ASSESSING TERRESTRIAL MMS 3D DATA FOR OUTDOOR MULTI-SCALE MODELLING

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ABSTRACT:

Mobile Mapping Systems (MMS) have recently benefited from the development of many fusion-based technologies with countless systems development based on cars, drones, trolley, wearable or portable mapping system. The scale of applicating range from the urban to the architectural scale. Recent solution are also based on visual or Lidar SLAM (Simultaneous Localization and Mapping), which substantially takes advantage of environmental features and techniques of continuous co-registration of the clouds, also in case of absence on GNSS positioning measurement. FARO Technology has recently developed the Swift, a fusion-based hybrid solution that integrates the sensors for 3D mapping in a trolley system configuration and recently, an external camera Panocam Theta Z1 is equipping the system enabling the possibility to associate radiometry to the acquired data. The working principle is the exploitation of a system of static and mobile configuration, using the so-called "*anchor scans*" co-registration as an hybrid intermediate solution between a typical static scan and a profilometers-based MMS point cloud. The co-registered clouds therefore yield a trajectory mode such as SLAM but benefit from the comparable range and density characteristics, according to user-customized settings, of static scans, with a duration of a few seconds per scan and a few minutes overall. In the present research the Swift System is tested in two different context and the assessment are conducted aimed at satisfying both the urban and the architectural scale instances in the direction of improving further evaluations.

1. INTRODUCTION

Buildings and urban mapping based on Mobile Mapping Technologies (MMT) have recently benefited from the development of based on sensor fusion thanks to the positioning solutions (GNSS-IMU) and the mapping segment (mainly based on LiDAR or images) (Elhashash et al. 2022).
As a consequence, an increasing number of fusion-based solutions have variously combined several devices prototypes designed to optimize the different parts of the process, the portability and the cost-related sustainability.
In the terrestrial sector, the control of the positioning and the estimation of the trajectory of the vector (also pedestrian) has been tackled with the improvement of the visual odometry (Zhang & Singhm 2018) or the SLAM (Simultaneous Localization and Mapping), based on images or LiDAR, which substantially takes advantage of environmental features and techniques of co-registration of the clouds (Huang, 2021, Sammartano & Spanò 2018; Tucci et al. 2018).
In the mobile mapping systems (MMS) categories, the vehicle-mounted systems and the portable ones are the most and for a long time diffuse and countless research experiences are nowadays available related to systems validation in indoor and outdoor performances (Elhashash et al. 2022; Nocerino et al., 2017). Conventionally for the outdoor 3D mapping, in the last two decades, car-based technologies have been tested and newly developed for urban mapping application (Halala et al., 2008) and also in architectural and urban heritage contexts (Rodríguez-Gonzálvez et al., 2017), with a large deployment of tailored solutions that explore both the integration of technologies in sensor fusion and the positioning issues.
Moreover, the mounted or handheld and wearable devices together with the trolley-based are among the most recent systems developed to be more flexible in the operator's pedestrian movement, especially for indoor mapping performance (Maboudi et al., 2018) and indoor positioning supported by Ultrawideband (UWB) (Dabove et al., 2018; Masiero et al., 2018). More recently, the experiments have also moved to hybrid outdoor-indoor test-cases thanks to an improved development of integrated GNSS and seamless positioning solutions (Elhashash et al. 2022).

The main features exploited from MMS point cloud datasets in the context of urban object classification are mainly related to geometric and topological features of the point clouds and radiometric values and intensity data from LiDAR sensor, in order to streamline the data structuring toward the object modeling. The aspect that has been specifically studied was that of the geometric characterization of these types of clouds for the automatic structuring of data through algorithms of segmentation and semantic classification, especially for vertical objects (Weinmann et al., 2015; Liberge et al., 2010) and planar surfeces, typically streets and buildings segmentation (Kumar et al., 2014). More recently, the reflection has widened to the exploitation of artificial intelligence (AI) and automatic labelling of point clouds (Zhu, J et al., 2020) also associated to cultural heritage objects (Matrone et al., 2020). Also, it has opened up to include reflections on semantic segmentation based on ontology-based semantic data model (Colucci et al, 2021).
Despite in the context of urban mapping the experimentation of fusion-based MMS for 3D city models has been investigated since 10 years in research (Stoter et al., 2016), according to recent innovations for sensor precision and positioning accuracy, the achievable level of detail (LoD), from an urban- and architectural- point of view, can be considerably relevant and diversified.

