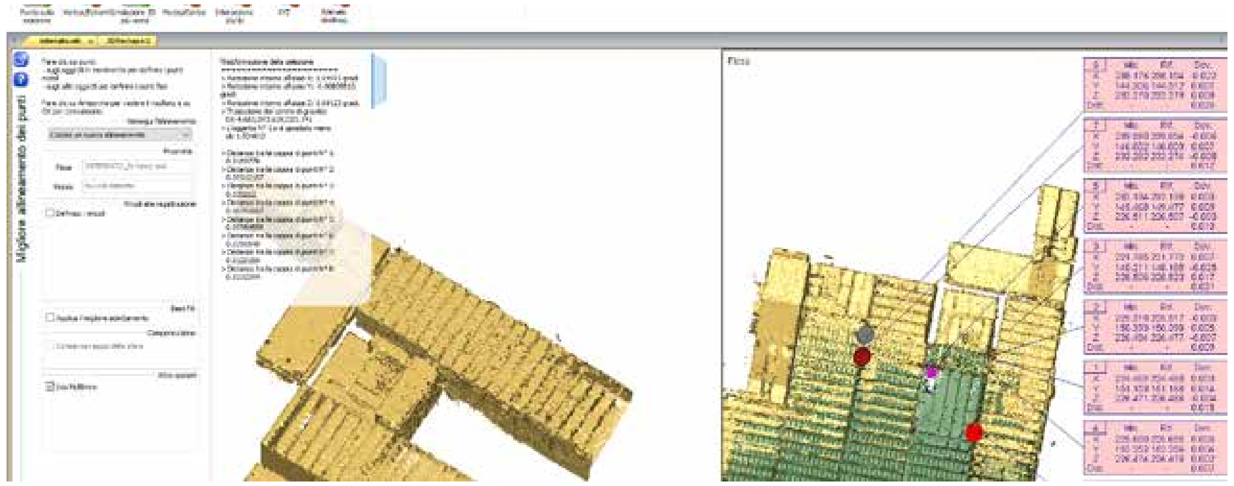
3a 7.4. a, b, c, d, e, f: Visualization of the Swift mobile scanner cloud with relative trajectories.
Section of the cloud with a sample of longitudinal measurements and verification of cloud density at floor and roof level.

3a.8 Integration of point clouds

In line with the methodological approach presented, and thanks not only to the targeted planning of acquisition technologies, screened and weighed according to the different environments, but also to the continuous use of topographical support for the adoption of the global reference system and the control of the propagation of errors, it was possible to achieve a complete 3D model relating to both the intrados and the extrados of the volumes. In short, the effective integration of metric data-oriented towards the 3D modelling concerned the external clouds from drone photogrammetry and the internal clouds from static and mobile LiDAR systems.

As regards the integration of external clouds, the approach ensured overall co-registration, thanks to the use of the same reference system in the measurement of photogrammetric control points and for those used in scans, both static and mobile via Swift[14].

SLAM clouds, on the other hand, required a complex approach to verify an accurate co-registration in the point model, in line with the accuracies sought for the purposes of the model, with a maximum error of less than 4-5cm. Once processed, verified and segmented, the SLAM clouds were each co-registered with the internal LiDAR model, thanks to the creation of correspondences on homologous points. An average error check was carried out on them (Figure 3a 8.1) and they were verified as being within the limits of acceptability.



3a 8.1: Co-registration of the clouds derived from the ZEB Revo GeoSLAM system in the global reference system thanks to the creation of correspondences with the static LiDAR cloud as a result of the collimation of points of common areas.

3a.9 Close range photogrammetric survey of non-destructive investigations

One of the planned objectives of the project is to integrate the larger-scale documentation of the points of interest and spatially localize the diagnostic activities of the multidisciplinary team and the investigations carried out in specific areas distributed over the hall surfaces.

This need was an opportunity to test a combination of consolidated digitization techniques and more innovative approaches on complex surfaces, thanks to the help of the forklift, which made it possible to establish closer projection distances of the sensors.

During the metric survey campaign, various additions were planned to use the terrestrial close-range photogrammetric technique, and therefore, several photogrammetric datasets were acquired. The objective of these additions was twofold: on the one hand to radiometrically enrich the LiDAR data where necessary. On the other, to carry out targeted focuses on elements of particular interest (e.g. those investigated by the team of structural engineers) to be able to achieve more detailed, high precision metric products. Furthermore (as regards Hall B), a very high-resolution structured light scanner was tested to acquire some lesions located on the great vault close to the exedra dome. The different datasets were acquired according to the following strategies:

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[14] For the verification of the morphological characterization of the envelope, see Paragraph 3c.

Hall C

A first dataset consisting of 1045 images (featuring high mutual overlapping) was acquired inside Hall C. A complete photogrammetric survey of the hall was conducted using a high resolution DSLR (Digital Single Lens Reflex) camera, Canon EOS model 5DSR, equipped with a Zeiss lens (model: Zeiss ZE / ZF.2 Distagon T* 25mm f / 2, focal length 25mm). The specifications of the camera used are shown in Table 4.

3a 9.1: Left, Canon EOS 5DSR. Right, Zeiss ZE / ZF.2 Distagon T* 25mm f / 2 lens.

3a. 9. TA: Table 4 Technical specifications of the camera used during the close-range photogrammetric survey.

Model	Canon EOS 5DSR
Sensor	CMOS 50.3 Mp
Sensor dimension	36 x 24 mm
Image resolution	8688 x 5792 pixels
Lens	Zeiss ZE/ZF.2 Distagon T* 25mm f/2
Focal length	25 mm

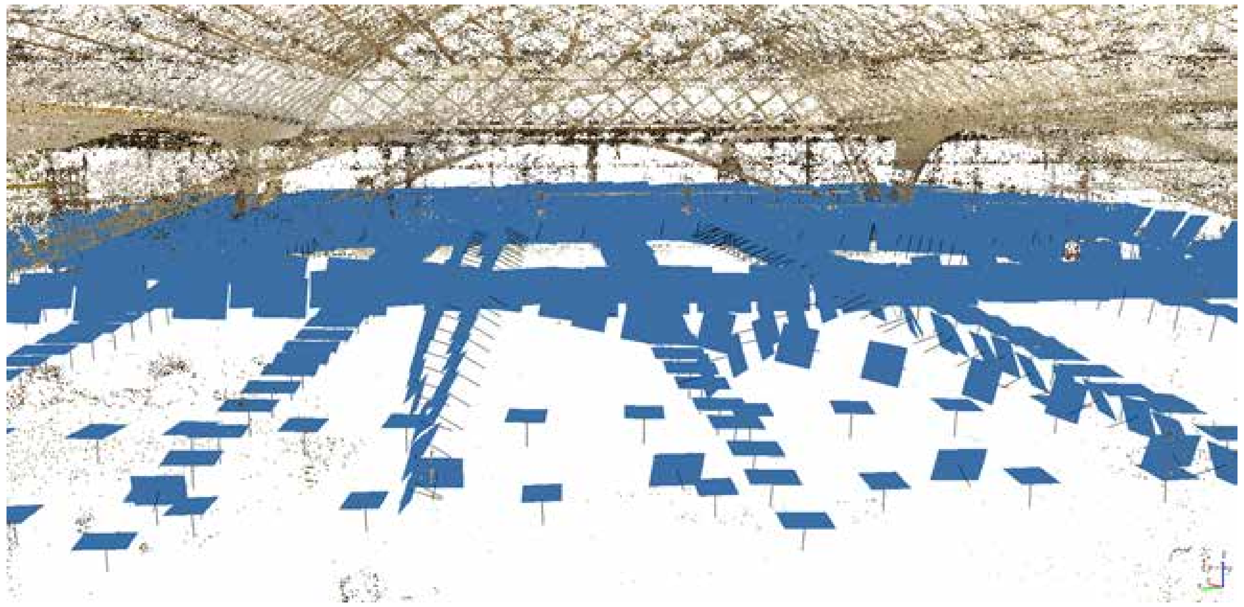
In this case, as specified above, the main purpose was to acquire as many surfaces as possible in the hall, in order to integrate the previously acquired LiDAR data (featuring a high spatial and geometric resolution) with the radiometric content of photographic data. The images were acquired with the following parameters: diaphragm opening: f/11 – exposition time: range from 1 to 8 s; ISO 100.

