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Article

Hybrid 3D models: when geomatics innovations meet extensive built heritage complexes

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Abstract: *This article proposes the use of a multi-scale and multi-sensor approach to collect and modelling 3D data concerning wide and complex areas in order to obtain a variety of metric information in the same 3D archive, based on a single coordinate system. The employment of these 3D georeferenced products is multifaceted and the fusion or integration among different sensors data, scales and resolutions is promising and could be useful for the generation of a model that could be defined as hybrid. The correct geometry, accuracy, radiometry and weight of the data models are hereby evaluated comparing integrated processes and results from Terrestrial Laser Scanner (TLS), Mobile Mapping System (MMS), Unmanned Aerial Vehicle (UAV), terrestrial photogrammetry, using Total Station (TS) and Global Navigation Satellite System (GNSS) as topographic survey. The entire analysis underlines the potentiality of the integration and fusion of different solutions and is a crucial part of the "Torino 1911" project whose main purpose is mapping and virtually reconstructing the 1911 Great Exhibition settled in the Valentino Park in Turin (Italy).*

Keywords: 3D models; multi-sensor; multi-scale; SLAM; MMS; LiDAR; UAV; data integration; data fusion; cultural heritage

1. Introduction

The creation of a 3D model, with the aim of documenting extensive complexes, is a great challenge where the geomatics techniques and methodology could play a key role.

A 3D model, relying on an accurate metric survey, could provide a useful base on which other analysis can be carried out, especially in cultural heritage domain where high detailed information connected to models and descriptive model data that provide a more general view of the studied object are necessary. An important aspect, that is related to the wealth of the available data after a multi-sensor acquisition, is connected to the optimization phase where it is important to follow pre-defined pipeline in order to optimize the model, not only in terms of file dimension but according to the detail of the recorded object as well. High resolution of digital models must be harmonized to high accuracy and density of information, but on contrary this compromise the capability of visualization, requiring more efficient hardware or a simplification of the model is necessary [1]. The creation of an accurate (level of detail depends on its final use) 3D model is the first step. The management of handy 3D model requires creation of ad hoc digital surface, this implies a series of reflections and choices referring to time and requirements both in acquisition and processing phases, geometric and radiometric aspects of final products, according to resolution and quality needs, but also weight and interoperability of files.

Nowadays digital 3D documentation of the built heritage presents a useful tool in the analysis and interpretation of the historical site. The employed sensors and methodologies for capturing the reality could be different and are actually mainly divided in image-based or range-based techniques. Since each of the aforementioned technique is connected with pro and cons, it is well affirmed that the right way for carried out a correct survey, that could be considered an important research issue,

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is the "hybridization" of the approach, in the sense of a combination or fusion of data in order to obtain a complete and usable and users-driven 3D digital model.

Starting from the work reported in [2], where the main issues connected to the use of a Simultaneous Localization and Mapping (SLAM) based system for surveying complex built heritage were discussed, the objective of the research presented in the next sections is to extend and evaluate the contribution of the multi-sensor approach; mostly referring to the connected techniques for carried out suitable 3D models for the documentation of extensive built heritage complexes. The different techniques employed for data acquisition and processing will be discussed and the adopted strategy, with the advantage and disadvantage, will be addressed in order to define a good strategy for obtaining a complete 3D digital model. Furthermore, in the second part of the paper the usability of the achieved models and the descriptive characteristics will be reported. The idea, following the actual development for 3D real time visualization, is connected to the improvement of the use of this new digital support for enhancing the knowledge connected to the documented built heritage. These instruments are able to recreate an interactive, virtual-reality experience usable by students, researchers and other users for explore the site's buildings and the related artefacts.

1.1. State of the art and related works

Architectural heritage, or more in general the complex built heritage, is a very interesting test field for 3D documentation purpose. The characteristics of those objects allow to experiment new sensors, methodologies and techniques in order to evaluate the pro and cons of each followed approach. Moreover, it is nowadays well assumed that the combination of the different techniques is the correct way to obtain a metric product that respect all the requirement of a correct survey in terms of accuracy, completeness and reliability.

Nowadays, the well consolidated techniques that are able to 3D recording the built heritage could be divided in two main categories, namely image-based and range-based techniques [3,4]. The image-based techniques are related to the use of photogrammetric acquisitions, mainly close-range or Unmanned Aerial Vehicle (UAV). Nowadays this methodology is probably the main used one in the architectural survey field, according to the significant developments of the last decade in terms of sensors and algorithms. Since it could be considered low-cost, easy to use, flexible (multi-resolution and multi-scale) and, thanks to the massive use of UAV, photogrammetry allows to move the point of view from the terrain to the air. As a consequence, in every work related to the survey of complex site, starting from the archaeological areas [5,6] up to the built heritage complex site [7–10], the use of photogrammetric techniques even more based on computer vision approach - the well-known Structure From Motion (SfM) - are massive used with the aim of extract 3D point clouds, 3D models or simple orthoprojections. Further development in this field are connected to the use of different sensors such us multispectral, hyperspectral, thermal or mobile device[11,12] and in the employment in terrestrial or UAV application of the new generation of panoramic /spherical camera [13,14]. The range-based techniques known as well as Laser Scanning or LiDAR (Light Detection and Ranging) could be dated back to the early ' 80 with the first experience carried out on airborne platform [15,16] and then tested on terrestrial devices and related applications [17,18]. Along the last year different strategies have been developed for data management and processing [19,20], several workflows were proposed for obtaining suitable products for 3D architectural documentation and naturally a lot of devices have been developed in order to produce high-performance point clouds in terms of accuracy (short-range vs long-range scanners), speed of data acquisition (Time of Phase vs Phase Shift) and radiometric quality (embedded or external camera). Starting from the reliability of the LiDAR in connection with the evolution of the computer vision algorithms and the improvement of the inertial systems in mobile platforms, an emerging methodology that is even more used for survey purpose is the SLAM approach. These techniques could be considerate as a Mobile Mapping System (MMS) where on a moving head equipped with a ranging measurement laser capturing 2D point profiles an inertial measurement unit with triaxial gyros, accelerometers and three-axis magnetometers is coupled. Over the last year different tests and applications has been carried out through the use of this system [21–23]. According to the achieved results, the approach could be considered more than

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suitable for architectural purposes, also in articulated and compound environments [24], with the aims to produces standard cartographic products and more. Probably, once some problems - such us the point cloud colouring and the reliability of the employed systems - will be solved in the instrument used for the SLAM survey, this platform will be the preferred one especially in complex indoor areas. It is nowadays clear that, with the introduction of the SLAM system, the possible survey approaches are totally covered, the main issues are now related to the data processing and management. The different techniques allow to extract or collect 3D point clouds and the fusion of the different achieved results is an affirmed methodology [25–27]; these products constitute the starting point for different next steps that could be drive the surveyors to carried out a traditional drawing, an orthophoto, a 3D textured model or to define the geometry of an HBIM. Starting from what the already available researches have obtained and shared, the next sections are dedicated to report the experiences of our research group, aimed at obtaining a final hybrid model, i.e. derived from a combination of fusion and integration of multi-sensor data.

2. The "Torino 1911" project: focuses and aims

The 1911 is a symbolic year in the Italian history, in fact in that year Italy celebrated the 50th anniversary of the national unity with the so-called "Fabulous Exposition" settled in the Valentino Park of Turin. The International Exhibition displayed the major works of technology and science from the entire civilized world. The spectacular architectures realized for this purpose were the mirror of society at that time: ephemeral elements characterized an overabundant of eclectic styles to magnify 7 million of visitors [2,28]. The Torino 1911 exposition celebrate the industrial fervour in the west part of Italy with it's robust and explosive production of "*goods, science and technology, national boundary and Capital*" [29]. The architects created a fantastic city on both banks of the Po River, a city of dazzling whiteness, with staircases, pediments, steeples and colonnades overburdened with friezes. The decoration was done with superfluous capitals as no one had ever seen before, with fountains, waterfalls and *tapis roulant*, *fastigiums*, *porticos*, statues of Victories with rustling veils, eagles with outstretched wings, angels playing trumpets.

The overall project *Torino 1911* aspire to virtually recreate that world that was revealed in 1911 and to facilitate constructive encounters between old world's fair technologies and new digital technologies. Today, the monumental Valentino Park preserves its historic structure with avenues and ancient trees [30], while most of the temporary buildings are no longer present. On the contrary, there are some monumental complexes, which, although not built for the occasion in 1911, constituted an integral and important part.


(**a**)


(**b**)

Figure 1. Test area: (**a**) The Rocca in the "Borgo Medievale" and (**b**) The Valentino Castle.

It is from this point that we started and that constitutes the main objective of this work. How should models of complex buildings be generated, organized and characterized that must be subjected to many different objectives at the same time? Being not only navigated but also investigated to know the intrinsic characteristics and the insertion in a scenario that has to be rebuilt?

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2.1. Case Study

The selected case studies are those that are most directly connected with the themes of survey and model generation from real-based methods, that is, the existing building complexes. Then, the analysis focuses on two castles settled in the Valentino Park of Turin: the *Rocca* (Figure 1) and the Valentino Castle (Figure 2), this last mainly referring to the noble floor.

The first one is part of a suggestive reconstruction of a medieval hamlet (*Borgo Medievale*), conceived for the 1884 Italian Exhibition. The latter is one of the Savoy Royal Residences (all inscribed in the World Heritage List for their outstanding value from 1997), built as the actual shape for Cristina of France in the XVII century and now hosting the Faculty of Architecture of the Polytechnic of Turin. The *Borgo Medievale* and the related *Rocca* were designed by Alfredo d'Andrade to symbolize the medieval Italian styles and materialized in architectures, furnishing, flourishes, utensils and works [31]. Enclosed by an enceinte and protected by a tower with drawbridge, the Borgo is composed by a church, some houses, workshops, a garden and the Rocca, the innermost keep; all these structures are a revisit of some real medieval architectures spread in two Italian regions, Piedmont and Valle d'Aosta. The *Rocca* is articulated in four levels and two towers, one circular and one square. All the rooms revolve around the inner courtyard, a double height open space with two level of wooden balconies and partially cover by roof, very similar to the Fenis one also for the mural paintings figuring Saint George over the stone staircase and philosophers, saints and heroes all around the balconies. Each local has an irregular plan, depicted walls and brick vault or wooden beam ceilings [32]; moreover, furnishing and usual accoutrements are designed to represent medieval life.

(**a**) (**b**) (**c**)

Figure 2. The main staircase in the courtyard of (**a**) the Fenis castle (AO) in 2004 and (**b**) back to 1884 [33]. (**c**) The same scene in the courtyard of the mediaeval Rocca in Turin.

The second case study refers to another type of castle; developed from a XV century suburban palace and settled alongside the river Po, the Valentino Castle [34] was transformed in royal residence during the XVII century for the Savoy family. During the XVIII century the Castle was involved in a urban planning in which it was the central focus for the design of the Valentino Park [35], a urban public space of 42 hectares and place of a series of national and international exhibitions, dated between the end of the 19th century and the beginning of the 20th century. The Castle began the headquarter of the Royal School of Engineers in the mid-XIX century and subsequently of the *Politecnico di Torino*. Nowadays, the noble floor is the most representative part of the building, also open to the public as museum in predefined days. The present research investigates some chambers of the Castle, in detail the Great Salon, the Fleur-de-lis and the Roses Chambers in the south apartment of the main floor. With its double height, favoured view of the river Po, mural paintings with never-ending scene spreads in the walls and sculpture masked in the corners, the Salon is the

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Honour chamber representing the Savoy family. The Savoy's military feats are celebrated in the Salon, whose decoration was carried out by various artists during the XVII century and restored in XIX and XXI centuries. The Honour Salon is the core of the whole castle, facing the ancient access from the river and the newest from the courtyard towards the city. The architectural works of the Valentino Castle were followed by Carlo and his son Amedeo of Castellamonte, which transformed the Palace in a "pavillon" Castle with French style. Isidoro Bianchi supervised the Cristina's apartment decorations between 1633 and 1642. The restoration of the entire noble floor of the castle, in addition to the ones affecting the artistic heritage, has concerned the structures, especially the vaulted systems, which have suffered damage and water infiltration. The vaults are so-called "fake vault" and are realized with plaster applied on reed mats, which are hanging on a rib wood frame. In addition to the historical restoration carried out by D'Andrade in the late nineteenth century, some consolidations of the vaults - made after the second world war to recover the damage of the bombings and other in 1978 - have already been studied to determine the safety conditions [36].

3. The 3D documentation project: the multi-sensor data acquisition

In these types of scenarios, many operative solutions are commonly deployed by endorsed workflows, as introduced, to overcome multi-scale and multi-resolution issues in outdoor and indoor spaces and some innovative mapping solution have been already tested [2] . Surely the multi-sensors approaches should be validated from a partial to a global viewpoint, in order to optimize effectiveness of each sensor data contribution to their integration, finalized to overcome their singular applicability limits and aimed at making an experimental workflow effective. The test areas present a variety of characteristics and restrictions that influenced the choice of which sensor was the best solution to perform a complete and continuous 3D metric survey. Therefore, various sensors, both image and range-based, were used during the acquisition phase and a general overview of the raw data is presented in (Table 1.).