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In the case presented, a system developed for internal environments and large open spaces such as airports, stations, factories, tunnel inspections will be tackled. The goal is to apply its working strategy in two enclosed urban environments, within the historic town of two cases in Piedmont.
In the experimented case, there is a double question to be weighted. The high detail richness enables the possibility of mapping entire urban blocks acquiring features of the façades corresponding to different LoDs up to higher ones, and scale of information that can be derived, as footprints and rooftop print, street limits, sidewalk and accessibility elements, road signs, street furniture, façade morphology, architectural details.

1.1 FARO Swift system

The authors' research group has recently tested and evaluated the accuracy of the Swift MMT, an integrated solution developed by FARO Technologies (Bonfanti et al. 2021).
The investigated system (Figure 1) is composed of a laser scanner, a 2D laser profiler which can compute the system's position in real-time through the SLAM function, and a smartphone connecting the two sensors by WiFi signal. Additionally, more recently, the possibility of equipping the TLS system with an external camera (model: Panocam Theta Z1) has been further provided, enabling the possibility to associate radiometry to the acquired data, allowing to colourise the collected point clouds.

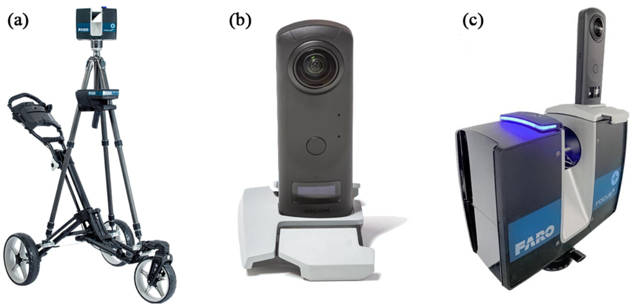
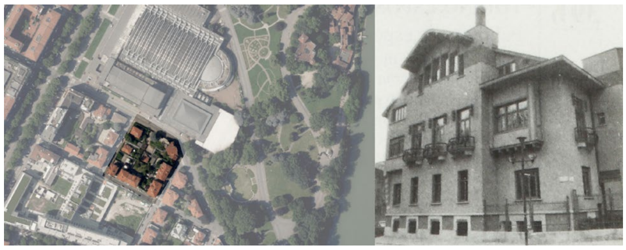


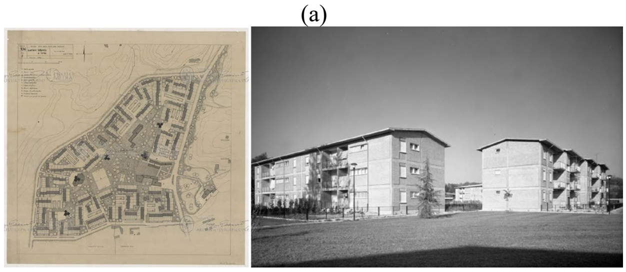
Figure 1. (a) FARO Swift system composed by (b) Panocam Theta Z1, equipping FARO laser scanner of the S series (c).

Following experiments carried out in indoor spaces aimed at assessing the efficiency of the SLAM, this paper is dedicated to evaluating an outdoor application, mainly by evaluating the effectiveness of the so-called *anchor scans* (acquired along the trajectory performing stop-and-go a short static-mode scan).
The application context in which this solution is intended to be evaluated is the urban environment, not extended to large extensions as the MMT solutions adopted on vehicles and equipped with GNSS-IMU can be, but outdoor urban environments, reduced to the size of one or a few blocks, which need to be represented with clouds that allow recognizing the architectural characters of the buildings, the constructive morphology and the characteristics of the public urban environment, such as sidewalks and signs.

