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Challenging multi-sensor data models and use of 360 images. The Twelve Months Fountain of Valentino park in Turin.

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Abstract: The cultural heritage and the ways in which it is today studied and analysed as well as disseminated and enhanced for the purposes of conservation, requires high attention in the choice of 3D survey and modelling methods. This manuscript investigates the possible integrations and fusion of methods and data, among the vast availability of image and range based systems, especially in the sphere of low cost techniques, which in the context of heritage documentation makes the whole and complex process of conservation more sustainable. The investigation is carried out on a historical fountain that includes a quantity of cultural values and the need to document its context: its location in the historical Valentino of Turin park, its architectural values and the geometry of the complex typically related to the tastes of the late XIX century that consist in the extreme refinement of the statuary complexes and the underground portion with the technological equipment for the activation of the water games. Basically, it will be possible to appreciate solved issues and permanent criticalities derived from the integration of close range and UAV photogrammetry techniques in addition to the LiDAR survey, both classic from a fixed position, and in the portable scanner mode, based on SLAM technology.

1. Introduction

Recently, image and range-based survey techniques for cultural heritage documentation are enriched with increasingly diversified and specialized systems to achieve modeling and representation goals suited for the variety, articulation and complexity of the built heritage demands. UAV (Unmanned Aerial Vehicle) photogrammetry with the employment of nadir and oblique acquisitions, can count on an offer of systems and platforms that allows flying over objects of interest at different distances and with extreme flexibility [1]. At the same time the new development of 360° imaging systems and sensors started a new era of the well-known spherical photogrammetry not only for photogrammetric approaches that allow to obtaining points-based models, but also to create navigable images models, useful for communication and dissemination purposes [2]. In the range-based scenario, mobile scanners with SLAM-based technology represents today the largest improvement and innovative tool for 3D survey if compared with the traditional acquisitions carried out by a typical terrestrial laser scanning approach. The different survey systems allow to calibrate the data acquisition phase increasingly closer to the needs and, moreover, are able to exploit all the possibilities connected with the use of low-cost systems, while the automatic and semi-automatic image-matching, images orientation and merging or fusion of multiscale clouds allows a spectrum of possible choices to achieve model optimization [3-5].

If many of the presented techniques are considered as "rapid mapping" methods, since the data collection times are extremely rapid, the chance to obtain accurate models, featured by information density and resolution of radiometric results (variable and depending on the morphology of the objects), continues

to be a time-spending operation. The object considered for testing the approaches investigated in this contribute will be a case study of particular historical interest: the Twelve Months Fountain in the Valentino park in Turin, built up in 1898 for the Italian General Exhibition, held in the park. Lastly a final remark concerns the 2D and 3D results, that have been achieved by a didactic experience involving students of the Architectural area of Politecnico di Torino is reported.

1.1. The Twelve Months Fountain in the Valentino park in Turin

The architectural complex of the twelve-month fountain of the Valentino park was conceived for the national exhibition of 1898 making it one of the main attractions, and took on a new dazzling configuration in relation to the rear of the England pavilion (Figure 1) during the course of the universal exhibition of 1911. The fountain was designed by the eclectic architect Carlo Ceppi, as coordinator of a conspicuous team of the best known decorators and sculptors of the time (eg E. Rubino, C. Reduzzi) [6] creating a whole in which the "*rocaille*" taste harmoniously marries sixteenth-century memories and *liberty* scrolls and movements (*liberty* is a term with which the *art noveaux* affirms itself in Italy).
New materials such as concrete aroused great application potential. The overall architectural values of the building, together with artistic merits of the statues of the twelve months and the four admirable statuary groups of the Turin rivers, are added to the impressive hydraulic engineering work of the fountain, including also the underground pumps and technological equipment. [7-9]

Figure 1. The fountain in the 1911 exposition occurrence (historical double card from [9].)