The parameters used aimed to ensure a correct depth of field, a reduced electronic noise of the images, and an adequate level of brightness. The high exposure time during the acquisition was due to the poor lighting and therefore not optimal. It was, therefore, necessary to use a tripod to stabilize the camera and a device for remote shooting.

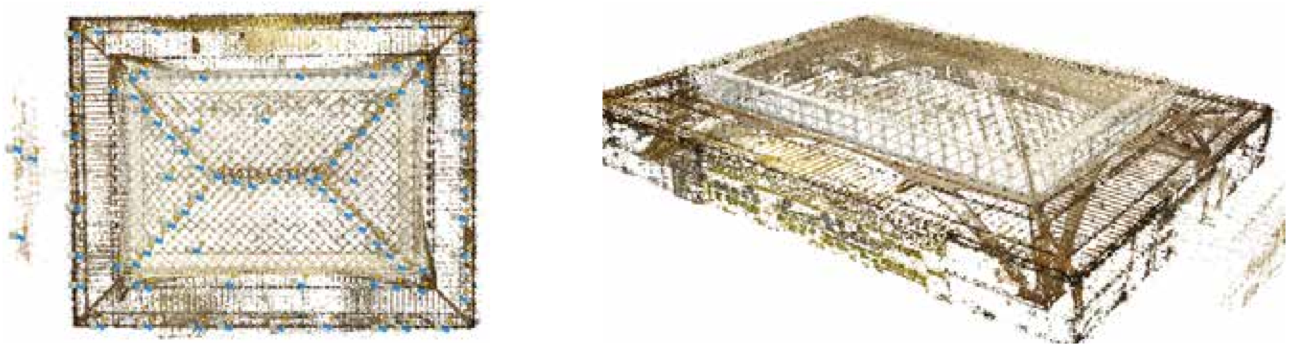
The estimated average acquisition distance was 13.2 m, with an average GSD of approximately 3 mm. A total of 1047 high-resolution images were acquired, which were processed with the photogrammetric software Agisoft Metashape (following the operational workflow reported in paragraph 3a.5 p.118). A set of 84 points was acquired using a total station, of these points a total of 62 were used as GCPs, whereas 22 were used as CPs. Table 5 shows the accuracies reached on the control points. (Figure 3a 9.3)

3a 9. TA: Table 5: Observed accuracies on control points (GCPs and CPs).

	RMSE [m]			
	X [m]	Y [m]	Z [m]	XYZ [m]
GCPs (62)	0.007	0.005	0.003	0.009
CPs (22)	0.006	0.003	0.005	0.008



3a 9.2: Oriented images and sparse cloud of tie points.



3a 9.3: (Left), tie point cloud with control points. (Right,) tie point cloud.

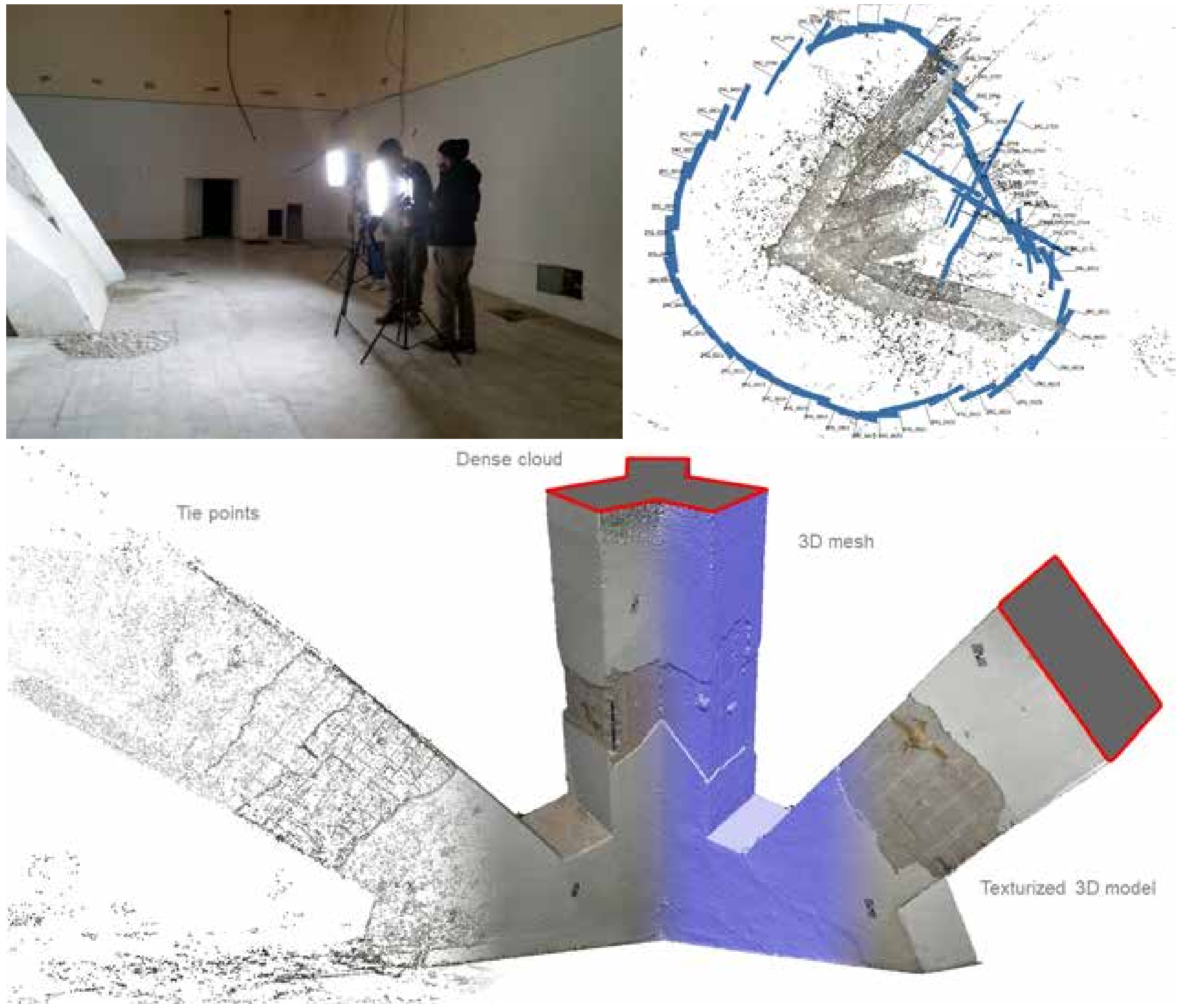
Special attention was also paid to the structural elements located at the base of the arches in Hall C, where the progressive diagnostic investigations were concentrated. A highly detailed, large-scale survey then focused on these elements. The multi-temporal documentation process followed the steps of the investigations, with the aim of acquiring all the various phases of the cognitive process using the photogrammetric method. In this case, the use of a similar strategy based on photogrammetric shooting proved to be a quick solution implemented during the activities to document the various investigative processes involving the bases of the arches.

In total, approximately 80-90 images were acquired for each element at an average distance of 3-4 m. The planning of the photogrammetric acquisition guaranteed a GSD <1mm to document in high detail the various phases of non-destructive tests that were carried out during the diagnostic studies by the team of engineers.

The camera used for close-range photogrammetric surveys was a high-resolution DSLR model Canon EOS 5DSR, equipped with a Zeiss lens (see above). The resolution of the acquired images was equal to 8688 x 5792 pixels. The images were acquired with the following parameters: diaphragm opening: f/16 – exposition time: ⩾ 1 s; ISO 100.