Table 1. Sensors employed in the acquisition phase and general overview of the amount of collected data for the entire project

Type of survey	Systems	Sensors	Medieval Rocca and Hamlet	Valentino Castle main floor
Range based	TLS	Faro Focus^{3D} X120 & X330	93 scans	112 scans
	MMS	GeoSLAM ZEB Revo RT+ZEBCam	29 scans	8 scans
Image based	UAV	DJI Phantom 4 Pro Obsidian DJI Mavic Pro Platinum DJI Spark	1919 images	264 images
	DSLR	Sony Ilce 7RM2 Canon EOS 5DS R	2455 images	1942 images
	Low-cost sensors	DJI Osmo+ GoPro Fusion 360	15 videos	10 videos
Topography	GNSS TS	Geomax Zenith 35 Geomax Manual TS Zoom30 Pro	18 vertices 145 targets	17 vertices 162 targets

Hereby, only the main results from some of them are later referred in detail. Moreover, another crucial aspect to be considered is that the acquisition campaigns, due to operative needs of the project, were organized at different moments, employing various group of surveyors to cover the entire areas and to achieve different levels of detail.

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3.1. Multi-sensors approach for multi-scale data

In detail, the investigated approaches are: a Terrestrial Laser Scanner (TLS), a MMS, Digital Single Lens Reflex (DSLR) cameras, various UAVs and some image-based low-cost and portable sensors, as steady cameras and action cams. Moreover, a geo-reference system was established thanks to the integration of a principal network acquired with a Global Navigation Satellite System (GNSS) system and a huge amount of materialized codified contrast markers and natural points from the scene, well distributed in the test area, acquired by a Total Station (TS) in order to obtain a reliable network of control and check points.

According to the complexity and the extension of the test areas, the FARO Focus (Figure 3) was chosen as TLS system, S120 and X330. Regarding the X330 the test aimed at testing the superior range in comparison with other range scanners. This sensor is a phase shift laser useful for its various uses, especially in these cases the characteristics of wide range distance in outdoor scenes and the high number of measured points in a short time guarantee high level of detail and the necessary speed of acquisition. Furthermore, the operator can choose the settings of the laser and image acquisitions to fulfil the needs of the work.

(**a**) (**b**)

Figure 3. TLS by Faro: (**a**) The FARO Focus 120 during the acquisition and (**b**) planimetric view of an outdoor coverage range of an X330 scanner

Another type of laser-based sensor is the ZEB Revo Real Time (RT) by Geoslam (Figure 4); contrary to the motionless TLS system, it is a portable MMS working with a Hokuyo UTM-30LX-F scanner technology and using a SLAM algorithm and an Inertial Measurement Unit (IMU) [37]. This type of sensor is promising for its "go-anywhere" definition and currently already quite investigated in the literature [2,21,38–46]. In fact, lightness, handheld solution and maneuverability characteristics allow to rapidly acquire a vast amount of points, especially in articulated, multi-level, narrow and extended area - such as the interiors of furnished museums, offices and underground spaces - where other sensors cannot be employed or would be very time-consuming. Furthermore, the tested sensor mounted a ZEB Cam, a commercial off-the-shelf (COTS) GoPro HERO4 Session.

The scanner works in pair with a tablet through a specific Wi-Fi connection, allowing the real time view during the acquisition; these two implementations increase the potentiality of the whole system compared to the previous versions, the first Zebedee [47] and the following ZEB1 [42] and ZEB Revo [48].

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(**a**) (**b**)

Figure 4. The ZEB Revo RT MMS by Geoslam: (**a**) The data logger, the rotating head and the Go Pro mounted above and the IPad Pro employed for the real-time view during the acquisition phase; (**b**) Operators scanning the Great Salon with the instrument

According to the aim of the work connected to multi-sensor and multi-resolution data acquisition and processing, in the analyzed areas different UAV has been employed (Figure 7) in order to accurately document the built heritage from different points of view. The flights were performed using standard approach according to the different characteristic of the used platforms (automatically for the Phantom and Mavic and manually for the Spark). In the next sections only the data acquired by the Phantom will be described, since the highest resolution of the images acquired by that platform allows to better integrate and/or fuse the achieved results with the ones acquired by the other sensors. Furthermore, in order to complete the multi-sensor survey a photogrammetric close-range acquisition was carried out to test different low-cost sensors and consolidated DSLR blocks and acquire different qualities of radiometric data as well.

PHANTOM 4 PRO OBSIDIAN	MAVIC PRO	SPARK
Sensor 20 MP, 4096×2160 px	Sensor 12 MP, 4000×3000 px	Sensor 12 MP, 3968×2976 px

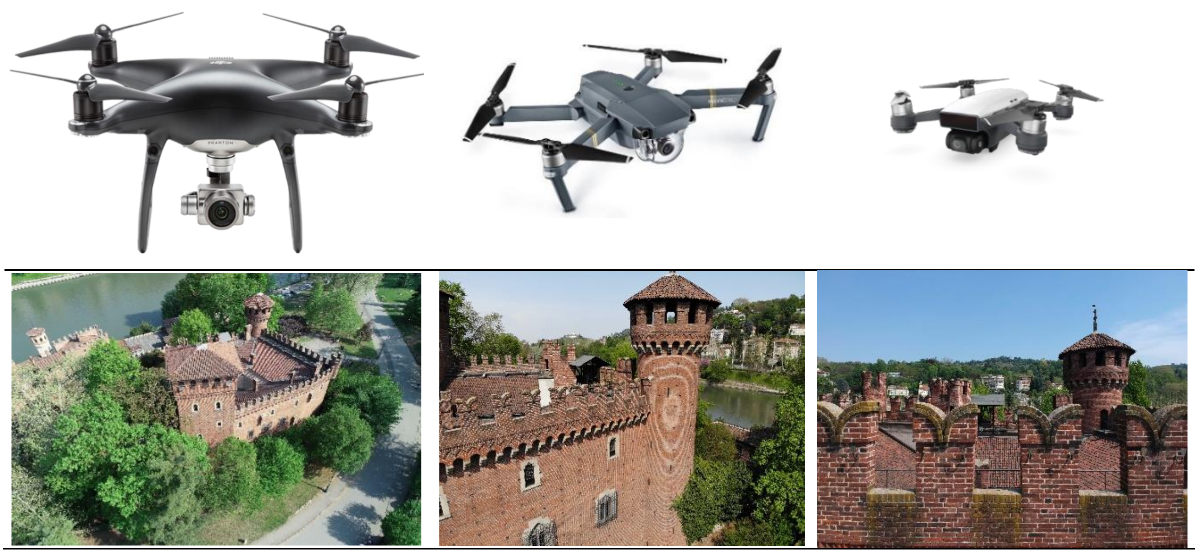

Figure 5. Different UAV platforms by DJI company and related sensors with captured images

3.2. Data acquisition strategy and data pre-processing

The strategies that have been put in action are addressed, as introduced, to the problem of data acquisition protocols optimization, especially if coming from different technologies use and the issues related to multi-scale and multi-sensors models creation and validation. Certainly, in such compound

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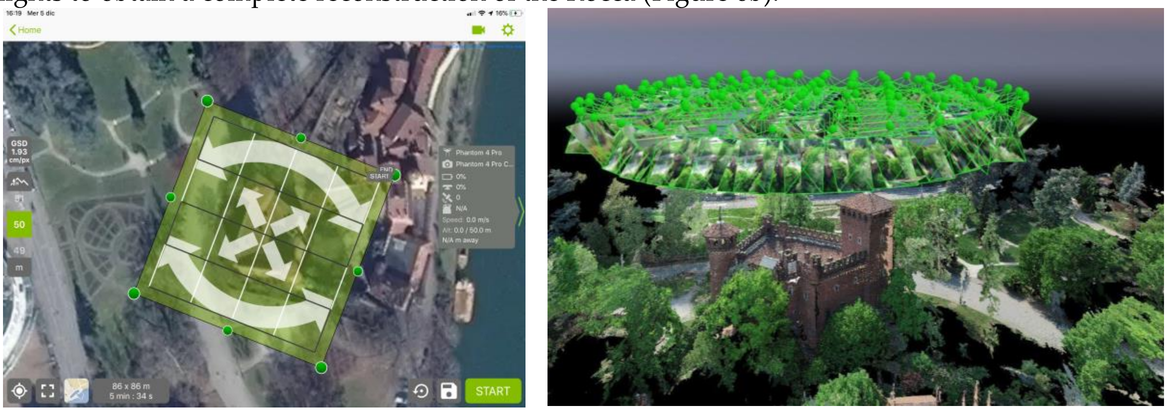
environments featured by large extension in interior and exterior spaces, the variables of space-to-be-covered and time-to-be-spend in composite operations workflows require to be deeply discussed. Therefore, different sensors and integrated strategies were tested for the indoor and outdoor acquisitions. Certainly, the castle royal rooms and medieval *Rocca* apartments have been challenging environments, also because furnishing indoor and trees outdoors forced to consider some aspects:

- Flight plan, overlap, resolution and UAV camera axes in oblique acquisitions: the moment of the year in which the survey is performed will be influenced by the presence or absence of the trees foliage.
- Number, position and resolution of TLS scans required to obtain a continuous surface with homogeneousness of recovering without horizontal and vertical shadings of 3D details: if they need to be increased, consequently the acquisition and processing time are time spending as well.
- SLAM-based trajectories in case of MMS deployment should be adapted to these types of locations: certainly, they will be successful in terms of time-saving but they would bring with it an increase in the already known problems of noise errors affecting the point clouds and the drift errors affecting the trajectory

3.1.1. The UAV flight on the Medieval Rocca

Over the analyzed area, a complete UAV survey was planned and performed using the aforementioned platforms in order to accurately describe the external part of the castle. Despite the use of different platforms, hereafter only the Phantom data will be considered as a general example of using the UAV for data acquisition and extracting 3D information from above. Complying with the consolidated trends in UAV image acquisition [49,50], the flights over the Rocca were planned with the aim of acquiring nadir and oblique images. According to limited extension of the surveyed object, first a double grid acquisition with the nadir camera axes was performed (Figure 6b). This first flight was made with longitudinal overlapping of 80% and a lateral overlapping of 70%. Furthermore, a circular flight with the camera axes at 45° was carried out, in this case the angle between adjacent images was 5° with the camera oriented to the center of the circle. The Rocca was covered with 137 images with 2 different flights at an average flight height of 50 m (the height of the Rocca is about 32 m). The application Pix4DCapture was used for planning (Figure 6a) and performing the different flights to obtain a complete reconstruction of the Rocca (Figure 6b).



(a) (b)

Figure 6. (**a**) The flights performed by Phantom 4 PRO (**b**) oriented UAV images block on the Rocca

The advantage of using an ad hoc application for the image acquisition phase is surely connected to the fully automation of the process, but the radiometric quality is not fully guaranteed, in fact a recurrent drawback is the over-exposition of images. During the different performed tests, especially in sunny conditions the automatic procedure implemented in Pix4Dcapture in most case delivers moderately overexposed images. In the case of the Rocca, fortunately the performed flights were carried out during a cloudy day with a perfect diffuse illumination, that allowed us to acquire the images in the best light conditions. Another problem connected to the automatic acquisition using

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the aforementioned application is related to the fixed altitude of the flight. In other words, with Pix4Dcapture it is not possible to change the height of UAV during the flight according to the slope of the terrain. In difficult areas (with large height gaps), as a result, this limit could cause the acquisition of images with uneven Ground Sample Distance (GSD). In the present research, according to the shape of the area/object, the flights were set up in order to obtain a GSD value (~2.5cm/px) - suitable for an architectural scale (1:100-1:200) – measuring 20 Ground Control Points (GCPs) and 8 Check Points (CPs) as reported in Table 2.

Specifications	Phantom 4 Pro Obsidian
Height flight	50 m
Area covered (Area of Interest AoI)	0.106 km^2 (4000 m^2)
Strips	1 circular (oblique), 2 nadir
N° of images	137
Time	45 min
GSD (cm/px)	2.34 cm
N° of GCPs/CPs	20/8
Pt density (AoI)	mean 1800 pt/m^2 (17500 pt/m^2)

Table 2. UAV acquisition specifications.

Nowadays, the only way to solve the two reported drawbacks is to perform manual flight. However, that does not allow to follow pre-determinate flight lines or circular acquisitions; therefore, according to the underlined problems actually, where the environment conditions allow to flight without any particular problem (high sunlight, obstacles or other significant issues) the automatic strategy is preferred.

3.1.2. Close-range photogrammetric acquisitions

In order to test other image-based sensors, in addition to the UAV data, different terrestrial acquisitions were carried out to document the analyzed areas. The followed approach is the one well consolidated in the community that require large image overlapping using parallel and convergent images [51], pandering above all the internal/external light conditions.