2. A multi-sensor data acquisition approach

The methodologies deployed for the documentation of the fountain and the surrounding park respond to the typically recognized principle of multi-scale and multi-sensor data acquisition as well as to the demand of data integration. In this specific case the main training and methodological purpose was to cover, with appropriate terrestrial and aerial techniques, all the documentation scale referring to the complex architectural and garden site. The UAV photogrammetry, based both on traditional RGB and 360° imagery, has been applied to document the environmental context of surrounding hilly area of the park, in which secular trees are contemporarily typifying the scene and challenging the flights planning phases. This determined to plan also SLAM-based acquisitions with the mobile mapping method, which in addition to helping to detect the areas of wooded and clearings zones were fundamental for the underground environments, which accommodate the hydraulic machines. The architectural complex, designed according to two elliptical ramps surrounding the fountain enclosed by a balustrade, was surveyed by TLS (terrestrial laser scanning). Furthermore, for the admirable statuary groups, consisting of imposing statuary volumes with basements, were the object of integration between traditional LiDAR survey and photogrammetric clouds derived from very light drones' flights. (cfr. section 3).

2.1. UAV acquisitions using 360° images blocks

As said in section 2, a part of the documentation of the Twelve Months Fountains was carried out using different strategies for image acquisition using UAV platforms. The traits of the site located in one of the main green areas of the city, involving the presence of trees and people, has been carefully considered before completing the flights. For a general survey of the area firstly the DJI Phantom 4 Pro have been used to perform automatic pre-programmed flights at a medium altitude, above the height of the trees near the fountains, in order to include all the object and its surroundings. For this purpose three different flights were planned and performed at an altitude of 50 meters above the ground level: a nadiral flight (camera axis perpendicular with the terrain), an oblique flight with camera axis oriented at 45° in respect of the terrain and flight directions parallel to the two roads that flank the fountain and finally another oblique flight with the same flight directions but using the PoI (Point of Interest) function that allow to maintain the point of interest of the camera axis on a selected location (in this case the centre of the fountain). The three different acquisition schemes are reported in the following Figure 2

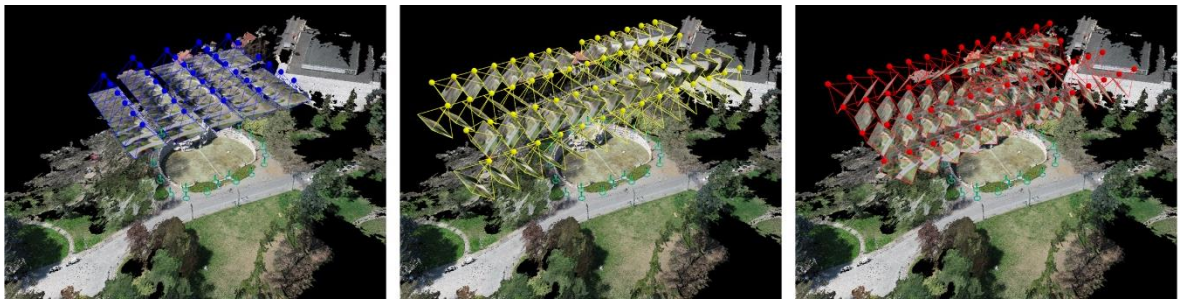


Figure 2. *The UAVs flight plans: Nadiral (left), oblique (centre), oblique flight with PoI (right).*