In this case, poor lighting was detected inside the hall; therefore, in addition to a photographic tripod and a remote shutter device, a system of artificial lighting (two LED Lupo lights) was also required in order to correctly acquire the images needed for the 3D reconstruction of the bases of the arches. (Figure 3a 9.4)

The photogrammetric blocks of images thus acquired were processed using the Agisoft Metashape photogrammetric software, following a workflow similar to the one described in paragraph 3a.5 p.118. Again, the model was oriented and scaled by means of the use of control points.



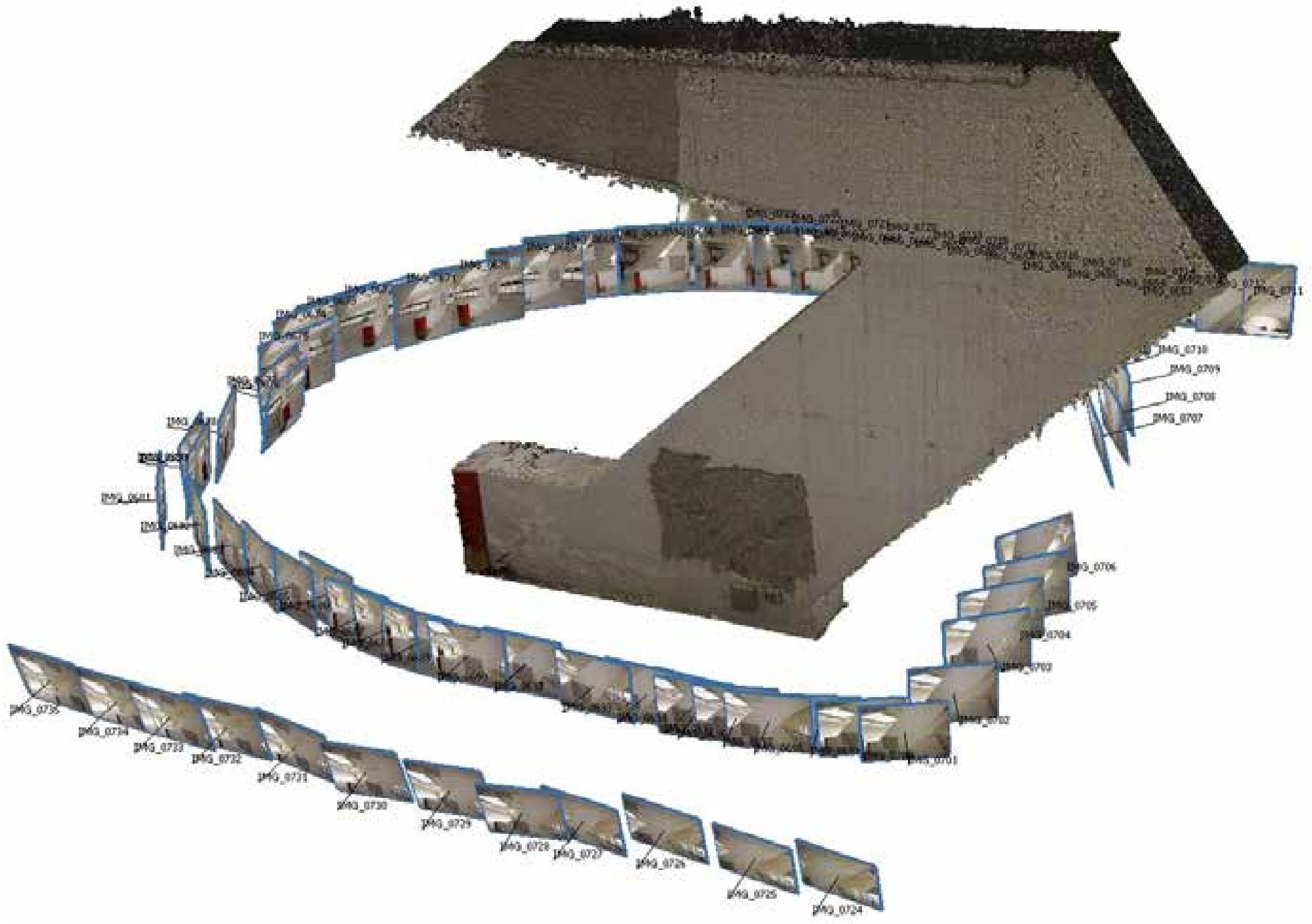
3a 9.4: Phases of image acquisition, the orientation of images acquired from close distances, the final model that integrates the visualization of the point cloud, triangulated surface (mesh), and textured surface.

The texturized model developed starting from the images acquired after the survey work made it possible to identify and measure the position (in the global reference system within which the metric survey campaign was developed) of the cores, and the diagnostic sensors exposed bars, crack patterns, etc. It was also possible to extract very high-resolution orthophotos to document the analysed surfaces with a high level of detail. (Figure 3a 9.5)

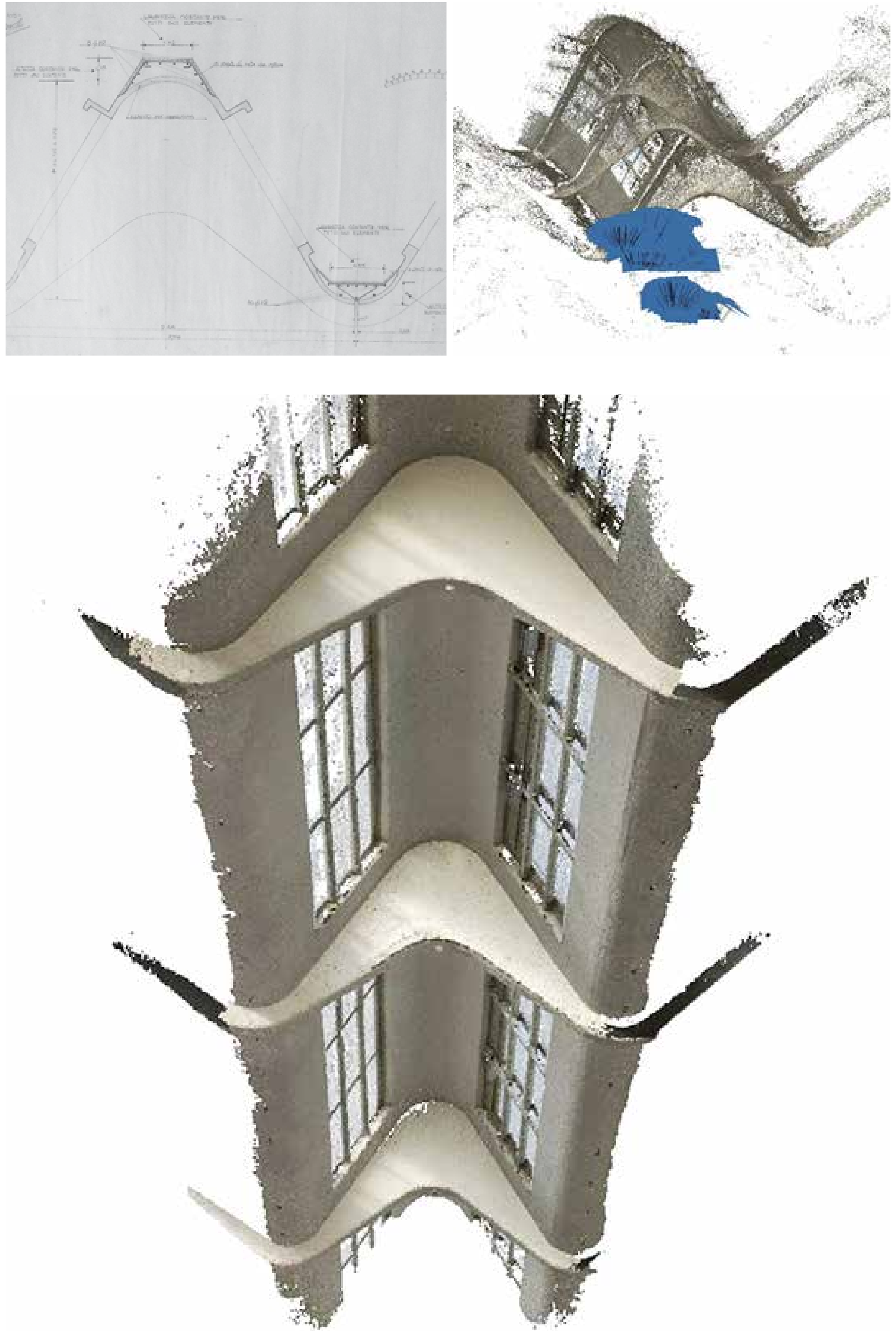
3a 9.5: Texturized model of the base of the arches, enabling corings, cracks and exposed iron to be located, and the positions of the sensors used during diagnostic investigations. Below: an example of orthophoto of a recognition area of the column reinforcement grid.