In the Valentino Castle, low cost platforms, such as DJI Osmo, GoPro Fusion 360 and high-resolution digital cameras (Sony ILCE-7RM2) were employed for recording the indoor and outdoor data. Using the Osmo and the GoPro, several videos were recorded and moreover the frame were extracted for performing the photogrammetric process as reported in [52]. The acquisitions performed with Sony ILCE-7RM2, that in our case was equipped with a 12mm focal length, were carried out according to the common practice. Normal and convergent images with large overlapping (more than 80%) were collected in order perform the photogrammetric process based on SfM techniques. In the Rocca the same low-cost sensors were employed while the DSLR acquisition was performed using a Canon EOS 5DS R with a 24 mm lens. The strategies were the same used for the Valentino Castle. In the next sections only the data obtained using the images acquired by the DSLR cameras will be analyzed.

3.1.3. The terrestrial LiDAR scans projects

According to the consolidated practice of traditional TLS acquisition [53,54] and scans registration, a huge amount of scans data were made out to cover all the architectural context. As usual, the scans acquisition was supported by control points topographic measurements and distribution guaranteed the suitable surfaces coverage with adequate overlapping.

First of all, the large number of scans is connected to the complex shape of the Rocca which is composed by narrow rooms connected to each other. Moreover, the furniture located in the surveyed areas were another important aspect that has increased the number of the acquired scans. The scan

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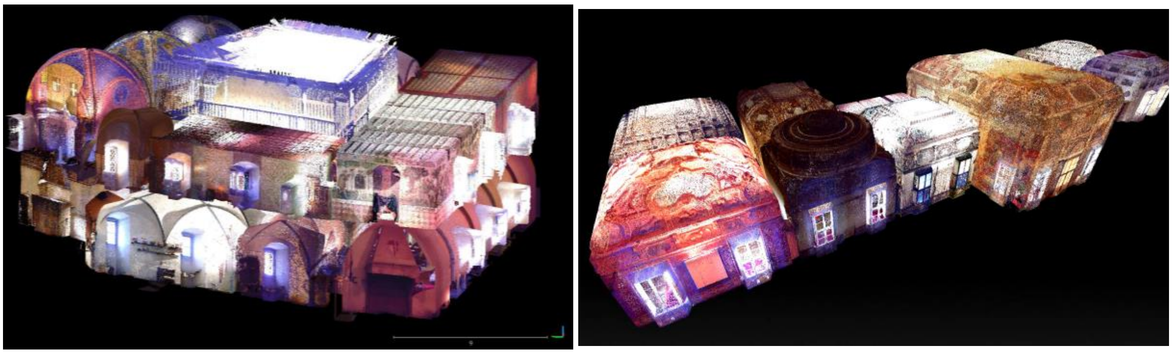
resolution was set up at ⅕ (that means 1 point every 7.74 mm at 10 m) with a quality of 4x (that means that each point is measured four times). As usual, after the point clouds acquisition, the images were also captured in order to color the point clouds. The high number of planned scans is also due to the prefiguration of accelerating the registration procedures, ensuring a high overlap between all the scans that is necessary for assuring an easy registration of the different acquisitions in line with the cloud to cloud approach, based on the well-known Iterative Closest Point (ICP) algorithms. In order to speed up the scans registration, the work was divided floor by floor and subsequently all the data were connected as showed in Figure 7. In the Medieval Rocca, the survey planning has gone along the complex distribution of the apartments, as summarized in Table 3 and the process is evaluated through values of mean for ICP phase and standard deviation (st. dev.) with Root Mean Square Error (RMSE) for the georeferencing one. A mean of 7 scans per room was collected, with a sum of 93 scans, on a total surface of about 1000m². Furthermore, as mentioned, the survey was operated in the Castle too, specifically, in the main floor of the building. This is composed by 11 main rooms with plaster decorations and frescoes, as reported before and 4 ancillary rooms (2 bathrooms and 2 corridor). The acquisition performed using the TLS were carried out with the same Rocca's strategy. For each main room at least 5 different scans were achieved (usually in the four corners and in the center), in order to cover the complete shape of the area with the decorations as well. In total 82 scans were recorded, a mean of 5 per room, on a total volume of decorated spaces of around 900m².



(**a**) (**b**)

Figure 7. A view of the registered scans from (**a**) Rocca (n. 93) and (**b**) Castle (n. 82)

Table 3. LiDAR acquisition specifications.

	Environmental features				*Scans*		*Registration/georeferencing*			
	n° rooms	**Surface** (m²)	**Volume** (m³)	**time** (h)	**n°**	**n°/ room**	**ICP** **Mean error** (mm)	**targets-based** **n°CPs**	**St.dev** (mm)	**RMSE** (mm)
Castle	16	900	3.600	18	82	~5	1.35	136	1.25	3.2
Rocca	13	1.000	14.000	22	93	~7	1.05	116	2.69	4.65

3.1.4. Experimenting 3D mobile mapping

According to the location characteristics, a test on the use of a portable mapping system was performed for evaluating the MMS strategy and the achievable products. As is commonly reported in several researches, SLAM-based devices are almost the best solution for enclosed ambient rich of features, because the SLAM algorithm exploits also the geometry to estimate 3D reconstruction of surveyed places. The optimal trajectories [2,23,46] requires closed loops and roundtrips rather than one-way mode (Figure 8a, b and Figure 9a) during the operator's rooms mapping.

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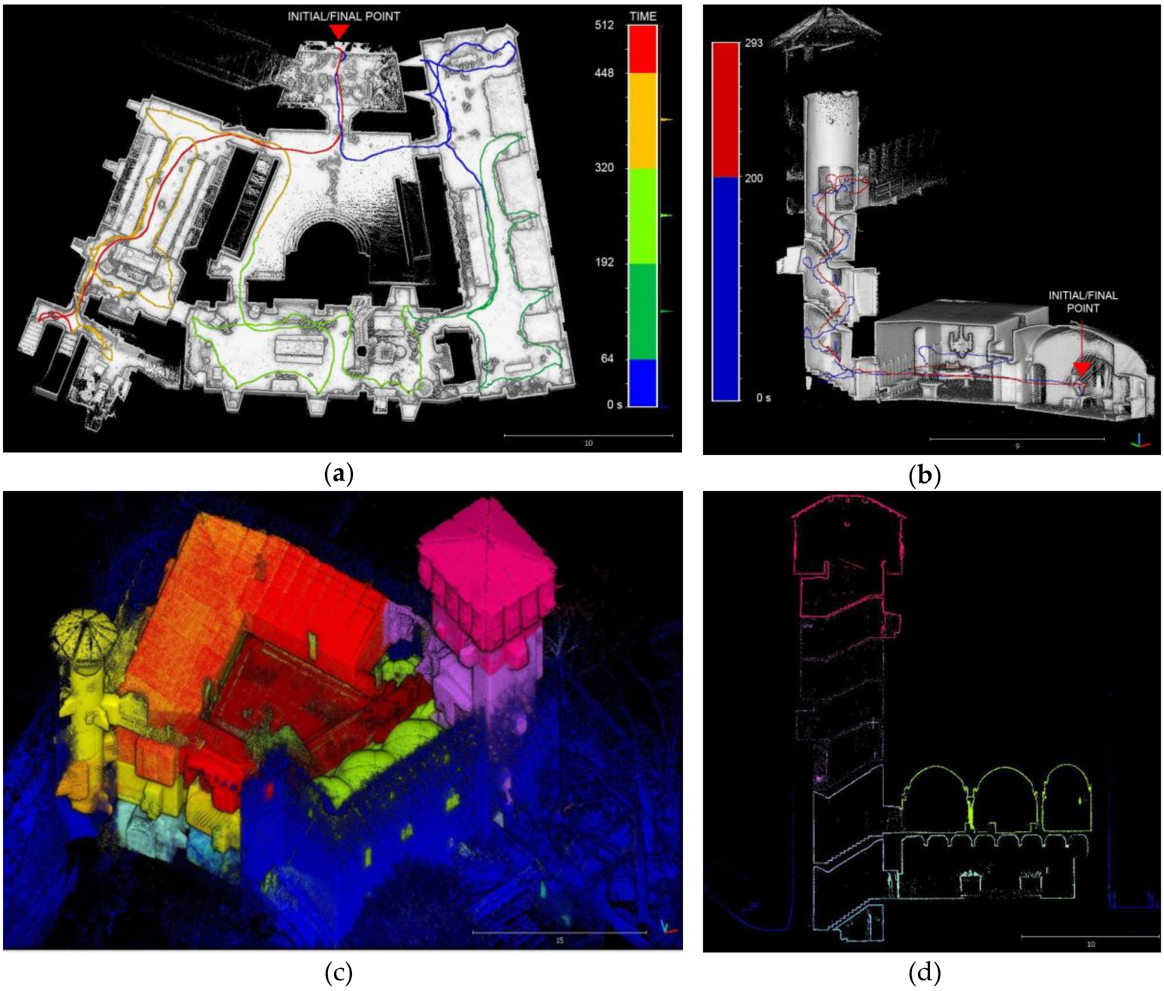

Figure 8. Example of SLAM-trajectory in the Rocca colorized by time: (**a**) Close loop with some roundtrip parts; (**b**) Roundtrip on the tower: going (blue) and return (red). (**c**) All the re-processed ZEB point clouds after the merge process, each color corresponds to one scan, in blue the external one an (**d**) vertical section of the point cloud.

One of the main matters affecting ZEB Revo point cloud, in parallel to the accuracy of the points model, is the lack of positioning data. The origin of reference system for each scan is in the starting point and the orientation of axes XYZ is related to the rotating head: in fact, the X reference axis is normal to the scanner's back plate. In this way it is possible, if initialized vertically, to rotate the X axis to the East and to perform the survey at least roughly following the North-South reference system, as investigated in [44]. Furthermore, the relative position between multiple scans of the same survey set are not assured to be aligned too, due to the possible change of position of the rotating head at the initialization moment. Therefore, in order to manage all scans in the same relative reference system, the simple single rototraslation and mutual ICP fitting applied on each ZEB scan can be now effectively avoided by application of *Merge* algorithm (Figure 10) implemented in the last desktop release of GeoSLAM hub software for the scans processing [23]. In the first step, the single scan is manually aligned one at a time to others to prepare the second step that is the re-computation of the SLAM data; the implemented algorithm - based on joint SLAM+IMU data - combines 3D data deriving from the overlapping parts between the scans and finally estimates a more accurate point cloud based on an improved trajectory.

In [2], the effectiveness of the *merge* and *re-processing* functions are analyzed and compared to the raw output data. Instead, to approach the solution of the problem of absolute positioning, this last software implementation plans to recognize and identify along the trajectory just those specific points in which the operator stopped at least about 5 seconds. Concerning these so-called "*reference points*", the processing algorithm extracts XYZ coordinates on each measured point, retrieving a set

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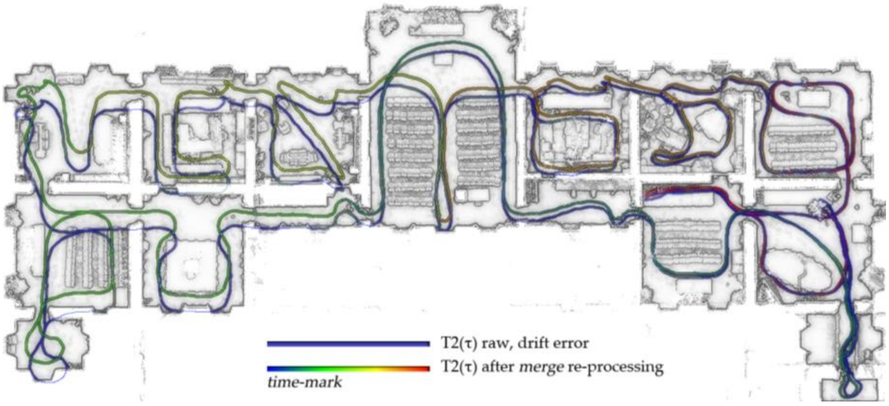
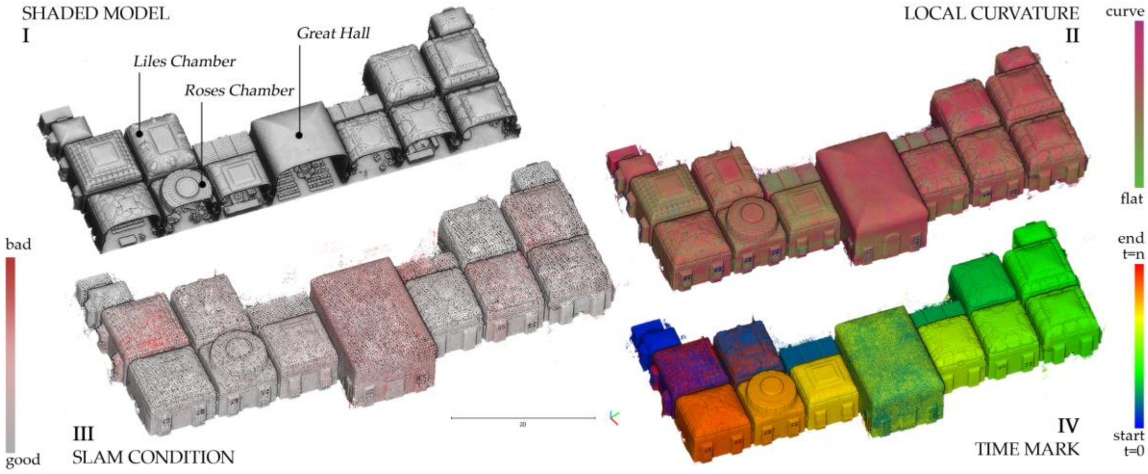
of points in a **.txt* output file. This is currently under research, but it is possible to say that this solution allows obtaining a set of local coordinates of some vertices related to a topographic network measured by traditional TS and GNSS techniques. Then, a roto-translation will enable to convert the ZEB point cloud from the local system to the global positioning.