Two case studies have been analysed: an urban block located in Torino (Italy), dating back to the early 1900s and featured by buildings that have the typical characteristics of the Italian liberty style, in particular for Villa Javelli (Figure 2a).
The second one is a residential building placed in the so-called "Quartiere Bellavista" in Ivrea, Italy, a residential block promoted by Olivetti to between 1956-1958 provide housing solutions for the workers. It was built during the industrial development occurred after the II world war and now UNESCO World Heritage site (Figure 2b).



(a)



(b)

Figure 2. The sites of the two test dataset: (a) the Liberty style urban block in the Torino area of the Valentino park, with Villa Javelli (Torino Geoportale and MuseoTorino). (b) The "*Quartiere Bellavista*" in Ivrea (*www.archivioluigipiccinato.it*).

2. METHODS

The evaluation proposed is aimed to assess the suitability of 3D models carried out by the trolley-based MMS, to satisfy accuracy, resolution, information density requirements and other parameters for different scales of analysis, ranging from the urban scale to the building and architectural elements scale of analysis.
In fact, considering the low acquisition time required from the collection of the anchor scans, the range of the employed laser scanner (Faro Focus S Plus 350, operational range ≈ 350 m), and exploiting the trolley rapidity, it is possible to acquire areas characterised by significant extension in a relatively short time.
As declared by FARO, the Swift system acquires point clouds using three scanning modes: traditional static scans; continuous scans based on a SLAM algorithm (implemented in the equipped ScanPlan); rapid static acquisitions (*anchor scans*). Each anchor scan requires approximately 15 seconds.
While the second scanning mode (as described in Bonfanti et al. 2021) is intended for indoor environments and requires the presence of horizontal surfaces and smooth floors for proper functioning, the third anchor scan scanning mode has been tested in the cases considered in this paper. For each case study, a set of anchor scans has been collected with the aim of covering the façades of the considered built complexes and the external areas of the surveyed urban blocks.
Acquiring data following this strategy, the SLAM algorithm embedded in the ScanPlan is used for a preliminary co-registration among the acquired anchor scans. The registration is subsequently optimised through ICP-based algorithms, which allow the achievement of an average deviation between the different anchor scans of less than a few millimetres (here in the test the observed deviations are between 2 and 7 mm).

2.1 Building scale

2.1.1 Data acquisition and processing. As far as the first case study – "Quartiere Bellavista" building – is concerned (rectangular-shaped brick building with reinforced concrete structure; approximate dimensions: 11x50 m^2), the scans were acquired by the operator using the trolley, performing a closed loop around the surveyed asset (Figure 3). The anchor scans were acquired from an average distance of approximately 5-10 m from the measured building; each scan was acquired from an average distance of 6-7 m from the adjacent scans, providing a high overlap in order to facilitate the subsequent ICP-based registration procedures. Overall, a number of 17 scans were required to cover the entire extent of the considered building.
The anchor scans were registered in the same reference system using the FARO SCENE platform. An ICP-based method has been used to perform the scan alignment. The average discrepancy between adjacent point clouds is approximately 3 mm, with approximately 60% of the collected points in each scan exhibiting a discrepancy of less than 4 mm.

Figure 3. Trajectory followed by the FARO Swift system for the acquisition of the anchor scans for the survey of the analysed building.

2.1.2 Data analysis. During the 3D metric survey, several stationary LiDAR scans were acquired using the traditional terrestrial static approach. These scans were used as ground truth to validate the collected anchor scans. In Figure 4 a comparison in terms of density between a static TLS scan (acquired with a resolution parameter 1/5, equivalent to a resolution of 1 pt/8 mm at 10 m of distance) and an anchor scan is proposed. The two point clouds have been acquired from approximately the same position and relative distance to the building.
A *number-of-neighbours* approach has been considered, estimating for each point a sphere of 0.3 m. The open-source software CloudCompare has been used to perform the proposed analysis. As it is possible to observe, the density – as expected – is significantly higher in the first case, where a mean value >40,000 pts/V sphere r = 0.3 m (with std. dev. > 50,000) has been observed. Instead, as far as the anchor scan is concerned, a mean value of approximately 2500 pts/V sphere r = 0.3 m is observed, with the std. dev. of ca. 2200. Therefore, it is possible to observe one order of magnitude difference between the densities of the two point clouds.
This is also confirmed by the analysis reported in Figure 5, where 80 x 80 cm portions of both the point clouds have been considered. The samples have been extracted in the area where a higher density has been observed, due to the proximity to the sensor and the lower angle of incidence of the laser signal on the analysed surface. In this case, the average distance between the points that compose the TLS point cloud is approximately 4 mm, while – concerning the anchor scan – the average distance between points in the considered point cloud portion is ≈12 mm (approximately three times larger than the TLS point cloud).
The evaluated points density is almost 32000pt/m^2 for static scans and 8000pt/m^2 for anchor scan data, with a mean points distance of respectively 1pt/0.44cm Figure 5b and 1pt/1.2cm Figure 5c.