Hall B (close-range photogrammetric survey and use of a structured light, 3D scanner)

Similar to what was implemented in Hall C, large and very large-scale surveys were also carried out in Hall B, aiming at the structural elements subject to diagnostic investigations. The acquisition procedure was similar to that described in the previous paragraph. The same camera and lens described in the previous paragraphs were used again. Each photogrammetric block, consisting of approximately 70-80 images for each element, was processed with the aim of obtaining dense, high-resolution data, suitable for efficiently documenting the various tests performed. (Figure 3a 9.6) Furthermore, as anticipated, thanks to the use of a forklift that made it possible to bring the position of the sensor projection centers closer to the hall vault, it was possible to acquire close-up images of a module of the hall roof with photogrammetric criteria. A total of 333 images were acquired, which made it possible to digitally reconstruct the geometry of the module in the interdisciplinary study. (Figure 3a 9.7)



3a 9.6: Oriented images and dense cloud of the sample pillar P12n.



3a 9.7: Project drawings of the wave elements of Hall B, and photogrammetric reconstruction of a module of the vault.

As regards the vault placed between the wav ceiling and the exedra dome, in addition to the photogrammetric approach, the use of the structured light laser scanner Stonex F6 SR was also tested (Figure 3a 9.8).

The Stonex F6 SR scanner works at distances between 25-50 cm, acquiring approximately 640000 points per second. A near-infrared (NIR) pattern is emitted, projected, and measured by the receiver as a mesh of 3D points in the measured space, thanks to a triangulation algorithm. With the use of this technology, it was possible to acquire very high-resolution, in-depth point clouds relating to the lesions located on the cylinder vault adjacent to the exedra of Hall B, to carry out very large-scale documentation.

These initial datasets (Figure 3a 9.9) made it possible to reflect both on the methodological issues relating to this type of structured light scanner and on the articulation and features of surfaces and materials to be documented using this technology, in order to establish repeatable operational workflows under similar conditions. Subsequent investigations and tests will be developed in the near future, together with possible in-depth analyses in view of larger-scale modelling of the construction elements of the dome.

3a 9.8: Stonex F6 SR - The forklift made it possible to reach distances of less than one meter in the great arch that separates the central nave and exedra. A portion of the surface where the investigations operated on the cleaning and removal of plaster due to a pre-existing crack was acquired on a very large scale, as can be seen from the preview shown in the photo.

3a.10 Representation of architectural drawings with integrated orthophotos

The representation of plans, elevations, and section profiles is a phase that enables a high degree of analysis of the overall morphology and that of the individual structural elements. The entire complex of 2D representations using architectural drawings was created by vectorizing thin portions of the point cloud, identified by horizontal and vertical section planes, and integrating the projected images of the point cloud on the section planes.

By way of example, we report the identification of an overall deformation arrow of the hall canopy in Hall C, which reaches 13 cm in the centreline of the light. This can be estimated on the digital elaboration, but certainly not from the simple view of the entire longitudinal section of the hall. (Figure 3a 10.1)

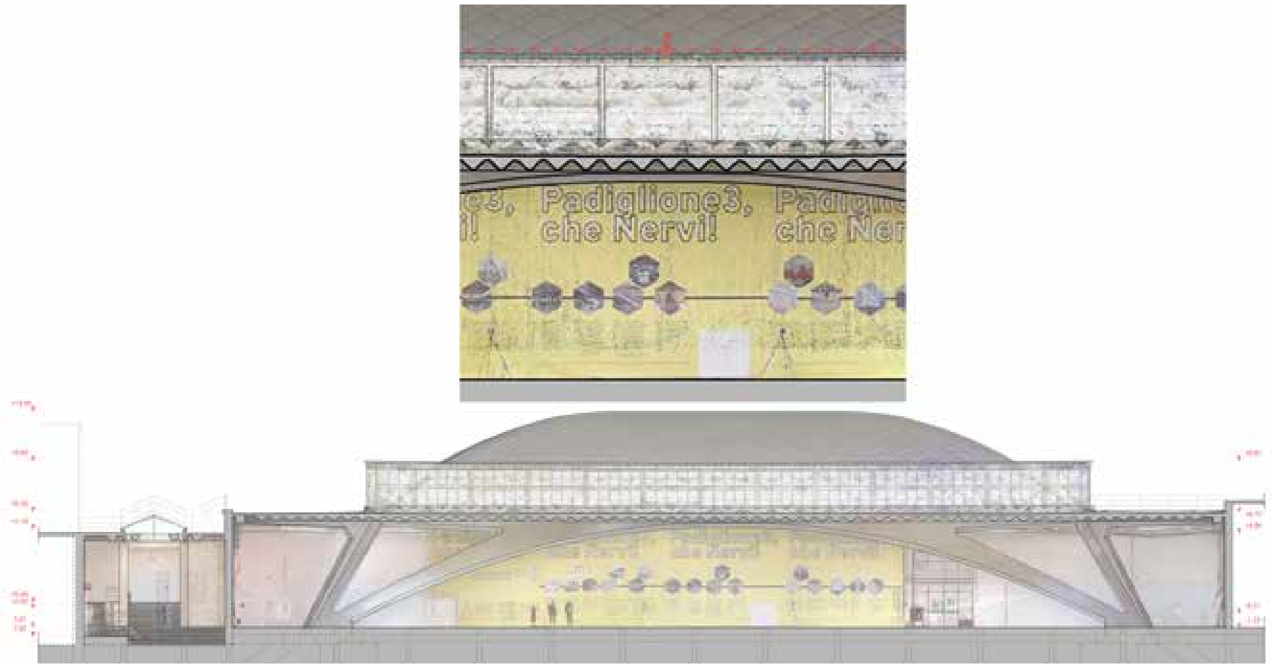
It's important to highlight that all the foundations' sections are derived from the project drawings by P.L. Nervi.

The purpose of the horizontal and vertical projections represented in the architectural drawings provided is to describe the main features of the building in a sufficiently exhaustive way. However, they can obviously be implemented and/or integrated according to the future needs of the study[15].