(**a**)



(**b**)

Figure 9. The ZEB survey in the Valentino castle: (**a**) The plan view with the closed loop T2(τ), performed, before (blue) and after (range colors) the SLAM re-processing by merge function correction; (**b**) the attributes related to ZEB-based point cloud processing, inside GeoSLAM Hub platform. Along with an axonometric representation of the main floor in shaded view (**I**), there are: normal mapping (**II**); SLAM quality condition during the scan (**III**); time-stamp information (**IV**). Each thematic result is associated to its own trajectory data, as well.

The collected ZEB-scans in the Castle and in the Rocca are thus processed in GeoSLAM Hub, where the re-processing and the *merge* algorithms are applied to the two scans sets. Table 4 reports the two sets of acquisitions and an average value of the amount of data collected by the MMS. The output point clouds consists in a set of different available formats (**.las; *.ply;*.E57;*.asc*) and very useful information can be calculated on the points surface, in the format of attributes associated to points (Figure 9b): i.e. *normal*, SLAM quality, time, elevation etc. These aspects will be discussed in next Cap. 4. The selected area of the Rocca meets the ZEB requirements; in fact, it contains both indoor articulated places and open enclosed spaces, as previously described (Figure 8c, d). In case of one-way blind tracks, as in the towers of the Rocca, the roundtrip trajectory was the only solution, to obtain good results. For this kind of environment, the employment of the ZEB Revo represents a useful solution thanks to its maneuverability and time speed that allows the operator to freely move in narrow spaces.

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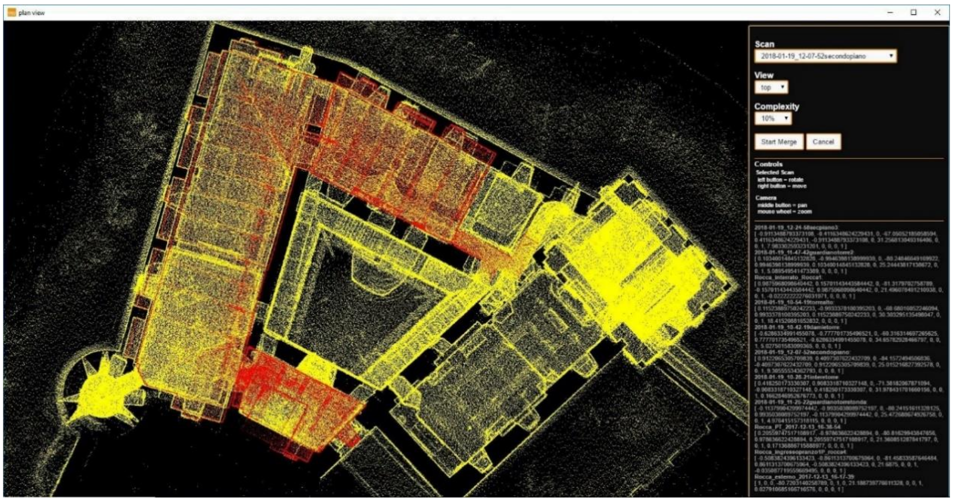

Figure 10. The desktop interface of the merge function in the GeoSLAM Hub software: in red, a single scan that is manually aligned, one at a time, to others, yellow. In the black box down right, the rototranslation matrix of each merged scan.

Table 4. ZEB acquisition specifications.

Specifications	Rocca	Castle
N° of scans	11	2
Time	~ 3h	~ 30min
N° of points	~181.100.000	~35.410.000

Contemporary a SLAM based acquisition was carried out in the Castle main floor as well and the adopted strategies were similar to the ones performed in the Rocca area. The rooms of the main floor were surveyed testing two different strategies, aiming to evaluate and validate the best approach for such large-range mapping in quite complex volumes, geometrically characterized objects and scenes rich of furnishings. As reported in [2], the first T1(τ) (almost 6min along 110m, 0.3m/s speed), was shorter and simpler, performed with best practices execution – a roundtrip -, travelling along the corridor and mapping two rooms and the extreme sides of the scans. It has been processed in *merge* function to help in rigidity the second T2(τ) (almost 12min along 350m, 0.5m/s speed), the complete trajectory across all the rooms on the floor coverage with a closing loop, in order to optimize the final alignment of the acquired data. In (Figure 9 a) T2(τ) is showed in the original trend after the acquisition and in scale-colors after using merge tool, that is the re-processing of the SLAM-algorithm with contribution of T1(τ).

4. Methods and strategies for complex environments and advanced 3D modelling

The optimization-driven approach, that underlies the data integration strategy and the experimental process of fusion, tries to tackle in the most all-encompassing way, but certainly not exhaustively, certain aspects typical of 3D digitization, downstream of the research experience conducted and the methodological innovation tested in recent years.

The attempt, as introduced, is to balance a role for cutting-edge techniques, alongside those more consolidated approaches, in order to compare them and to obtain different deliverables useful to users-oriented scopes. Special attention was given, in this paragraph, to the 3D mapping via ZEB Revo MMS in order to investigate, in such kind of applications, how far it can be self-contained and where it needs a supporting integration, or better, in which way its potential, in terms of speediness and manoeuvrability, can be a worthy basis for reasoning on potential data fusion processes.

Thus, the open issues, faced in these tests and clarified hereafter, mainly referred to the multi-sensor problem in case of ZEB single data or a combined use within the mapping of complex scenarios, are tackled with experimental integration- or fusion-based approaches and proposed for:

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- The management of the *reference system* (4.1.): relative alignment and absolute (geo)positioning;
- The *geometric reconstruction* aptitude (4.2.), relating to decorative and morphological aspects;
- The examination of a *fusion-based pipeline* solution for the geometric/radiometric attributes enrichment in point clouds and surfaces (4.3.).

4.1. Positioning issues for complex and extensive indoor-outdoor environments

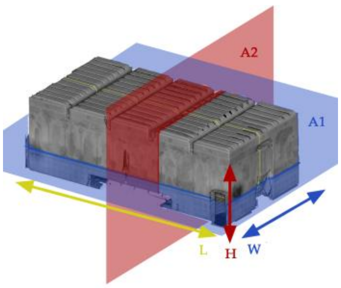
As introduced, the positioning question related to the ZEB point cloud could be currently solved by a rototranslation and ICP procedure with another positioned point cloud used as a reference (i.e. TLS model). This evidently requires a LiDAR survey (topographically-based) to be performed in parallel to the MMS survey.

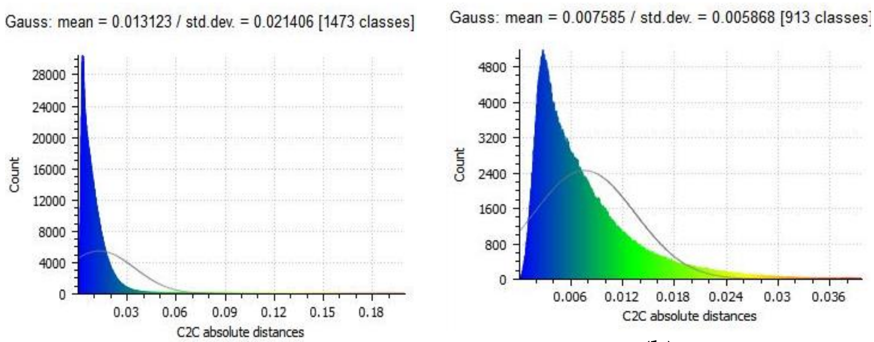
The research testing tries to split the problem matter and to lead a differential evaluation of ZEB performance in relation to a 3D model ground-truth: this is due for the possibility to consider the SLAM-based point clouds result in a *local* or *global* perspective. In fact, the operation of SLAM-based algorithms during the processing should simultaneously meet the needs of geometry (*locally*) and trajectory (*globally*): i.e. balancing of the influence of SLAM and IMU data in the trajectory estimation. This is the reason why ZEB mapping usually suffers from some drift errors in trajectory reconstruction (planimetric and altimetric drifts), even if the local reconstruction of a single space returns very positive values of deviation from the reference surface employing Cloud-to-Cloud (C2C) analysis by CloudCompare software. The configuration considered for the analysis are:

I. Local result, indoor, single enclosed area
II. Global result, indoor, single-level floor, evaluation of planimetric drift error
III. Global result, indoor, multi-level floor, evaluation of planimetric and Z drift error
IV. Global result, outdoor scenario with UAV data

Table 5. Results of (I.) Dimensional and C2C comparison of ZEB and LiDAR point clouds on the Throne Chamber.

Cases	*n° of pts*		Dimensional comparison (m)				
			Length	Wide	Height	Area 1	Area 2
ZEB	2.209.937		12.6289	6.130	4.2117	75.9021	22.7629
TLS	16.661.778		12.6163	6.1231	4.2088	75.9006	22.7668
		Δ	*0.0126*	*0.0069*	*0.0029*	*0.0015*	*0.0038*
C2C comparison			No filter (fig. 11a)		Noise filter (fig. 11b)		
Mean			**0.0131**		**0.0076**		
St. dev			0.0214		0.0058		





(**a**) (**b**)

Figure 11. Statistical graphics of C2C comparison ZEB and LiDAR point clouds on the *Throne Chamber*: mean and st. dev. distribution (**a**) before and (**b**) after noise filtering applied to ZEB data (C_1-C_2 cases).

I. Indeed, if we consider a single room, i.e. the Rocca's Throne Chamber (around 6x13x4 dimensions) and the two point clouds, ZEB 2 mln points and TLS 16.6 mln points, their comparisons

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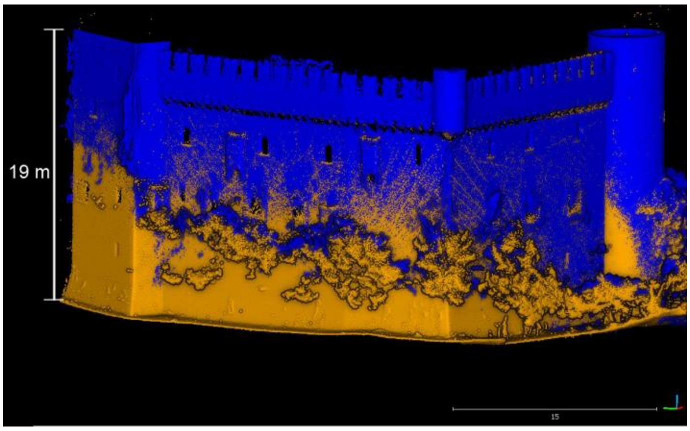
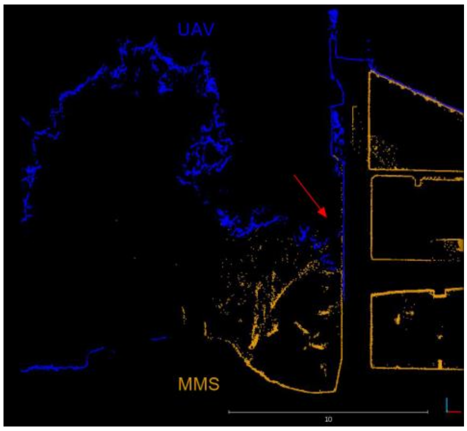
demonstrating very good results of ZEB technology in local 3D reconstruction. Particularly the dimensional comparison of main dimensions and areas estimation, as reported in Table 5, shows very accurate results as modest residual deviation errors from the reference dimensions (LiDAR) exist. The computation of C2C algorithm, in the second part of Table 5 considers the down sampling of the data by filtering approach to the ZEB point cloud due to the noise errors typical of these SLAM-based acquisitions. In fact, the compared mean and the st. dev. results considered before and after the procedure and represented in Figure 11b, c, reach almost 1 centimeter (±2 st. dev.) and then less than 1 centimeter. It is also visible the variation in the statistical distribution of points after the filtering process.

II. & III. If we consider now the global results of a ZEB set of mapping data in a typical indoor scene, it is possible to summarize that in case of both single floor of multi-leveled environments, a residual drift error in extensive and articulated trajectories is inevitable but it is possible to control and limit it too. The test cases have been the honour floor in the Valentino Caste and the apartments of the medieval Rocca. The execution of partially repeated and overlapping trajectories, for example in the spaces designated for horizontal and vertical distribution (corridors, stairways blocks), together with the re-computation of SLAM algorithm wit*h mer*ge re-process, significantly improves the ZEB results according to a comparison with a LiDAR ground-truth surface, as is reported in [2].