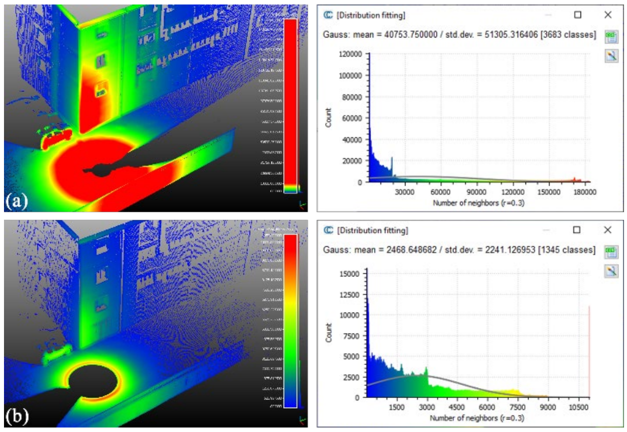
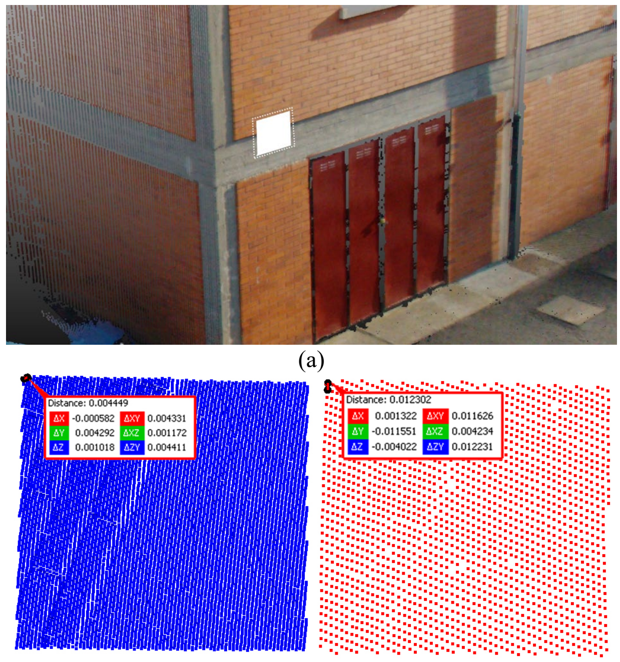


Figure 4. *Number-of-neighbours* analysis evidencing a significant difference in terms of density between (a) static TLS scan (resolution: 1pt/8mm@10 m) and (b) Swift anchor scan.



(a)

(b) (c)

Figure 5. Detail of an individual anchor scan evidencing how the acquired radiometry allows the detection of any degradation or details (e.g., bricks of the surveyed façade). Points density of (a) Traditional TLS scan and (b) Swift anchor scan.

Additionally, a *cloud-to-cloud* discrepancy analysis has been carried out (Figure 6), with the aim of assessing the density and the metric accuracy of the model derived from the short static acquisitions (anchor scans) using traditional TLS scans as reference. In this case, the average discrepancy observed between the 2 point clouds is approximately 1 cm, with a millimetre-level standard deviation. Considering the high nominal precision of the TLS scan – adopted as ground truth – this result highlights how the metric accuracy of this type of scanning is consistent with the representation scales commonly used in most architectural frameworks (1:50 – 1:200).