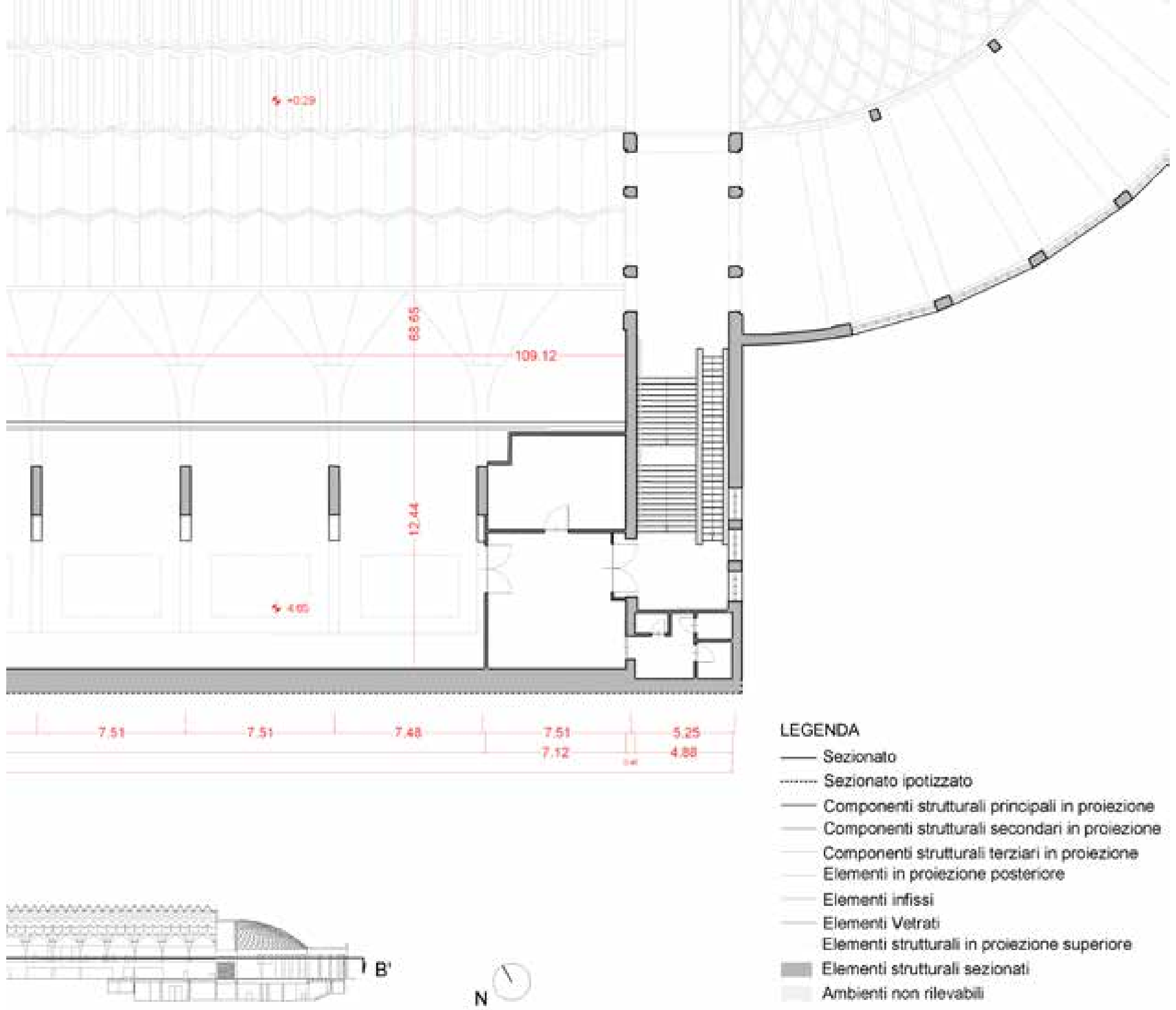
The roof plans, with and without orthophotos, are shown to a scale of 1: 500 in A1 format; in general, plans and vertical sections are shown in A1 format to a scale of 1: 200 and 1: 100. However, they are all equipped with an informative content adapted to the scale of 1:100 or higher[16].

The overall urban scale plan of the roof with orthophoto of the Turin Exhibition Center site is represented in the reference system WGS84 / UTM32 N, ETRF 2000[17]. Scale 1: 500.

Many linear and altimetric dimensions were inserted with the aim to evaluate the information contents of the drawings. Some examples in Hall B and C are reported. (Figure 3a 10.2)



3a 10.1: Identification of the 13 cm arrow in the middle of the light of the hall dome of Hall C.



3a 10.2: Example of the information contents of a drawing file, extract of the south-east portion of Hall B, with the customary key giving the hatching line types according to architectural representation rules.

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[15] A specific number of the entire complex of architectural drawings is presented at the end of the volume.

[16] For information about the accuracies given in the detailed surveys, compare the previous paragraphs. In general, it is important to highlight that the resolution of graphical documentation is higher than the metric accuracy in most cases.

[17] WGS84 (World Geodetic System 1984); UTM (Universal Traverse Mercator), ETRF 2000 (European Terrestrial Reference Frame 2000.

In the following pages, a reasoned selection of the panels is proposed with brief comments to guide reading.

The architectural representation of the roofs (Figure 3a 10.3), together with the orthophoto completed with altimetric and linear dimensions, obviously enables the analysis of the extrados of the vaulted roofs of the halls. However, they also enable an estimate of the volumes of the systems located on the roofs, or of the size of the refrigeration plant in the courtyard.

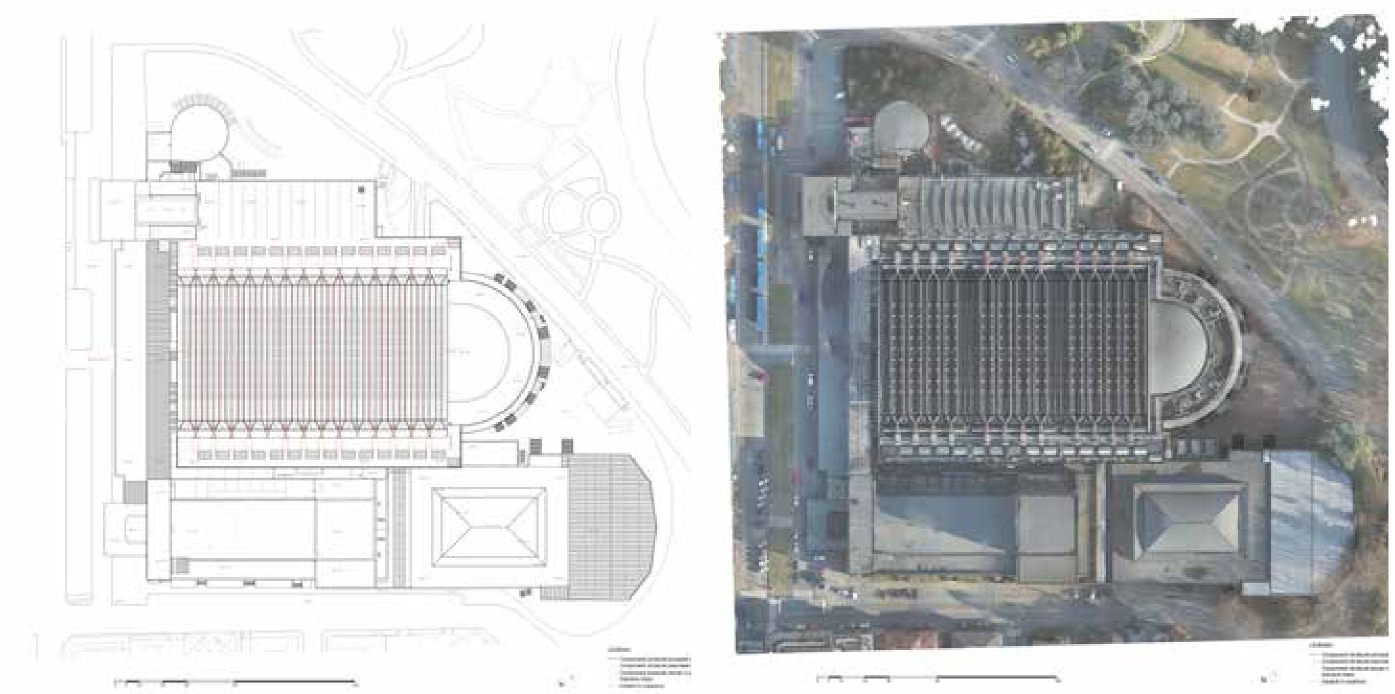
The panels relating to the two building levels of Hall B allow us to read the structural grid of the pillars-arches, which are clearly visible in their upper development in the south gallery, but hidden by the service areas of the ground floor and of the north gallery. The inclusion of the linear dimension system has tried to highlight the proportional and position ratios of the main structural system.

The plans of the different building levels show the projection of the vaulted system, for Halls B (Figure 3a 10.4 and Figure 3a 10.6) and C, whereas there is only a sample of the restitution of the prefabricated panels of the floor in the basement.