(**a**)



(**b**)

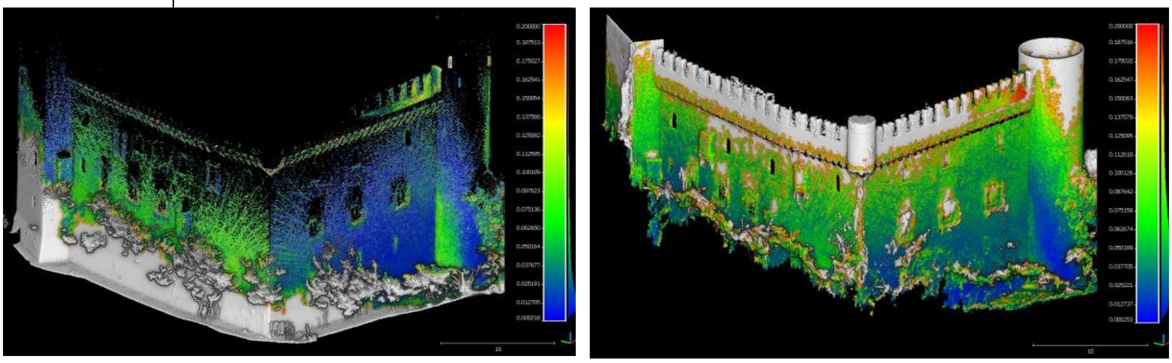
Figure 12. Extension of point clouds, UAV data coloured in blue, ZEB data in orange: (**a**) angular view of the external walls with presence of vegetation and (**b**)vertical section of the Rocca.

If we lastly consider the evaluation of the SLAM-based mapping into a *global* perspective in outdoor scenario, another question connected with the ZEB data is the scale and the coverage of the point cloud. If the data is collected as usual by a walking operator in a close-range framework, the results will return a point cloud characterized by range distance proportional to the outdoor laser extension, declared as 15m. In (Figure 12) the research direction has considered, as recently investigated in different types of large-scale scenarios, the integration between these two assimilable strategies of rapid-mapping and expected comparable final scale: the terrestrial SLAM-based mapping with contribution of high scale aerial data coming from UAV photogrammetric data.

As previously described, the Medieval Rocca is a great example of a complex architecture where the performance of UAV, LiDAR and MMS systems are proved, but the presence of vegetation hinders the ground level and covers a portion of the walls. The UAV point cloud Digital Surface Model (DSM) enables to obtain the external geometry of the surroundings and the Rocca, especially with its roofs and with the upper parts of its curtain walls and towers. Thanks to the easy maneuverability of ZEB Revo it is possible to integrate this lack. Moreover, the employment of a handheld solution for the inner apartments speeds up the acquisition and the processing phase as well. For these reasons, the integration of these two systems could be the best solution to be face up. In fact, a surfaces comparison proposed in Figure 12 and their C2C distance computation (Figure 13) show the potentialities of the enriched 3D descriptive capabilities of both integrated digitization of the Rocca. In (Figure 12b) a noteworthy section of the integrated model and a critical point of the trees leaning against the curtain wall. Wherever the mapping operator managed to pass near the walls, the reconstruction was continuous, with a maximum displacement of distances, in the upper part of about 9cm and a minimum in the lower part of about 1.5cm.

Table 6. Results of C2C comparison ZEB point cloud and UAV DSM on the *Rocca* volumes

Cases	**A**	**B**	**C**	**D**
	Complete ZEB-complete UAV	Outdoor ZEB-complete UAV	Outdoor ZEB-optimized UAV	n°12 Points-based alignment
RMSE (cm)	**76.4**	**52.2**	**5.27**	**6.26** Min 1.33 Max 9.27

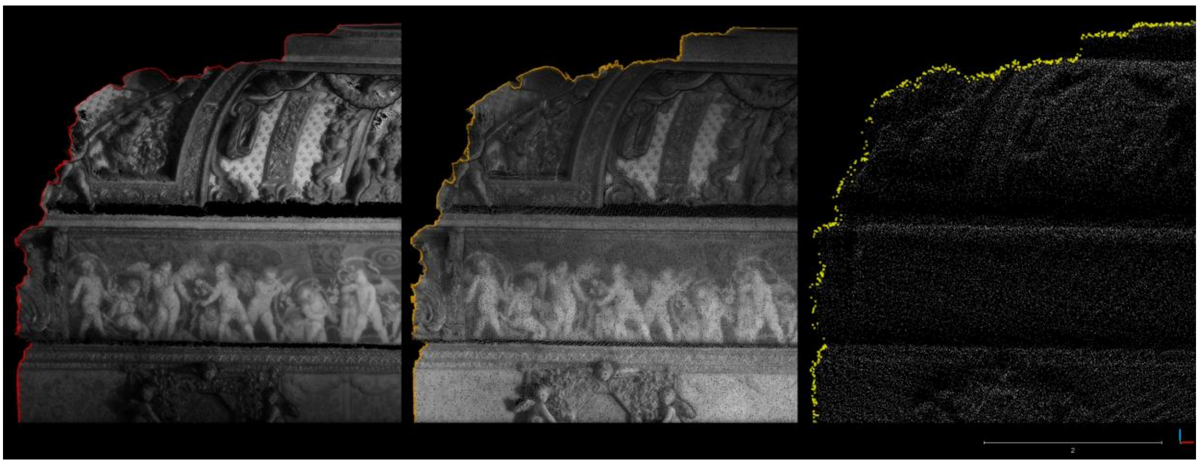


(**a**) (**b**)

Figure 13. Complementary representation of C2C points distances between the two point clouds: (**a**) ZEB distances on UAV data (min. 1.33 cm, Max. 9.27 cm) and (**b**) vice-versa projection and values in Table 6.

4.2. SLAM-based 3D modelling: testing descriptive capabilities in digitalizing complex surfaces

Hereafter in this second analytical step, it will be considered the problem concerning the geometric and radiometric featuring of sensors' models in comparison with ZEB surface, applying the validation strategies presented in [58]. Particularly, a benchmarking analysis focuses of some example of richly featured surface of frescoes and 3D details of decorative apparatus of the Valentino Castle, as previously described as a great example of a complex architecture with completely decorated indoor spaces, that are, for distinctive reasons (Figure 9b-above left): the *Great Salon* and the *Fleur-de-lis Chamber* with pavilion vaults and the particularly terraced *Roses Chamber* vault.



(**a**) (**b**) (**c**)

Figure 14. The benchmarking analysis on multi-sensors data of Fleur-de-lis Chamber in the Valentino Castle. (**a**) SfM points cloud (**b**) LiDAR points cloud and (**c**) ZEB points cloud.

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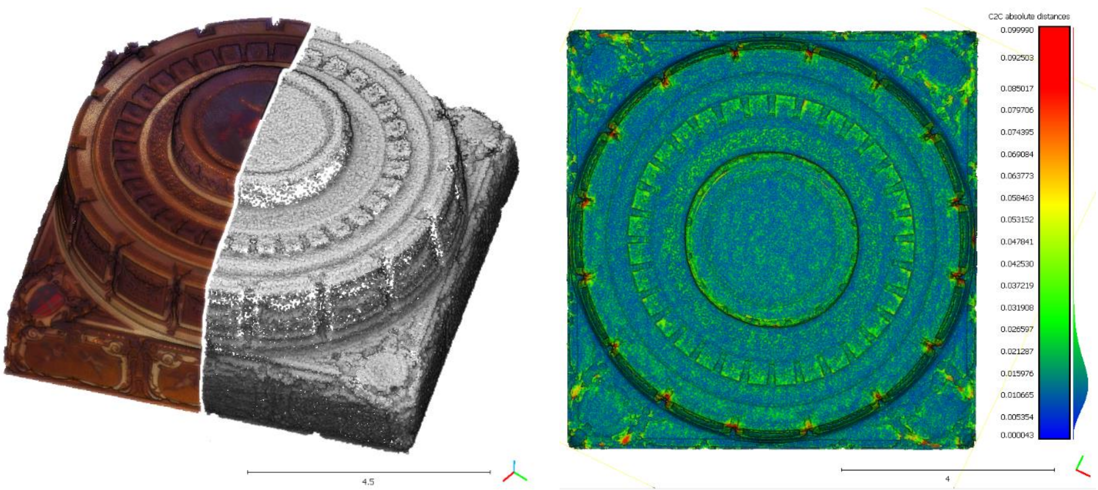
The surface model of typically decorated stucco's vaults, extracted from the point cloud, are the ones in Figure 14 and Figure 15. The problem of digitization of emphasized 3D decorations is proposed in Figure 14, where it is visible the risk of vertical shadings: the lack of information in undercut areas corresponding to the stucco frames appeared as a drawback mostly in (b), caused by the fix position of scanner and moderately in (a), (c). In Table 7 the quality values of the point clouds are related only to the vault parts: the close-range photogrammetric dense cloud can be compared to the massively rich LiDAR point cloud only just after a 1:3 filtering ratio. Conversely, for the ZEB point cloud, the density ratio turns out to be 1:20. In Figure 15, the deviation distances map between LiDAR ground-truth and ZEB mapping is presented on the vaults of the *Roses Chamber*, the only great terraced vaulted structure of the honour floor. The values of C2C comparison implie average values of accuracy between 5-20mm (blue to green).

Table 7. Comparison of point density related to close-range photogrammetric model, LiDAR scan and ZEB scan of the *Fleur-de-lis Chamber*.

	(a) Close-range SfM	(b) LiDAR					(c) ZEB
		Original	Filtering				
			3mm	*5mm*	*10mm*	*20mm*	
N° points	69.650.000 (*)	213.270.000	67.420.000 (*)	25.550.000	3.617.133	1.688.825 (#)	1.440.000 (#)
Density (pt/m²)	197.800	556.000	185.000	60.000	15.000	3.000	2.400

In Figure 16 the density distribution of the *Roses Chamber* vault is presented in color range map, according to a density computed in number of neighbors in a sphere with r=0.05m (CloudCompare density analysis implementation). The thematic map not only shows noticeably the difference of precision of the two sensors in the surface 3D digitalization, but also makes possible the interpretation of statistical values of density in the left graphs. In fact, it is clearly visible from the distribution values and the curve trend, that the ZEB data doesn't admit the accurate description of the detail's geometry in the recorded objects, as a TLS.

Specifically, studying the ZEB descriptive aptitudes in surfaces reconstruction, it should be considered that a single scan, travelling the whole honour floor in almost 30min and collecting almost ~35 mln points, manages to model some interesting morphological aspects of the architectural surfaces, i.e. anomalies from the generative geometries behind the walls course or vaults curvature.



(**a**) (**b**)

Figure 15. The *Roses Chamber* vault and the (**b**) C2C distances analysis between LiDAR and ZEB

In Figure 17b the optimization of DSM of the *Great Salon* pavilion vault is thematized by height values, already investigated by LiDAR-based approach finalized to the structural analysis of the

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restored wooden structures in [55]; in white color the extraction of isolines from LiDAR DSM and in black color the ones extracted by ZEB-based DSM. The ZEB-based DSM scale detail certainly couldn't support high accuracy analysis for structural purposes, but these two examples support the hypothesis that ZEB Revo MMS allows, through a rapid mapping, a dense point cloud and potentially advantageous collection of medium-high-scale information, especially for the morphological analysis of internal settings. Figure 17a shows a displacement map of T_2-T_1, between two ZEB acquisitions at time T_1 and T_2 and identifies a localized anomaly on the central part of the *Fleur-de-lis Chamber* vault, which has undergone restoration works and bedding phase for the wooden structures: it has been detected by MMS acquisition and furthermore confirmed by a LiDAR scan.