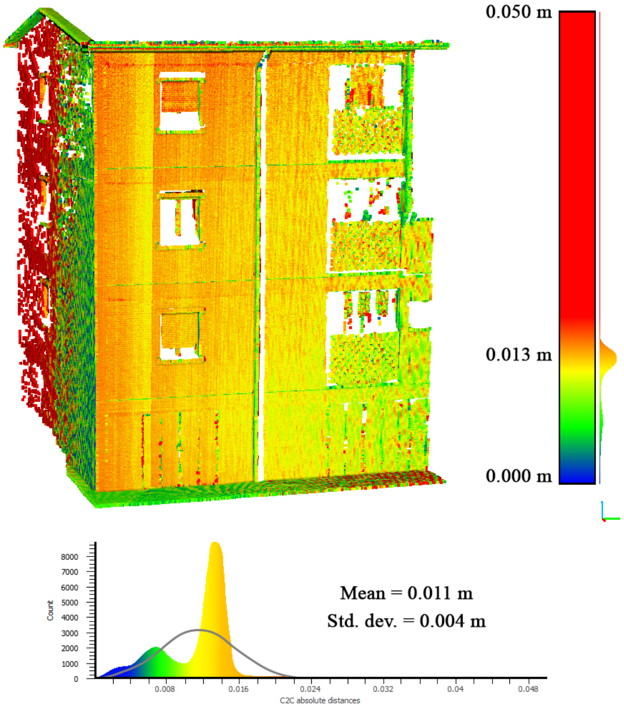


Figure 6. *Cloud-to-cloud* discrepancy analysis between anchor scan and traditional stationary scan (ground-truth) evidencing an average discrepancy of 0.011 m with a st.dev. of 0.004 m.

Another consideration pertains the use of this type of data in the framework of documenting built heritage. Compared to the previous version release of the trolley mobile system (as reported in Bonfanti et al. 2021) the ability to acquire radiometry of the scanned surfaces opens up a range of scenarios aimed at applications related to restoration, conservation and, in general, all disciplines contributing to the enhancement of built heritage. This is possible thanks to the implementation in the Swift system of the Panocam Theta Z1 high-resolution digital camera (Figure 1b). The possibility to document construction elements characterised by small dimensions (in the case of the measured façade, the individual brick, with an approximate size of 0.06m x 0.25m) or subtle deteriorations, mainly recognizable through the radiometric component, represents a significant advantage when these elements are considered (as often occurs during restoration or conservation projects).

2.2 Urban scale

2.2.1 Data acquisition and processing. Concerning the test dataset located in Torino Municipality the specific characteristic of the park area and the *Liberty* block allow a wide acquisition area (Figure 7) with different trajectory tests. In (Figure 8) the squared trajectory along the square urban block and the L trajectory, in the area of the wide tree-lined boulevard.
As already introduced, the ICP-based al on SCENE interface allowed the co-registration of the mobile scans called "anchor scans", 34 anchor scan data on the square block (Figure 9) and 42 on the L trajectory, with the spans ranging from 75m in the wide boulevard up to 25 on the secondary street and 12, the block street. The mean deviation error on ICP is 5mm with 47% points <4mm.

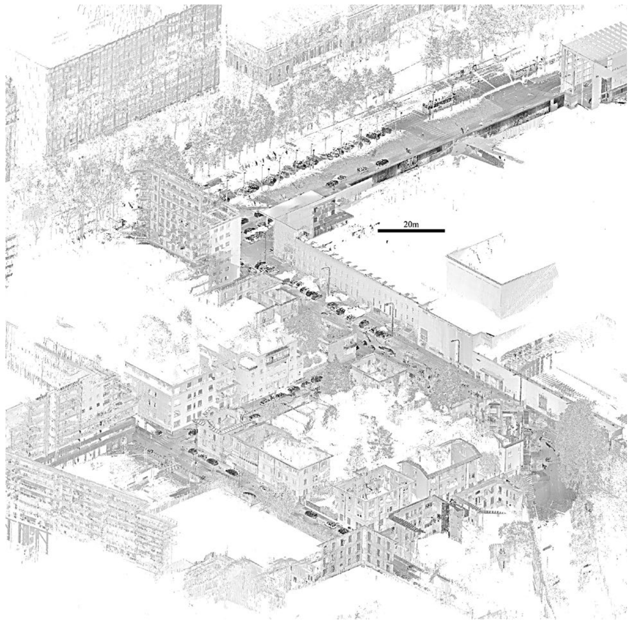


Figure 7. A 3D view of the point cloud of the urban block in Torino, collected with the Swift MMS.