In the basement (Figure 3a 10.5), the repetition of the two plans with heights and projection of the frame of the floor is also an opportunity to represent the staircase leading to the basement in greater detail.

The longitudinal and transverse sections of Hall B cross all the building levels to better document the correspondence of the pillars to the different building levels (Figures 3a 10.7 and 3a 10.8.). As regards the coverage of Hall C, it was decided to also bring the different representations[18] to the scale of 1: 200 to better understand their characteristics. (Figure 3a 10.9)

There are also some examples of drawings from Hall C, for which the number of arrows in the centre has already been highlighted. Figures 3a 10.10 and 3a 10.11 show two longitudinal sections with and without orthophoto. Some reading rules apply to both series of drawings: for example, the elevations that are shown in the vertical sections concern different building levels if written on the left, whereas on the right, they focus on the significant elevations of structural elements.



3a10.3. a, b: Plan of the roof, with and without the UAV orthophoto.

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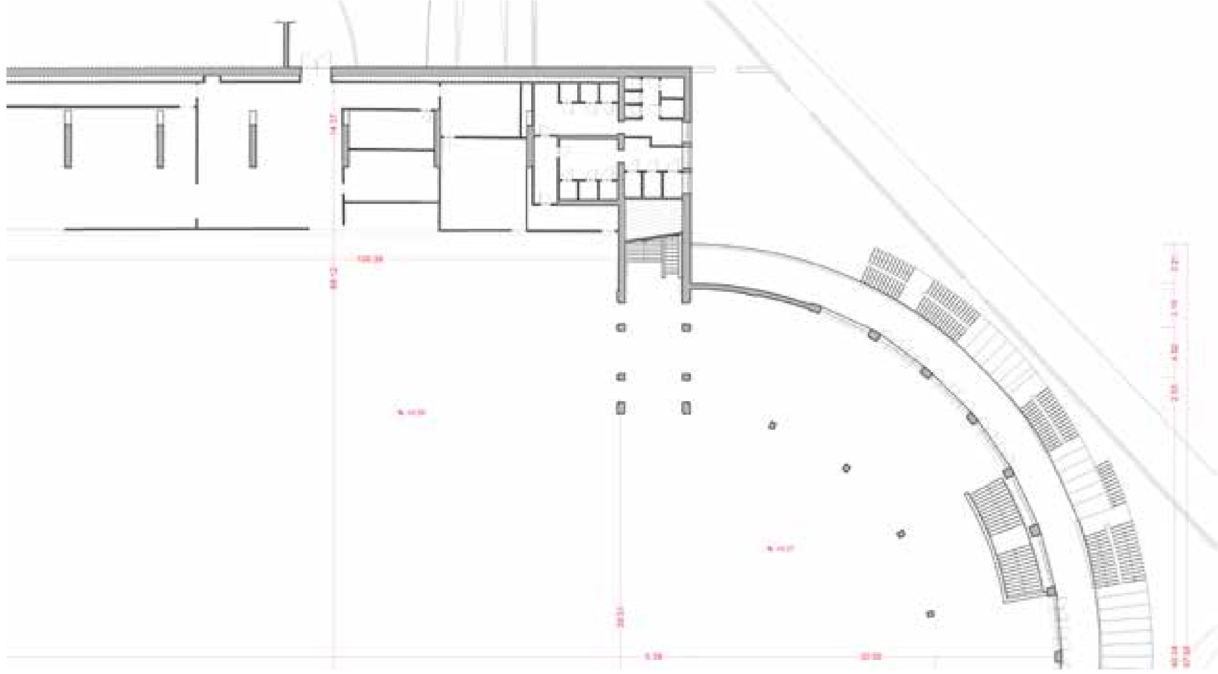
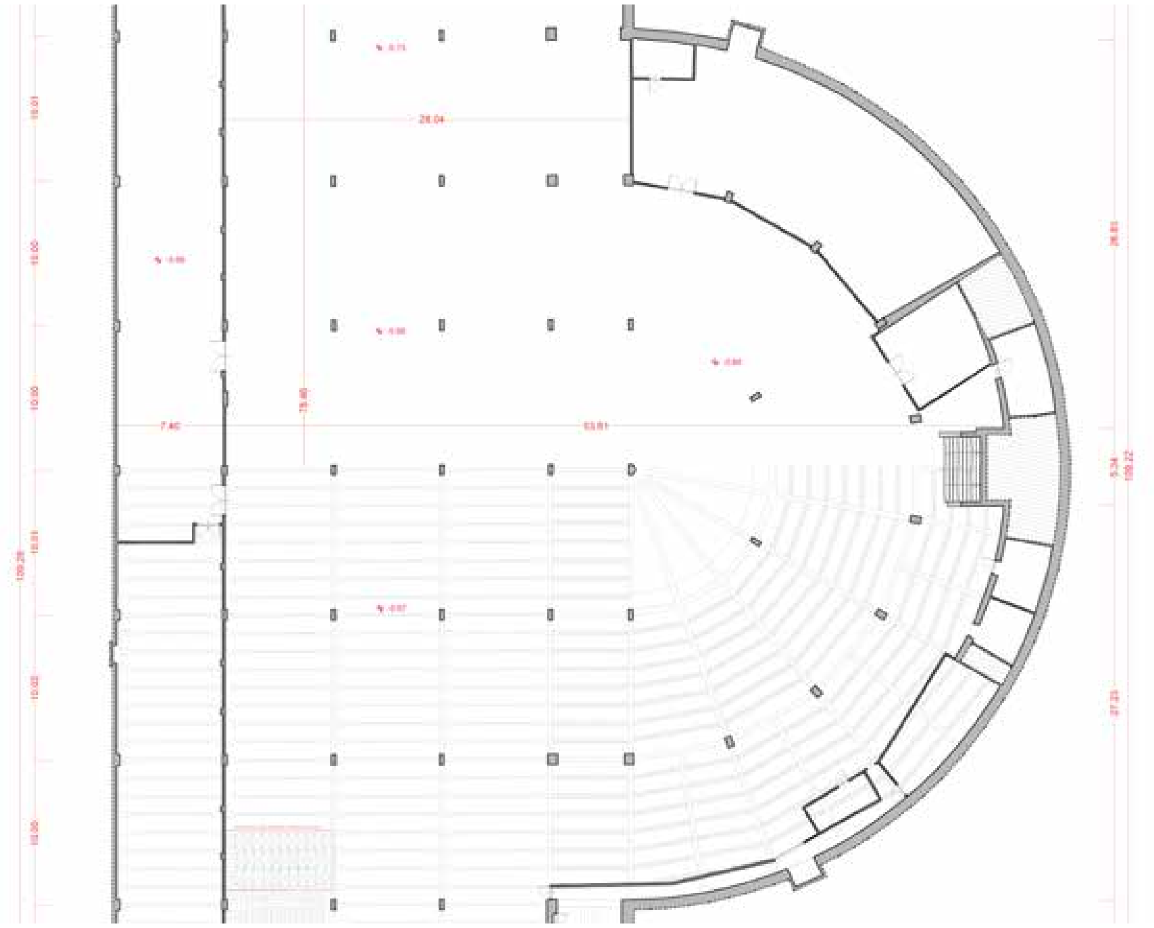
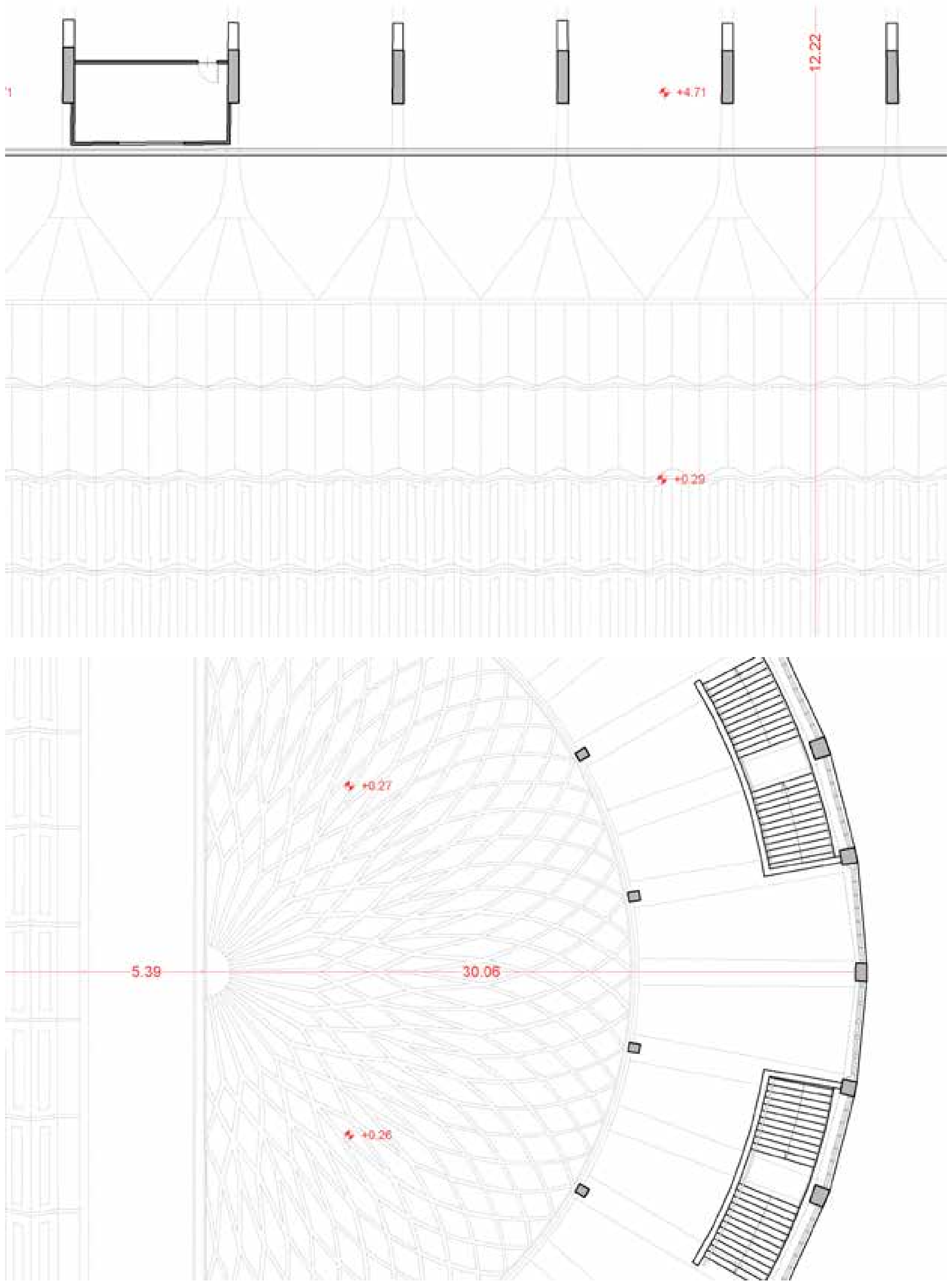
[18] In the next paragraph 3.c, the DSM (Digital Surface Model) of the roof of both halls will also be presented and discussed.