(**a**)

(**b**)

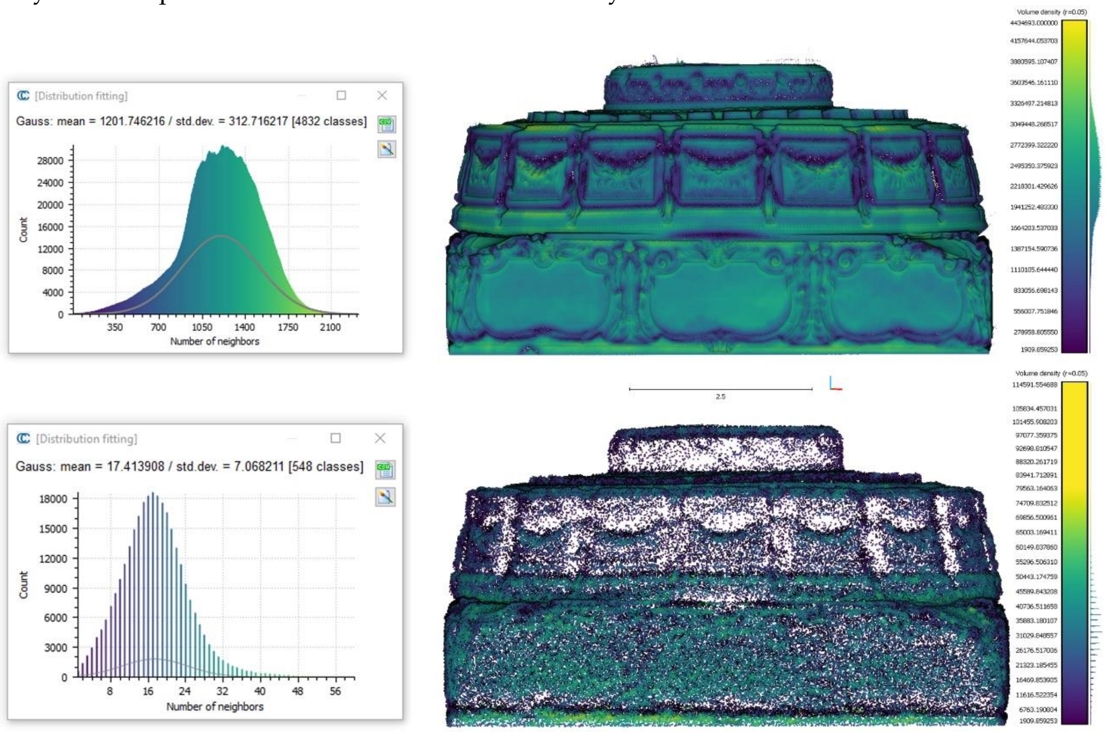
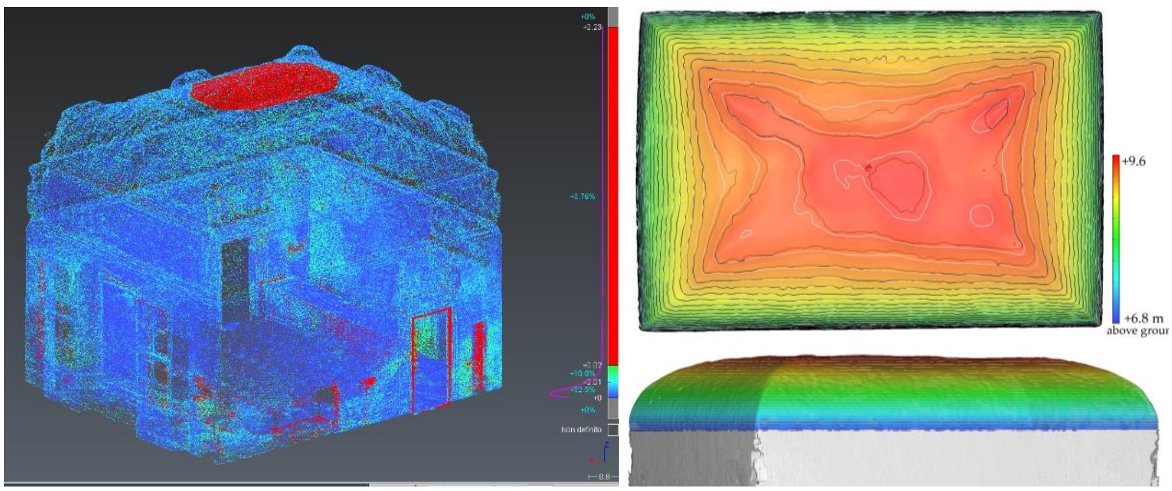


Figure 16. The two density analysis maps on the *Roses Chamber* in (**a**) LiDAR and (**b**) ZEB models.



(**a**) (**b**)

Figure 17. Morphological anomalies detected by ZEB sensor: (**a**) the central part of the *Fleur-de-lis Chamber* vault in displacement map of T_2-T_1 and (**b**) in the *Great Salon* vault, with the comparison of isolines from the LiDAR DSM (white) and ZEB (black).

4.3. Fusion-based strategies toward geometric and radiometric enrichment and self-supporting

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The fusion-based strategies are commonly developed where Cultural Heritage documentation projects are based on extensive and heterogeneous starting data, from passive and active sensors, for efficiency and optimization purposes in multi-scale and multi-resolution 3D models. As proposed previous in research [56,57], the concepts of fusion and integration methods are often the subject of crucial arguments concerning definitions and usages. First of all, the fusion needs arise from the purposes of 3D data features enrichment, i.e. the aim of overcoming of the sensors own limits (image-based and range-based). Moreover, the *levels* of processing steps on which the data are managed in the fusion, can be the raw data or the processed ones or more, post-processed ones. Lastly, the t*ypes* of information behind the interchange and effective provision between approaches.

Hereafter, a set of these topics are faced up in the perspective of a fusion-driven approach based on data and methods fusion: mainly the photogrammetric approach with the range-based method recognised as both the innovative MMSs point clouds and the contribution of more accurate terrestrial LiDAR data. The data fusion is aimed in a way at optimization and validation of geometrically and radiometrically enriched MMS SLAM-based surfaces:

- Fusion in data processing
- Fusion in meshing model generation
- Fusion of geometric and radiometric data

This simplified workflow tries, thus, to answer to some open-ended questions, such as the ones hereafter reported. Is it possible to constitute a schematic pipeline in which sensors' contributions are optimized? Is it conceivable a self-supporting use of the ZEB SLAM-based survey for a kind of extensive and building-scale mapping, even admitting as introduced, a forthcoming autonomy in the georeferencing issues? So, how accurate could be a photogrammetric blocks alignment, quickened by the non-involvement of topographic work, using alternatively geometric GCP extracted from georeferenced SLAM-based 3D models? And instead what about the use of TLS-extracted GCPs? After a fusion-based Bundle Block Adjustment (BBA), what would happen if simply the block of oriented images was enough to interfacing with a ZEB point cloud proper georeferenced, evading the photogrammetric densification phase? In this case is it promising to fuse the photogrammetric images, exploiting the oriented block *tie points*, with dense ZEB clouds in a typical Graphic User Interface (GUI) SfM platform, in order to perform the geometric and radiometric enrichment of point cloud and triangulated mesh surface in a unique space workflow?

4.3.1 ZEB-based photogrammetric block-orientation (o images block-orientation): a hybrid model

The photogrammetric approach commonly requires a set of coordinates - involved as control points (geometric features as well as contrast markers) in the BBA and in the accuracy check phase – that are generally acquired during time-spending topographical operations, in a different survey moment than the images shooting phase. The availability of a geometrically rich 3D point cloud derived from a MMS as the ZEB Revo survey, meets some remarkable requirements together with the time savings, practicality and manageability. For example, in this case, the ZEB point cloud would like to offer an experimental solution as a source of points coordinates to be exploited in the photogrammetric process of BBA, avoiding topographic measures. This method could be a useful solution in case of a photogrammetric acquisition without measured targets or with data acquired at different times. This proposed data fusion solution to orient a set of photogrammetric images is hereby proven. The considered example is a dataset of 263 photos captured by Sony ILCE in the inner courtyard of the Rocca. The images are aligned with coordinates obtained extracting a selection of n°20 points well distributed in the entire space. It has been chosen to compare the alignment with RMSE results, Table 8, using the manually extracted GCPs from ZEB point cloud, with others two type of reference values:

- images BBA RMSE results using the same n°20 manually extracted points from TLS point cloud
- images BBA RMSE results using n°20 topographic measured GCPs with typical contrast markers

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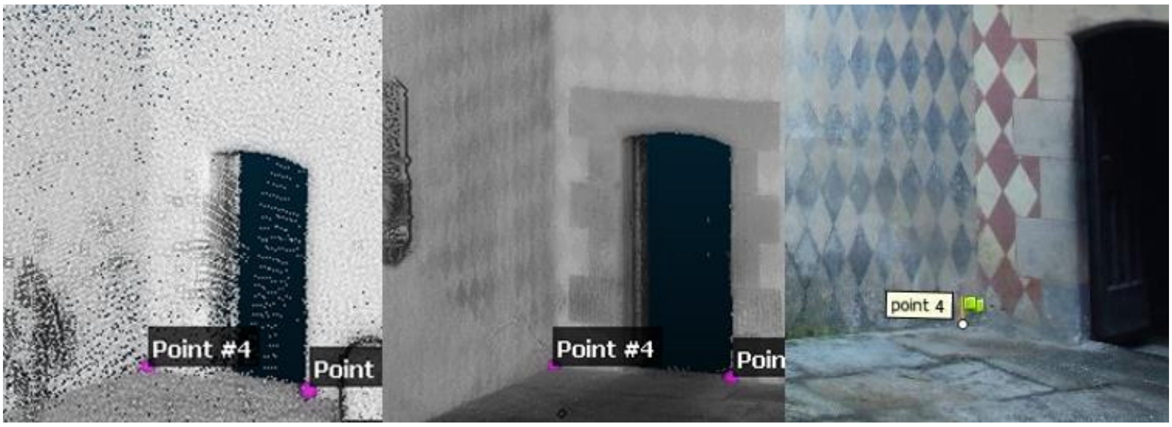
The main difficulties refer to the identification and manual extraction of the point in point clouds, because of their lack of direct radiometric accurate data. In fact, RGB information is currently not available in ZEB point clouds, so it is not possible to exploit color recognition (for instance contrast markers, as in case of LiDAR usual pipeline), but it is necessary to pinpoint geometric features (for instance architectural ones as corners window, edges, 3D decorative element, or 3D targets), as visible in Figure 18. To reduce the operator imprecision in manual collimation phase, each point has been selected and extracted n°5 times, by piking-points selection (implemented in CloudCompare software), then the arithmetic mean and *st. dev.* were calculated to estimate the precision of manual point extraction and the effectiveness of the proposed method. The st. dev. related to TLS-extracted coordinates varies from 0.11 cm to 1.47 cm, meanwhile the ZEB ones from 0.44 cm to 9.42 cm, as reported in Table 8.

Finally, the mean X, Y, Z values of each point selections were employed as GCPs coordinates to orient the photogrammetric block. In order to evaluate the effectiveness of these method, the results of BBA are compared on CPs errors with the ones calculated with more accurate coordinates obtained measuring targets by TS and GNSS survey. The results are presented in Table 9. It is tested that decorative corners are less recognizable in ZEB and LiDAR point clouds and affect the result.



(**a**) (**b**) (**c**)

Figure 18. The n°4 points selected in (**a**) ZEB and in (**b**) TLS point cloud for coordinates extraction and finally the point was detected and placed on the (**c**) DSLR photo, for the images block orientation.

Table 8. The precision of coordinates derived from the test of the manual pick-point selection, statistically repeated 5-times on 20 points and applied on TLS and ZEB point cloud.

5-time pick-point	TLS-extracted coordinates				ZEB-extracted coordinates			
	X	Y	Z	TOT	X	Y	Z	TOT
σ_{min}	0,0011	0,0024	0,0028	0,0021	0,0054	0,0044	0,0060	0,0053
σ_{MAX}	0,0120	0,0101	0,0147	0,0123	0,0599	0,0287	0,0942	0,0609
$\boldsymbol{\sigma_{mean}}$	0,0047	0,0049	0,0061	**0,0053**	0,0163	0,0136	0,0249	**0,0182**

Table 9. Results of the photogrammetric block adjustment using differently accurate set points: the topographic reference measurements on target points, the GCPs extracted from the LiDAR point surface and the ones from ZEB point cloud

BBA RMSE	**Topographic coordinates**	**TLS-extracted coordinates**	**MMS-extracted coordinates**
15 GCPs error (cm)	0.43	0.95	7.72
5 CPs error (cm)	0.54	1.37	11.03

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4.3.2 Fusion-based mesh triangulation oriented to high-scale 3D digitization and optimization

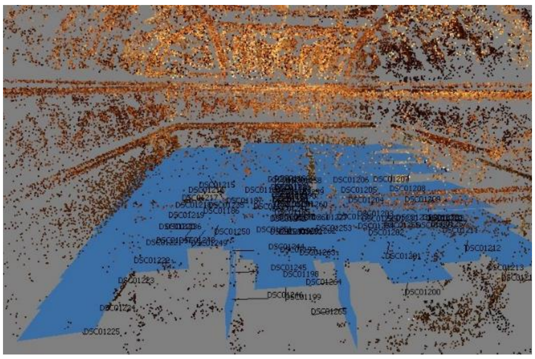
The second experimental pipeline within the proposed workflow aims at exploiting the best of descriptive capabilities of each employed method in such kind of multi-sensor and multi-scale survey approach. The chance of creating a multi-resolution model, for example in extensive and compound areas, as in [58], offers a solution toward data selection, segmentation, integration and addressing to the appropriate level of detail wherever necessary to be increased and concretely approaching.