The three UAVs acquisitions were thus processed together following the standard photogrammetric approach and using the well-known Agisoft Metashape software. The photogrammetric processing with 144 images (Ground sampling distance GSD=1.8cm/pix) generated ≈ 40 mln points, with an average RMSE on Ground control points GGPs (10)=7mm and Check points CPs (4)=8mm. The data products were then used both for the creation of the traditional 2D representations and for detailed analyses on the 3D models during the training activities of the course.
Moreover, the Phantom 4 was deployed on the field for another type of acquisition: it was used to acquire all the images necessary to create spherical images in pre-selected positions. The use of this type of images is indeed a trend topic in the community of geomatics researches [10-12]. In this test case spherical images were used with two main objectives: firstly, to test their use as a tool for dissemination and communication through the creation of virtual tour and secondly, to experiment their use also in the photogrammetric process. The acquisition of these images is generally achievable with two different methodologies: the use of *ad hoc* 360 cameras (e.g. tested also as UAVs payload by [12]) or the use of different images acquired by the same camera and stitched together in a single spherical image. In this case the second approach was adopted using the acquisition modality embedded on the DJI mobile application DJI Go 4 and the images were then post processed and stitched together using the AutoPano Giga Software by Kolor, an example of the process of stitching is reported in Figure 3.
For the Twelve Months Fountain six panoramas composed by 34 single images were acquired following the described approach; after the stitching phase, an online solution was used to create a virtual tour dedicated to the fountain. Instead, as is well described in the [13-14], the photogrammetric processing of this type of images poses different problems and there are several approaches to deal with the issue connected with it. The main idea behind the photogrammetric use of these images for the documentation of the fountain was to test the integration in the photogrammetric processing of spherical images not acquired for this specific objective but for the creation of a virtual tour.
Three different strategies were tested for the processing: (1) The images acquired for the different panoramas were considered as camera groups and processed following this approach; (2) The images

were previously stitched and then used in the photogrammetric processing as spherical panoramas; (3) The images were treated following the standard photogrammetric processing and used as single images.

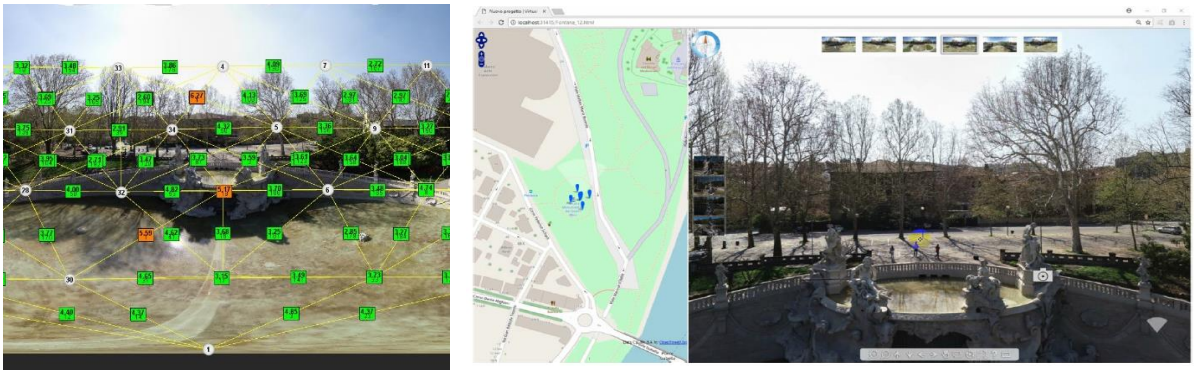


Figure 3. *(left) Stitching of the images acquired by the Phantom 4 in a single spherical image using Autopano Giga by Kolor. (right)A web-based navigation of the fountain by 360° panoramas.*

It is interesting to report that in this specific case the best results were obtained by the last configuration (single images acquired from the UAV adopting a standard workflow). The first solution failed in the phase of camera orientation and it wasn't possible to reconstruct a correct geometry of the cameras position. The second modality succeeded in a rough estimation of the camera positions but with a low number of TPs (Tie Points) extracted and clear effects of a poor correction of the distortion introduced from the spherical images. According to the achieved results it was decided to follow the standard photogrammetric approach. At this point other processing solutions was tested, in order to evaluate a possible integration of the images acquired for the panoramas with other UAVs datasets. Three different processing strategies were tested: the nadiral flight alone, the images acquired for the panoramas alone, the two previous datasets together.
These three datasets were processed using the same parameters and were thus used to complete some considerations (section 3); the main terms of the processing of these datasets are reported in Table 1:

Table 1. Main parameters of the standard processing the three different datasets acquired with the Phantom 4 combined together.