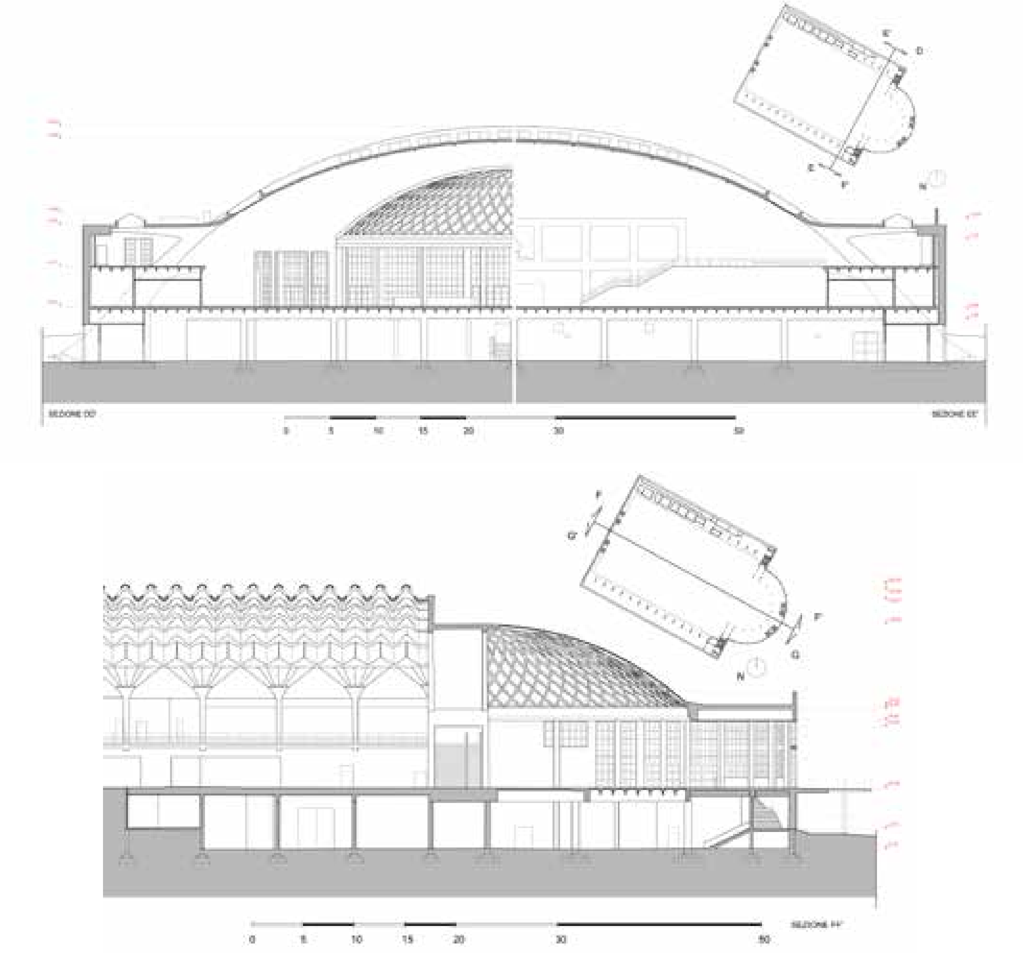
3a 10.4: Plan of the ground floor of Hall B.



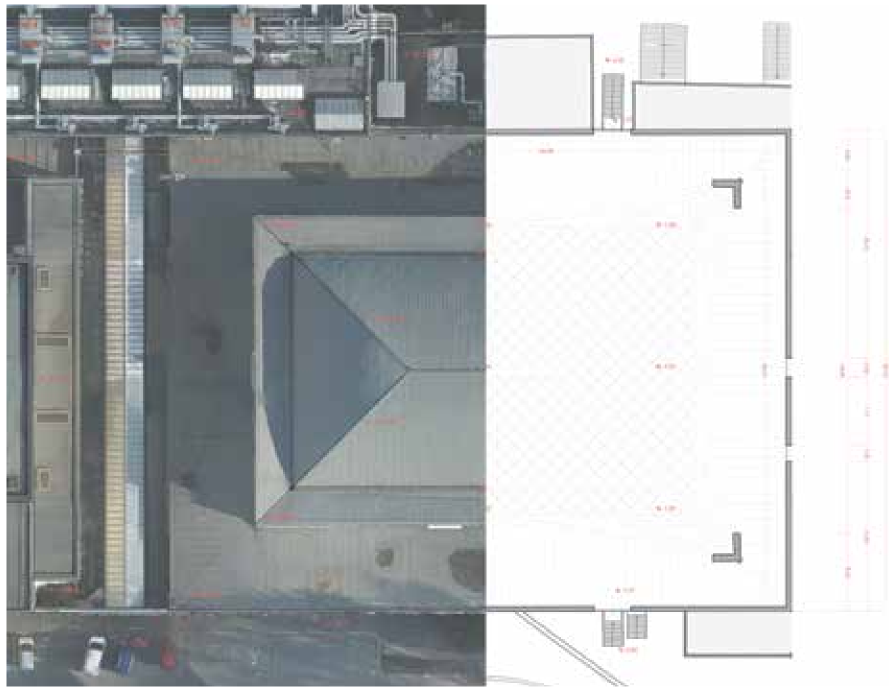
3a 10.5: Plan of the underground floor of Hall B.