It is based on a triangulated high quality textured surface computed by an optimized multi-sensor points cloud. The starting data conveyed in the integration test process are:

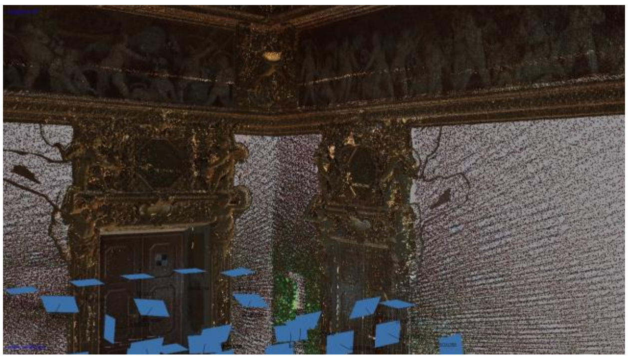
- ZEB Revo point clouds based on portable rapid mapping technique
- Photogrammetrically Oriented image block
- LiDAR point cloud from TLS acquisition

The efficient integration in the same pipeline of the LiDAR data and photogrammetric dense cloud have been partially investigated by low-cost 3DVEM – Register GEO tool in [27] but the processing was not yet in the same platform of SfM workflow. Here, the photogrammetric-based workflow for data fusion was performed using Photoscan Pro by Agisoft GUI (today Metashape, https://www.agisoft.com). The recent releases interface can efficiently solve the problem of interoperability in point clouds data import/export from other sensors as well (is it possible to import in **.las, *.e57, *.ply, *.asc* formats). For example, the same image-based point cloud could be externally processed (filtered, segmented or optimized), or a laser point cloud can be imported with or without its radiometric attributes. Moreover, in the GUI it is also allowed to merge a photogrammetric image block (Figure 19a), oriented using the MMS-extracted GCPs coordinates as reported before with ZEB data. As a result, the colorization phase is applied both to the MMS point cloud and to the fusion-driven built mesh, using as primary data the oriented photogrammetric image block. The test has focused on the *Fleur-de-lis Chamber* and is consisted in the use of different point cloud surfaces, related to the Table 7 analysis: the photogrammetric based one (almost 70mln points); the LiDAR (original not considered, *5mm* filtering, 25.5mln points and *1cm* filtering, 3.6mln points); ZEB SLAM-based point cloud (1.4mln points). The *normal vectors* calculation of the input point clouds should be accurately controlled for a uniform distribution and orientation, if a finalization to the triangulated surface calculation (*mesh),* is foreseen. Despite photogrammetric surface *normals* are correctly computed embedded in the SfM process and dense reconstruction, a range-based data should generally be subjected to a *normals* data re-computation or finalizing.

A noticeable aspect in the GeoSLAM Hub processing platform is the managing of the *shape* attribute in output files, as previously reported (Figure 9b, III): this effectively concerns the computation of suitable embedded normal values data associated to the ZEB point cloud output, but the formats required for the export exclude **.las*, as non-compatible with normal data.



(**a**)



(**b**)

Figure 19. (**a**) The oriented images block in the *Fleur-de-lis Chamber*. (**b**) The Photoscan Pro GUI allows importing external integrated point cloud for the fusion-based mesh triangulation.

The CloudCompare workspace offers an implemented *Normal Computation* algorithm, anyway, working on octree strategy and using the setting of a point neighbours radius area to simplify or

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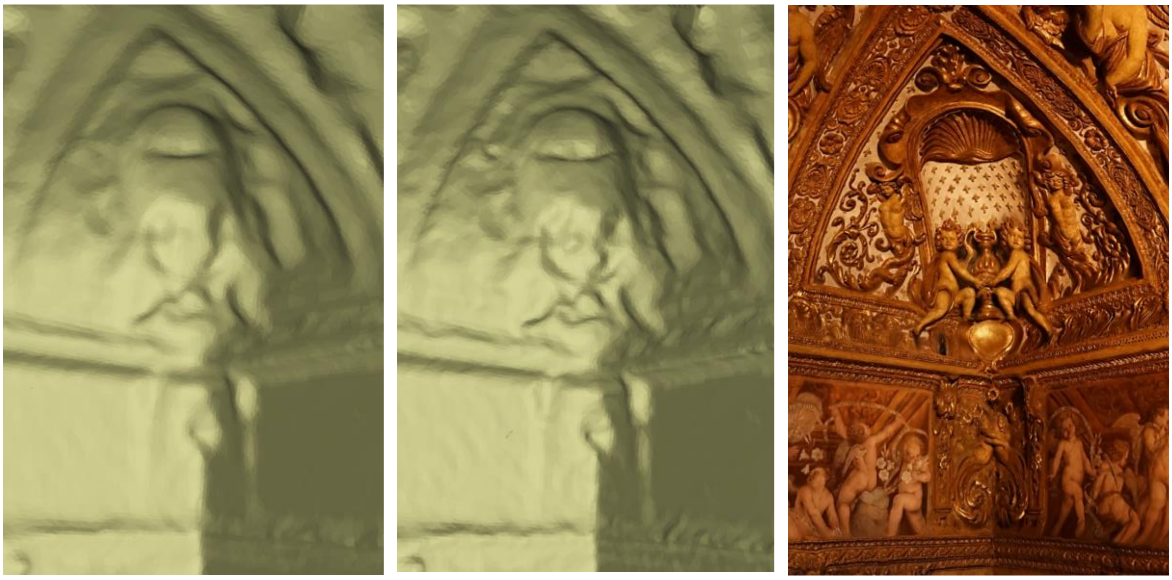
improve the computing. So, the ZEB surface used for the meshing processing has been exploited in original format, as exported from raw processing and with re-computed *normals* in CloudCompare, with a neighbours radius of 5mm and 15mm. After the mesh triangulation process compared in Table 10, simplified surface have been respectively reconstructed, as showed in Figure 20 a, b. Finally, as it is reported before, the oriented images acquired by Sony ILCE 7RM2 were used to associate the radiometric attribute with the "*colourize*" function as presented in Figure 20 c.

Table 10. Results of mesh triangulation process, based on different sensors point clouds

Mesh model	Close-range SfM	LiDAR (*5mm*)	ZEB	Fusion-based
N° triangles	13.937.030	5.110.790	318.232	3.391.239
**.obj (*.obj+ *.jpg)* file size (Mb)	*1366 (1798+4)*	*215 (386+9)*	*24 (33+8)*	*186 (297+9)*



(**a**) (**b**) (**c**)

Figure 20. The ZEB-based surface reconstruction: (**a**) mesh processed with normal data computed with 15mm radius and (**b**) computed with 5mm radius; (**c**) with HQ texture map applied on (b) surface

5. Discussion

When geomatics techniques encounter the difficulties in workflows arranging for surveying, modelling, organizing and sharing large cultural heritage, as Valentino Castle and Borgo Medievale, some challenges must be considered and various solutions must be critically analysed. Interesting solutions derived from sensor integration and data fusion are auspicious, such as sensors and software development to speed up recording and processing time, in operational workflows. This should be addressed to the best possible interoperability of multi-dimensional data with emerging ICT innovations: digital devices and virtualization of models in the real scenarios are useful implementation for the cultural heritage fields users, allowing to digitally explore "immersive" 3D model and related information. It has been validated that geomatics increasingly provides strategies to deal with specific needs and favouring multidisciplinary approach, also encouraging wide dissemination of digital culture. But the 3D documentation phase of an extensive built complex still proves to be a difficult challenge nowadays. It implies various technical aspects concerning both data acquisitions, their interoperable management of data and their finalization to all user-oriented aims.

The present research tries to underline most of these aspects, in particular advantage and disadvantage of the achieved results are summarized below, mostly focusing on creation of hybrid 3D models (5.1) and their usability and potentialities (5.2).

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5.1. Multi-sensor data complexity: hybrid 3D models

In recent decades, with exponential increasing of technological solution based on sensor improvements and fusion, Geomatic community proposed many ad hoc solutions of multi-scale and multi-sensor methods and little about the guideline and practices to execute them, especially in the built heritage domain.

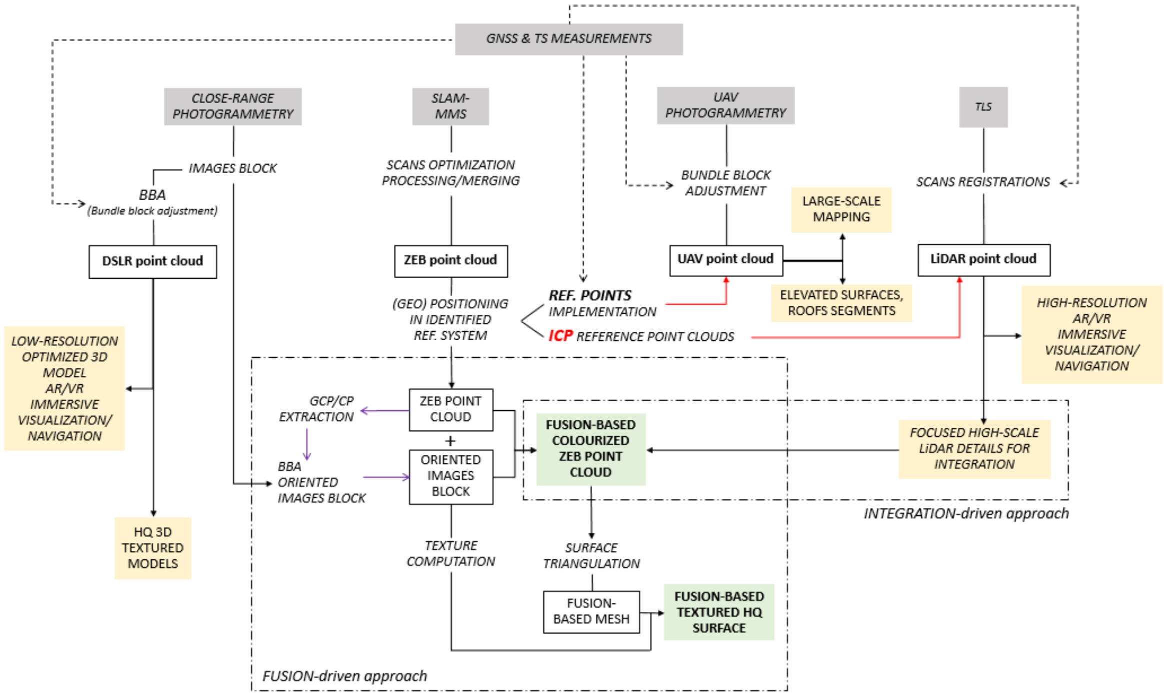

Figure 21. Graphic workflow of the *hybridization* of 3D models, deriving from integrated methods and fusion-based approaches. In grey the acquisition methods, in green the achieved products with the possible connections. In the dashed box the fused and integrated results.

The generation of a hybridization-driven 3D model could surely return positive effects in the whole workflow, not only in data acquisition and processing phases, but also in terms of data modelling, editing and optimization for user-oriented purposes. The main idea is constantly to change perspective on digitization approach and to pre-select and pre-orient ex-ante the data content to the request level of detail, instead of ex-post customary lightening, simplification or drastic filtering. In this paper the problems about preservation of the descriptive abilities in 3D models are mainly addressed, both in terms of geometrical accuracy and in the integration of radiometric contents, so important in the projects that must satisfy future immersive enjoyments.

Thus, the combination of sensors is exploited according to their specific abilities in terms of resolutions, characteristics and behaviour in certain operational fields, also in critical ones, both indoor and outdoor scenarios. A sensor all over effectively working does not exists as well as a single sensor approach represent a limited approach, although often it is the most used one. After the series of extensive testing, it is possible to summarize some consideration and evaluation, reported in Figure 21. Obviously, the strategies for achieving multi-sensor and multiscale models are those chosen to face this challenge, maintaining a high attention, as seen above in paragraphs 3-4, on models created by recent rapid mapping systems, which offer leaner and handy points models, less heavy in terms of file weight compared to those derived from the more traditional LiDAR technology.

Advantage and disadvantage of each sensors combined with critical environment suggest undertaking a mixed approach of techniques to obtain a hybrid model. Integrated and fusion based approach could be a winning solution, customizable according to specific needs, in terms of time, costs and sensors finalize to obtain pre-determinate final products with specific levels of detail, as

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shown in Figure 21. Following general procedural steps (planning, survey, processing, analysis and communication), different consideration can be stress.

Furthermore, the possibility to integrate data acquired with different sensors and at different times underlines the ability of sensors in record geometrical differences and suggests further interesting analyses. In planning phase, it is necessary to consider setting conditions. Spaces like the ones studied in this paper provide some challenging examples where to perform a survey because of: building sizes, multilevel and articulated spaces, light conditions, presence of movable elements, little details and fragile elements as many cultural heritage assets and occurrence of occlusions, as furnishing and artworks. In parallel the presence of outdoor tall trees standing and leaning on the curtain walls, influenced the survey very much: in most cases, they cover the architectural structure of the buildings and increase the non-continuity and noise errors of the dense clouds.

Sometimes - as proved in 4.1(IV) - UAV photogrammetry can deliver affordable data comparable to MMS one in terms of resolution, allowing the georeferencing MMS data and promoting their integration; in this way a combined use constitutes a rapid approach in architectural mapping also in case of extreme condition, such as low overlapping areas. Furthermore, another fast approach can be pursued extracting 3D coordinates from MMS point cloud and using them to align a set of images captured with a DSLR. Referring to deeper level of detail, a products fusion can be pursued exploiting LiDAR data for minute parts – as decorative elements -, MMS data for a general overview of the context – such as walls or simple geometries – and close-range photogrammetry for radiometric quality derived by an oriented block of images. After the discussed experienced and the reported results, it is possible to assert that both the Rocca Medievale and the Valentino Castle justified such kind a multi-sensor approach to obtain a complete 3D model. In the following figure a schema of the proposed approach for 3D model's *hybridization* is reported.