N° Dataset	N° of images	10GCPs error (m)	(4) CPs error (m)	GSD (cm/px)
1 (Nadiral)	34	0.007	0.010	1.3
2 (Pano)	204	0.008	0.015	0.5
3 (Pano + Nad)	238	0.006	0.009	0.7

Moreover, one of the main aims of the survey was also to document with high detail the different sculptural groups of the fountain and it was thus decided to perform other flights with a very-light UAV (DJI Spark). The flights necessary to perform the acquisition for the 3D reconstruction of the single statues were completed in fully manual mode at a low altitude, few meters from the object, a choice that was again necessary due to the closeness of the different statues and the trees. Furthermore, the reduction of the acquisition distance allows maintaining an overall good resolution of the images acquired and consequently a valuable GSD (0.2 cm/px): the acquisition scheme of the single statues and a sample of the acquired images is reported in the following Figure 4. As will be reported, both the data acquired with the Phantom 4 and with the Spark were then processed and used from the students of the course to extract the traditional 2D representation (Figure 8).

Figure 4. *Flight schemes of the DJI Spark on the sculptural groups (left) and some examples of the acquired images (right).*

2.2. SLAM-based underground mapping in the hydraulic pumps engines.

The relevant underground environments pertaining the fountain still host nowadays the ancient machines of the pumps engines. They are accessible from two hatches by a spiral staircase from the park level and they develop in a room of about 100m^2, from which, long corridors of about 20m start under the basin up to the central jets spring. This challenging mapping was performed using a handheld scanner called Zeb REVO RT capable to map narrow and complex environments, especially indoor and enclosed ones, based on SLAM algorithm. It works very efficiently, as already investigated in recent research [4, 5], profiting the rich geometric features of spaces for solving the positioning problem by triangulation and Iterative closest points ICP-like approach of the Lidar profiles from the rotating units that is hold by the user continuously walking. Thanks to the portability and manoeuvrability of the instrument the articulated space of the hall the machines and the corridors (Figure 5) were mapped, achieving a dense point cloud of about 3200 points/m^2 in 20min time period. As a result, it was possible to generate a high-detailed 3D model (point cloud and mesh), comparable to 1:100 scale, of both the specific machines and the surroundings.

2.3. Terrestrial Laser Scanning for the architecture of the water basin.

The multi-scale 3D model of the fountain based its greatest contribution about extension and higher level of detail on a set of n°35 Lidar scans organized all around the hill and the balustrade, performed by TLS: a Faro Focus^{3D} X330 instrument (class 1 laser, wavelength λ= 1550 nm and max. range 330m) and a 120 model (wavelength λ= 905 nm and max. range 120m). The total amount of almost 20mln points/scan, and 16Gb data, were managed in order to apply typical ICP- and target-based co-registration, accuracy control, filtering and optimization in order to derive 2D and 3D metric products (see 3.1 paragraph) for the geometric and radiometric description of the fountain rich architecture.

3. Discussion

The historical fountains with their statuary groups and their materials, bronze, marble and obviously water, with their reflecting issue that sometimes carries out complications for 3D survey techniques, attract the interest of geomatics specialists, in fact they are often used to experiment cutting-edge system and new applicative modalities. [15-17] Concerning the UAV survey, it is important to notice that the introduction of the panoramic images in the nadiral dataset allows a slight reduction of the error on both GCPs (Ground Control Points) and CPs (Check Points). This is thanks to the contribution of the oblique images derived from the panoramic acquisitions. As expected, the introduction of the panoramic images has an impact also on the geometrical reconstruction of the fountain: it is crucial for the reconstruction of the vertical components of the fountain, while the nadiral images highly contribute to strengthen the

geometry of the photogrammetric acquisition. On the other hand, due to the fact that the panoramic images have been recorded on a different time of the day and present also a lower resolution, the overall photogrammetric model is affected by a higher noise in the 3D reconstruction. A critical summary of the integration of methods is reported in **Table 2**.