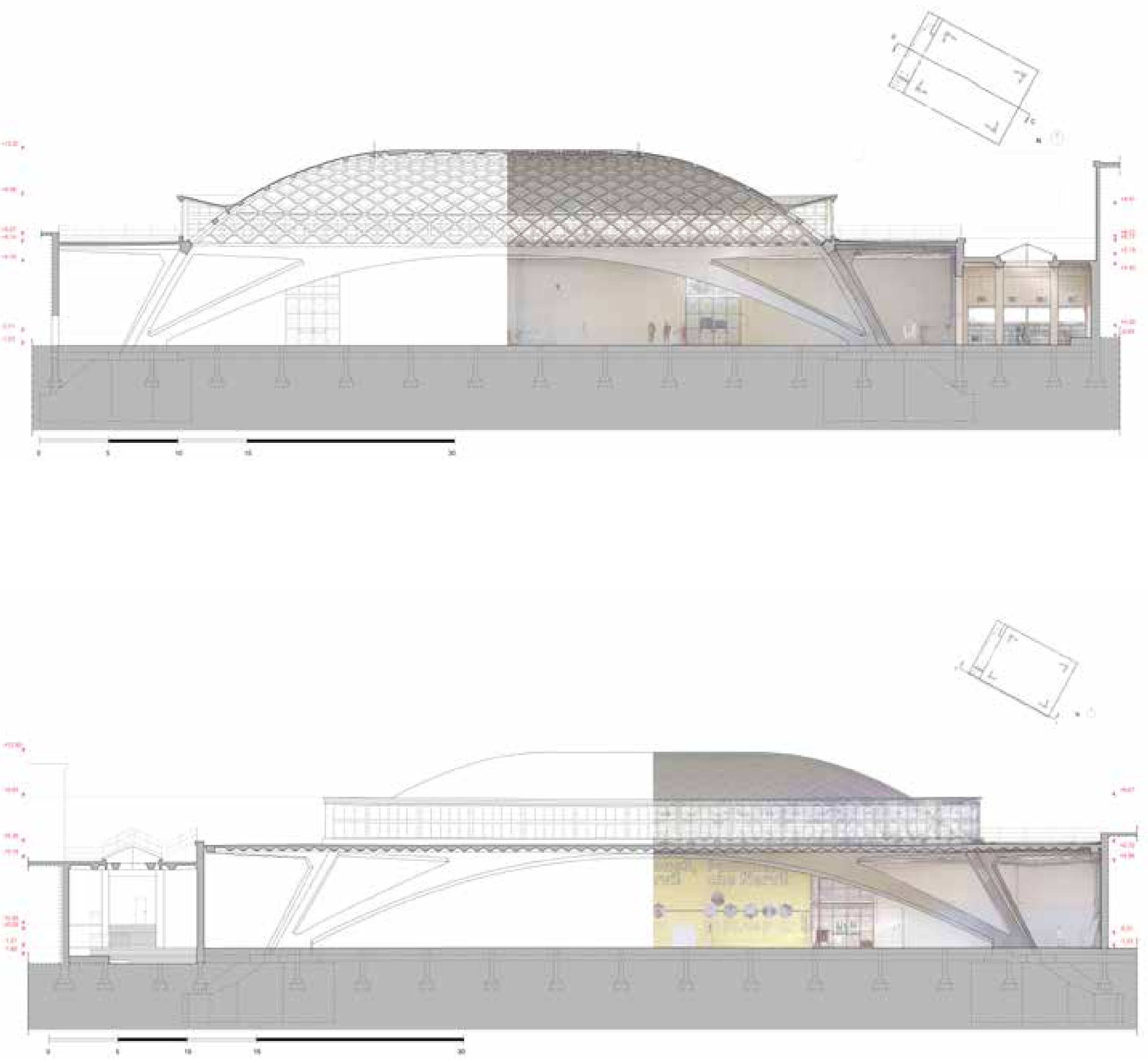
3a 10.6a, b: (Above) Plan of the gallery floor of Hall B with projection of the wave vault. (Below) Plan of the exedra with projection of the vault.



3a 10.7 and 3a 10.8: Transversal (above) and longitudinal (below) sections of Hall B



3a10.9: Plan of the roof of Hall C with orthophoto (left), and ground floor plan (right).



3a10.10 and 3.10.11: Two longitudinal sections of Hall C, with and without the orthophoto

3b Geometric interpretation of P.L. Nervi surfaces

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[2] Politecnico di Torino, FULL – Future Urban Legacies Lab interdepartmental centre

Geometry has always been a means of proportioning and sizing architectural constructions and has permeated the ways of conceiving buildings from the classical, modern, and contemporary ages, ensuring aesthetic and technical values and thrilling architects and treatise writers.

Structural engineering and studies to evaluate the structural behavior of masonry structures are consequently often aimed at highlighting the close relationship between the geometry and the safety level of structures, such as the arches, the vaulted systems and the domes in particular, based on the primitive geometries of architectural heritage.

Nonetheless, even when geometric techniques aim to assess the buildings' state of health, they provide strategies for directly comparing the architectural forms detected with reality-based techniques, i.e. photogrammetric or laser scanning, with models of primitive geometries that are interpreted as used by the designers in the construction (spheres, cylinders, etc.), to highlight whether or not alterations of the architectural elements exist.

As regards the works of P.L. Nervi, it has been established and shared that the "reckless static intuitions" combine with a structural conception that is inspired by and ends in geometry, and from which the designer draws an aesthetic and constructive synthesis.

Both the reports of his activity as a designer and builder and the reinterpretations of his work reveal the close connection between the new, spatial concepts and the scrupulous craftsmanship in manipulating materials arising from innovative construction systems, such as the patented ferrocement, which generates architectural spaces that continue to encapsulate their own modernity.

It is interesting to consider that the NerViLab research activities, which aimed to represent and analyze Nervi's exemplary synthesis between structural composition, geometric shape and construction, are based on the reconstruction of digital models. These were then retranslated into physical models by means of stereolithography, starting from the documentary complex of the project and executive drawings of Nervi's works.

The Nervi laboratory of the Milan Polytechnic uses models, original drawings, a rich photographic set of construction site images and topical photos to illustrate Pier Luigi Nervi's entire creative path. It has worked in close collaboration with the PLN Project, a foundation committed to the protection of Pier Luigi Nervi's architectural heritage in Italy and internationally, contributing to the development of a design culture to redevelop modern architecture via didactic and dissemination activities,

In this context, the contribution we propose downstream of the 3D metric survey of the Nervi pavilions in the Turin Exhibition Center. Despite the partiality of the investigations on the project geometries investigated, this coincides with the interpretation of the geometric matrix of the designed form, directly deduced from the constructed form. It uses the reality-based model derived from the 3D metric survey with geometric techniques to subsequently compare them with the project drawings of the designer Nervi.

As already highlighted above (paragraph 3a), the finalization of multi-sensor and multi-scale models derived from the 3D metric survey supports different purposes. These range from a global knowledge of the spaces which focus on the thickness of the structural and ferrocement elements, to the morphological characterization of the structural elements, suitable for identifying architectural values. The latter also support the detection of not only a possible mechanical deterioration of the elements, but also a degradation of the surfaces.

In the next sub-paragraphs, it will be possible to observe some experiments carried out on the constructive elements of Halls B and C, which also introduce the developments of paragraph 3c aimed at identifying possible alterations of the shapes. These investigations are often only possible when the original shape of the building elements is clarified in advance.