5.2. Usability and flexibility potential of 3D models

Once the model is available, after the analysis and validation, an important issue is the use of the achieved products. Without addressing wide-ranging issues such as the primary ones in the domain of communication of built heritage (4D recording, fruition of multidisciplinary information, 3D inventories, user friendly web platform), we intend now to present some examples of one of the most promising and cutting-edge applications related to the immersive use and navigability of the 3D data. Hereafter some examples are reported in connection with the analysed built heritage.

5.2.1. Navigation of LiDAR points cloud

It is very important to consider that tools enabling the model navigation (and video recording) are available; they allow to overcome to a certain extent the criticality of the difficult management of large amounts of data. The Recap Pro software by Autodesk (*https://www.autodesk.com/products/recap*), for example, offers a navigation within points clouds particularly decimated, able to support navigation in real time also through the use of smart devices that connect via the server the navigation of the model. The application shown in Figure 22 was created starting from the complete LiDAR points cloud, coloured by the automatic process of the Faro system equipped with the coaxial camera. The total huge weight of this registered clouds is equal to 66.4 Gb (in **.e57* standard format) as it is composed of 3268mln point points; once filtering, with 5mm distance constant value, the point cloud size became of around 325mln (8.3 Gb **.las* format and 5.8Gb **.e57 standard format*). Despite on this platform the possibility of user interaction with the 3D model is limited, the navigation with the subjective point of view that moves all around the space represented by the digital model is certainly immersive and suggestive and it does not suffer from the amount of points data, which are rendered only with the level of detail to be zoomed in.

It is undeniable, in fact, that this navigation makes it possible to observe and learn some of the main characteristics concerning the decorative apparatus of the rooms. In the *Fleur-de-lis Chamber*, a stucco frieze and triangular coves in the corners support the impressive composition of the vault, enriched with a dance of putti, ribbons, amphorae and floral decorations. It is certainly not possible

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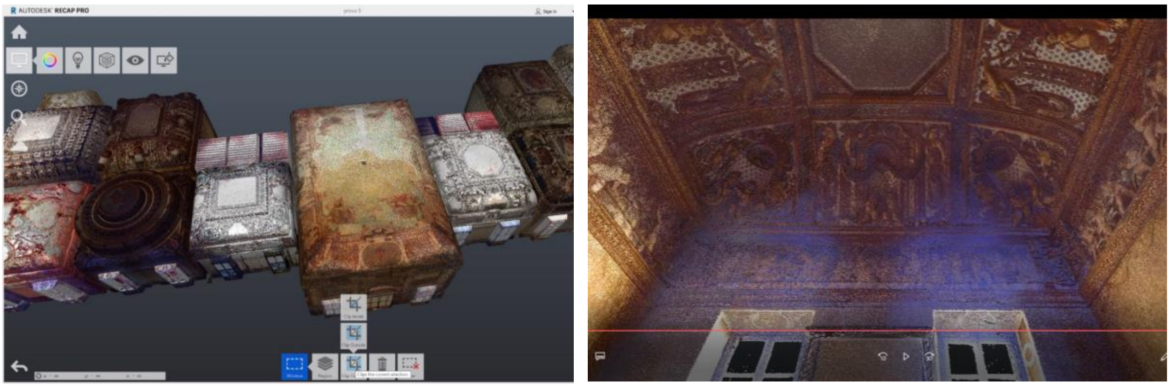
to recognize authors or learn other specialist information, but the communication purpose for general fruition is achieved (Figure 22).



(**a**) (**b**)

Figure 22. (**a**) A screenshot of the LiDAR points model managed in Recap environment. (**b**) A screenshot from the video navigation achieved from LiDAR points cloud.

5.2.2 Augmented reality (AR) experiments

The next two examples of using image or range-based models for fruition purposes are two augmented reality (AR) experiments applied to two different rooms on the Valentino castle's main floor. As known the augmented reality, or computer-mediated reality, also growing in the cultural heritage domain, consists in enriching the human sensory perception through digital information, which would not be perceptible with the senses. Elements that "increase" reality can be added through a mobile device, such as a smartphone, with the use of a PC equipped with a webcam or other sensors with vision devices. The new representation techniques (virtual and augmented reality), provide immersive experiences in virtual heritage field; the digital object can be queried by the user through the same dynamics present in the world of digital entertainment, a factor that surely is recognized by a relatively young audience, but intrigues a wider target audience, becoming a means of communication that meets today's expectations [59,60].

Quickly, the first application concerns the Honour Salon [61]. Here a LiDAR model was preferred to the image based one because the large hall with openings on the short side is dark and difficult to illuminate, together with the criticality represented by the huge historic chandelier that has been masked in all images used for the photogrammetric matching and the SfM process. As already ascertain, the block of oriented images has been used to texturize the LiDAR model, superior and less noisy as far as metric accuracy is concerned.

The triangulated continuous model achieved both with the open source MeshLab software and with the commercial 3Dreshaper software, which had provided completely similar qualitative results, had been texturized and optimized with Blender software, the most efficient and widespread in the field of simplification and optimization of texturized models. The initial filtered cloud of 10 million points had been reduced to a polygonal model of about 180k vertices.

Then, using the AR software solution by Metaio (no longer active, since acquired by Apple) two applications for the operating system of Apple iOS were generated.

The first allows to view the Honour Salon by simply moving the device, just as if you were inside the scene (Figure 23a), while the second app, thanks to the framing by the camera of the simplified grayscale DSM of the dome, enable the visualization on it of the 3D model (Figure 23b).

It's rather interesting the shared use of technologies: the 6D Augmented Reality Holodeck tech. (named 6D-AR) takes advantages from SLAM algorithms and from the on-board IMUs motion sensors to attach the virtual environment to the real world, exploiting the camera of smart device [62]. Also, in this case, it is obviously possible to learn the decorative themes of the frescoes, which consist in the exaltation of the Savoy family through the re-enactment of military enterprises. At the same time, it is possible to examine the expertise of the scenic installation that reproduces twisted

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columns and a balcony executed by Isidoro Bianchi who painted with the collaboration of the sons between 1633 and 1642 [35] (Figure 23).

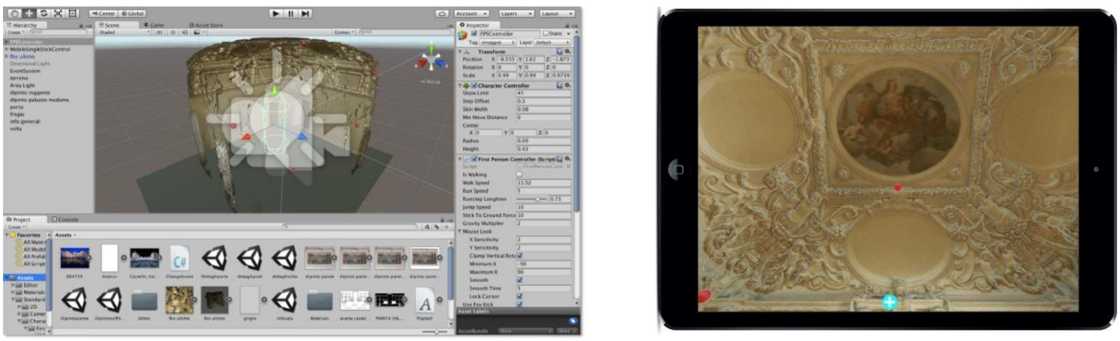
(a) (b)

Figure 23. (a) The SLAM for full 6D VR/AR application running on iPad. (b) after the gray scale model recognition as marker, the running application on iPad providing information about the frescoes.

The second AR test concerned the Hall of feasts and splendours, for which the window surfaces with respect to the dimensions, as well as the richly decorated vault with light stuccos in high relief, allowed to generate the texturized model using DSLR images and SfM algorithms, obtaining a customary accuracy around 1 cm [63]. The whole process of modeling the triangulated surface (about 5ml of polygons) and its texture were performed using the software Photoscan.

The game engine selected for the application development is Unity 3D, widespread and widely used in this sector as it allows high interoperability with different devices and platforms; (The software is considered cross-platform, i.e. able to develop the WebGL project for PC, Android, iOS and Windows Phone for mobile devices) (Figure 24a). Also in this case, the final objective has been reached, that is, besides testing the interoperability of instruments and data between different application fields, it was to create a basic communication product composed of a navigable model characterized by an interactive system capable of providing informative details on the Hall, through the pressure of characteristic points arranged within the model (Figure 24b).

The criticalities in integrating models derived from geomatic techniques and game design software are still high and consist mainly in the criticality of using models derived from millions of points in systems designed to manage models of reality much more simplified.



(a) (b)

Figure 24. (a) Arranging camera position inside the 3D textured model using FirstPersonController of Unity. (b) Interactive model of the hall showing typical points enabling to reach additional information.

6. Conclusions

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3D documentation of extensive build heritage complexes still proves to be a difficult challenge nowadays. It implies various aspects concerning both acquisition, management of data, their interoperability and their finalization to all user-oriented purposes.

The research here proposed mostly refers to an essential answer to the diffuse increasingly spread of innovative input and traditional requests in Cultural Heritage domain belonging to digital era: it has to face many domains (disciplines, users, purposes, data, formats, software, supports, type and mode of visualization) connected each other.

With different depth, this paper has been dedicated to addressing both the evaluation of the effectiveness of the models and the current critical issues related to management tools have been considered too. Moreover, the themes of data interoperability, operating times in acquisition and processing and issues related to the management of large amounts of data have been discussed. The achieved results connected to technologies progress are above presented, nonetheless, to pursue it some issues remains and must be solved.

Once derived from data acquisition and processing, reality-based models offer a wide range of applications, responding to specific needs of costs and purposes, such as documentation, analysis and sharing. The possibility to integrate other sources – textual and/or graphic – lead to creation and manage of digital georeferenced databases. Thanks to different supports – pc, smartphones, tablet, visors – varied users can explore these models in online or offline mode; in these visualizations immersive, interactive, augmented or virtual realities offer a more and more growing way to understand and discover. These aspects require the capability to handle huge amount of multidimensional data - among others geometry, time, radiometry – characterized by digital formats and standards created, managed and visualized in various software, applications and platforms.

It has been proven that geomatics provides strategies to deal with specific needs and purposes, favoring multidisciplinary approach, also encouraging wide dissemination of digital technologies. Geomatics for heritage digitization address, in these cases, the entire workflow to manage the concept of complexity behind the building challenges (Figure 25). Once derived from data acquisition and processing, reality-based models offer a wide range of applications, responding to specific needs of costs and purposes, such as documentation, analysis and sharing. The possibility to integrate other sources – textual and/or graphic – lead to creation and manage of digital georeferenced databases.

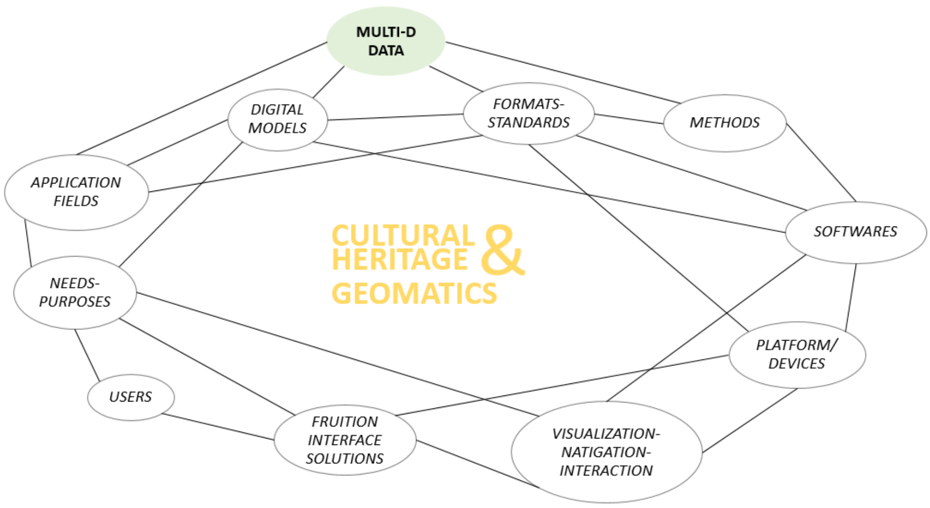

Figure 25. Relations between many deterministic factors turning around the Geomatics approach working on in cultural heritage domain

Thanks to different supports – pc, smartphones, tablet, visors – varied users can explore these models in online or offline mode; in these visualizations immersive, interactive, augmented or virtual realities offer a more and more growing way to understand and discover. These aspects require the capability to handle huge amount of multidimensional data - among others geometry, time, radiometry – characterized by digital formats and standards created, managed and visualized in

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various software, applications and platforms. If the future the idea is to work in the direction of allowing the user to move freely in the reconstructed scenario, then it is obviously essential to consider the completeness constraints of the model, which constitutes, in addition to the previous, one of the quality parameters for the evaluation of the models of the reality.

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