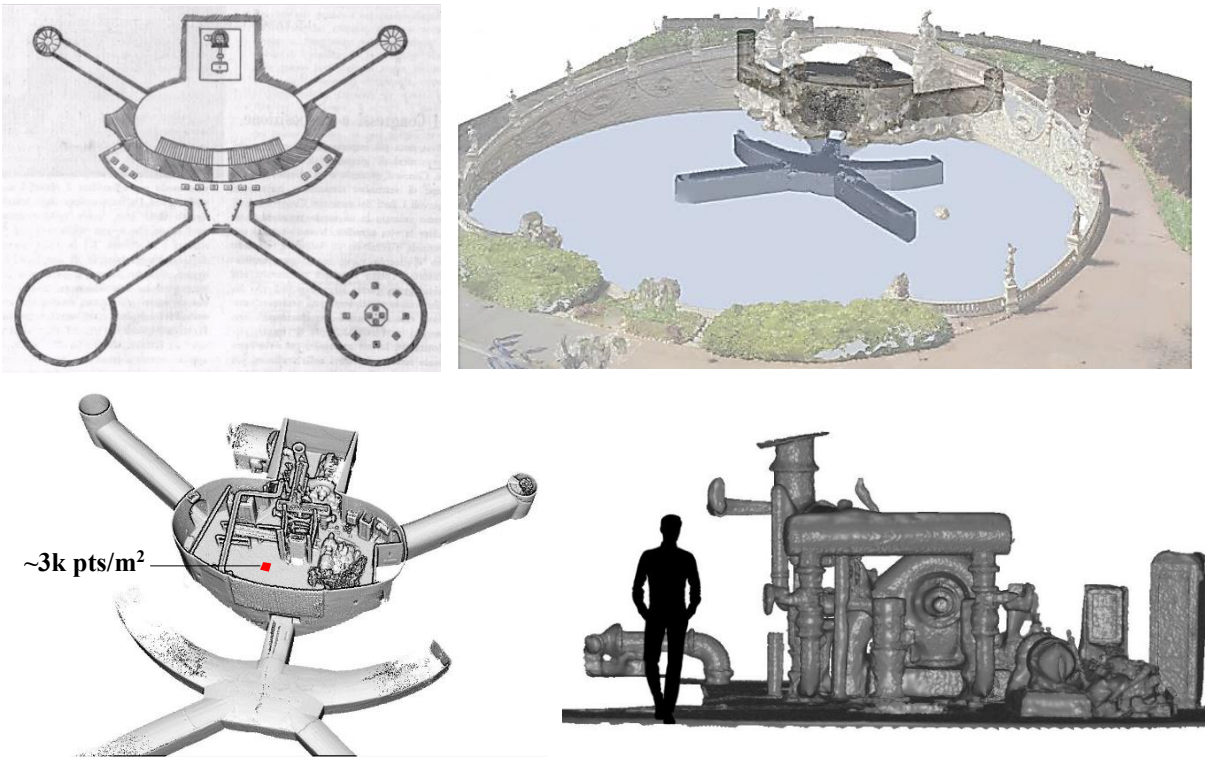


Figure 5. The "*pianta dei sotterranei della fontana luminosa*", Carlo Ceppi 1898 in [8]: the design drawing of the underground spaces which accommodate the hydraulic machines with the whole current 3D mapping made by Zeb REVO. The indoor mesh surface models in a virtual reconstruction with the outdoor environment, and a focus on the descriptive capability of the Zeb REVO point cloud for the 3D reconstruction of the pumps machines room.

3.1. *Lighting and water condition effects*.

In order to execute accurate measurements with well-established instruments as Lidar methods, some context-related issues should be taken into consideration in order to avoid gross errors in point cloud generation and processing.

An unusual, if not unique, contingency of boundary conditions in the sunlight of the site caused big artifacts errors in the final points clouds of those scans located in front of the lower edges of the fountain **Figure 6**. In fact, the water surface behaves like a perfect specular reflector for the Lidar ray in the water's edge area because of the specific use of the X330 scanner with capacity of $\lambda=1550\ nm$ wavelength (the phenomenon didn't occur with the λ from Focus 120), together with the sunlight diffuse conditions and the water motionless conditions due to the fountains not working. The analysis of the punctual point cloud values matrix P = [X, Y, Z, R, G, B, i] for the area along the water level [18], and specifically the intensity values, indicated the crucial threshold value at $1505<i<1570$ A.U. (arbitrary unit) where it is possible to identify the false mirroring points. This artefact point cloud is affected by a sinusoidal noise error but it repeated quite exactly the real surface part apart from the point density that is slight smaller. In the sample area in Figure 6 (down left), the two point clouds parts differs from almost 1000pts. However, the test executed in the same day with Faro 120, as well as the duplication of the Focus X330 acquisition in different weather condition (cloudy with fountains running), confirm the exceptionality of the phenomena related to the water reflection effect.

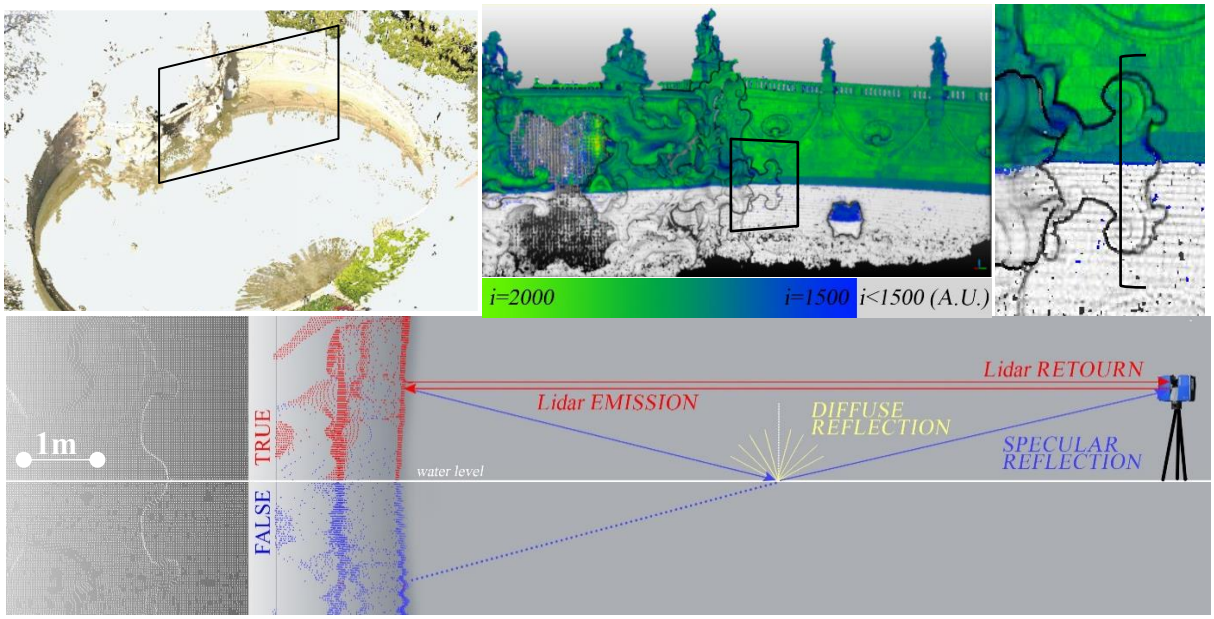


Figure 6. The Lidar point cloud appearance due to lighting condition with the mirroring effect at the water level, in RGB (left) and intensity values (right). A focus of the point cloud in the real/false surface. The artifact generated by the particular condition of light reflection affecting the laser scanning rays, that are both returned to the scanner and reflected on the water.

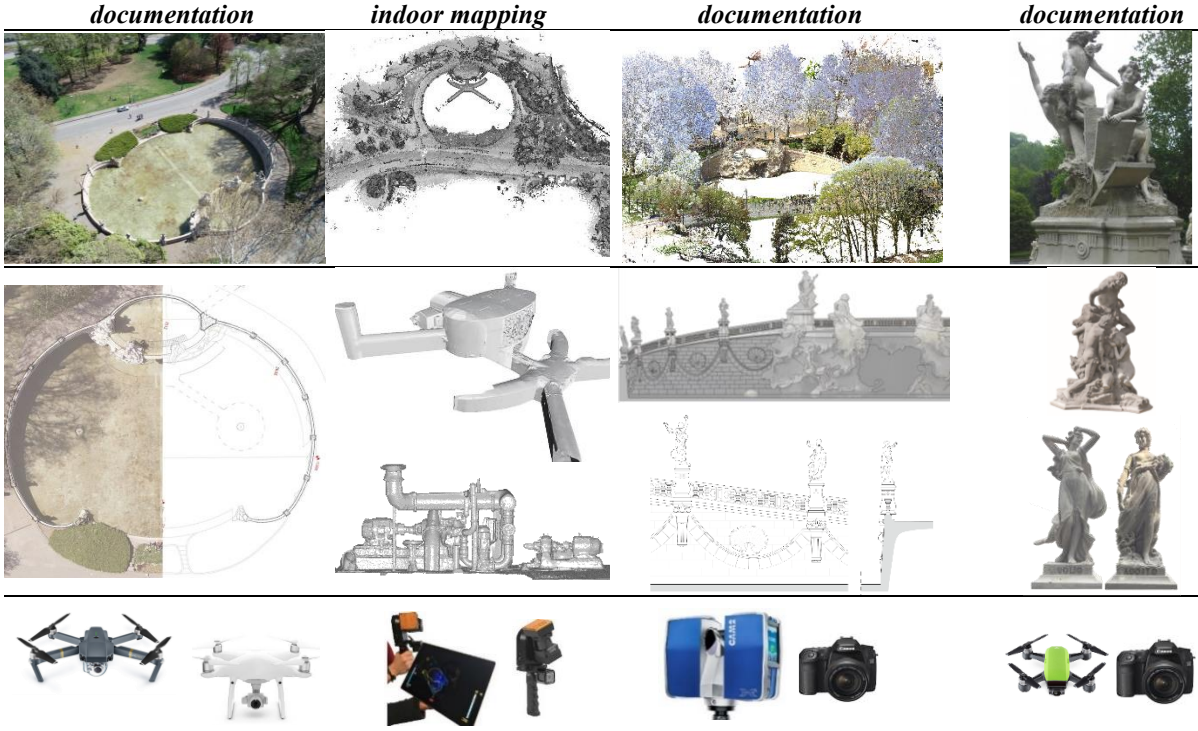
3.2. 3D digital documentation results.

Thanks to the different followed approach that were employed during the survey and the processing steps carried out during the workshop course activities, it was possible to test the integrated multi-sensor image-based and range-based data and the production of 2D and 3D drawings and models useful for an accurate documentation of the fountain. Here below an example of the achieved 2D and 3D architectural metric drawings. In the Figure 7, the underground space of the hydraulic machines placed in spatial relationship with the survey 3D data of the external space of the fountain thanks to the use of the unique topographic reference system. Consequently, the derivation of the fountain bowl intrados, can be integrated with the respective measurement from the extrados.

4. Conclusions and future perspectives

As known, multi-sensor and multiscale modelling ensure the best diversified possibilities of use of the results of the 3D survey, starting from the multiple cognitive values that can therefore support various activities such as monitoring to found the strategies of ordinary maintenance and restoration, up to being able to support the dissemination projects of the historical values inherent in the places, materials, artists and artistic products of the artefacts, which contain multifaceted, technological, historical and artistic cultural values. The use of UAV systems that integrate the possibility of acquire both traditional and 360 ° images and shooting strategies that combine imagery taken in different ways (nadiral, oblique, subject to points of interests), together with the possibility of integrating photogrammetric, TLS and/or slam based clouds (co-registration, fusion of LiDAR DSM with SfM oriented blocks of images) are among the most relevant directions of interest in the area of heritage documentation, that have been addressed in the systems presented in this reflection paper. In terms of sharing results, even in perspective, the main interests focus on the exploration and navigation of 3D models or panoramic images in digital systems such as digital web archives. On the local level, but it is a mirror of the wider and affirmed interests on the international level, there is the interesting Turin Museums system [19], which could be implemented with the possibility of navigating 3D models in combination with bibliographic resources and archive documents relating to the local heritage.

Table 2. Employed features for the 3D multi-scale and multi-sensor survey and modeling for the fountain

Medium-large scale documentation	***Medium-high scale and indoor mapping***	***Architectural scale documentation***	***Very large-scale objects documentation***
			
UAV photogrammetry	*Mobile mapping system*	*LiDAR / close-range photo.*	*UAV / close-range photo.*
GSD=2-10 cm	*~10^3 pts/m^2*	*~10^4 pts/m^2 / GSD=0.5-1 cm*	*GSD=2 mm*
Coloured point cloud	*Point cloud*	*Coloured point cloud*	*Coloured point cloud*
1:200- 1:500 scale	*1:100-1:200 scale*	*1:50-1:100 scale*	*1:50-1:20 scale*

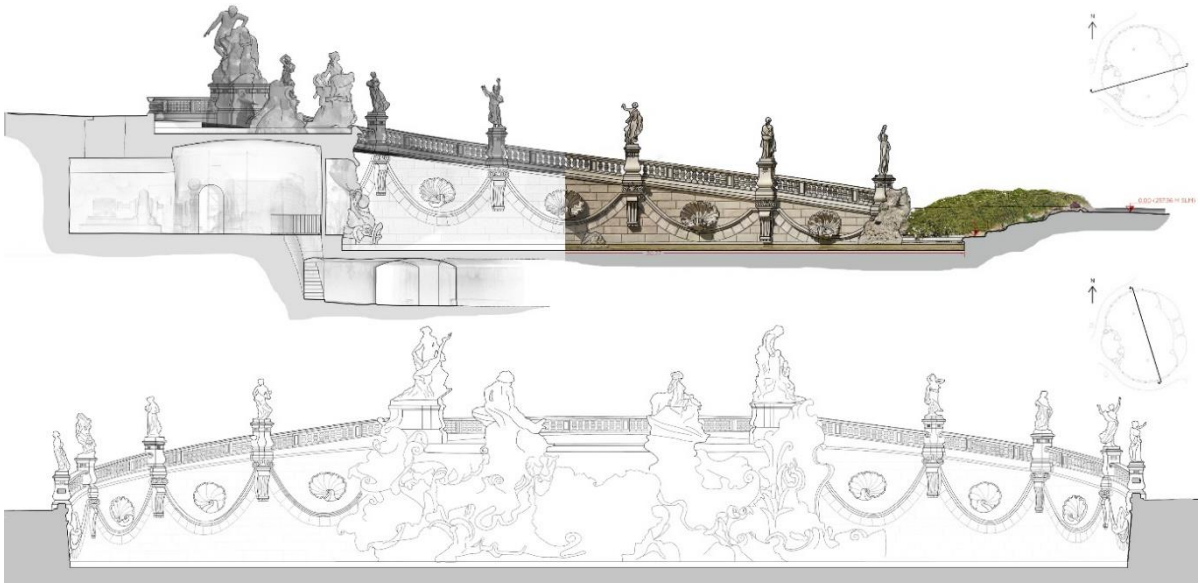


Figure 7. Metric drawing of the fountain architecture derived from integrated data: longitudinal (top) and (down) traverse section (Work by: Brruku F., Cigliutti C., Doninovski A., Pasquale A.)

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