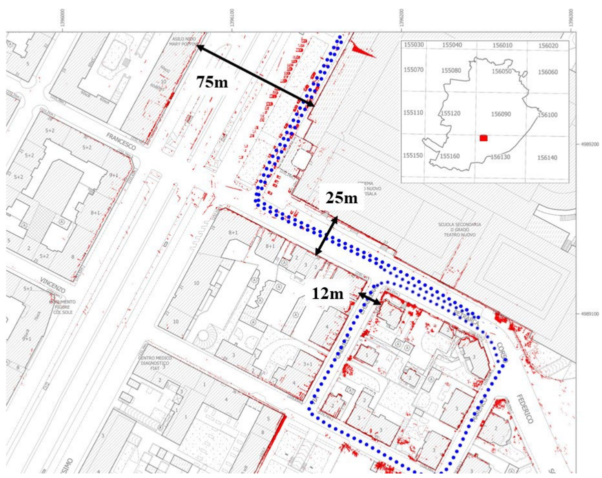


Figure 8. Horizontal urban section of the acquired blocks referred to urban cartography, with indication of the range spans where the system has been tested. Blu dots: the two trajectories. Red points: Swift point cloud collected.

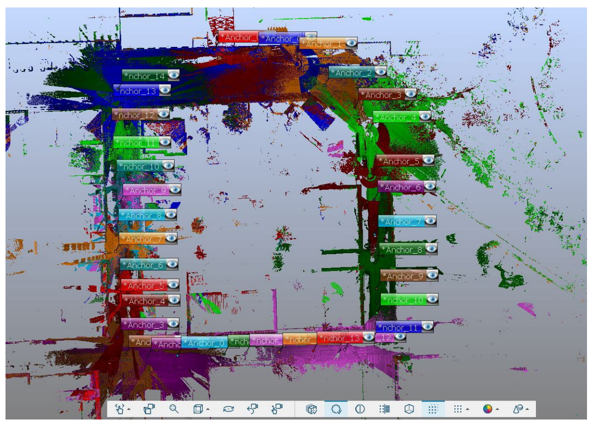


Figure 9. The correspondence view from Scene Sw interface showing the system of the 34 co-registered anchor scans, referred to the trajectory of the Liberty stile block

As part of the experimentation on the study area, a large UAV photogrammetric dataset was also acquired according to the regulations in force on a national and European scale. The acquisition plan was conceived as discussed in recent years research (Toschi et al., 2017; Nex & Remondino, 2014) with integrated images strips, nadir and oblique configuration, with a mean flight height of about 50m, and with a planned GSD=2cm/px, using the Phantom DJI 4 RTK. A set of n°12 topographic measurements on the ground have been collected in order to support the metric control of the 3D reconstruction. Final RMSE on n°8 GCPs is 3.4cm and on n°4 CPs 5.2cm. For the image alignment, bundle block adjustment and dense cloud generation, the Agisoft Metashape interface have been selected.

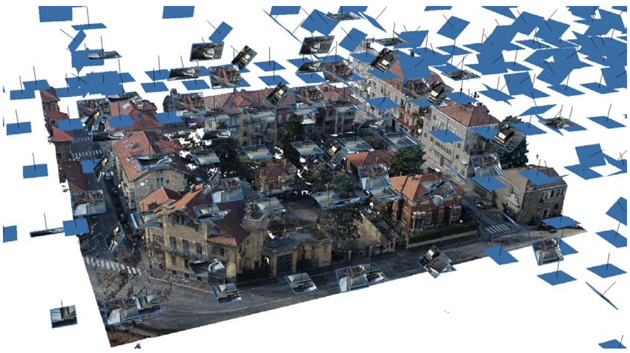


Figure 10. The photogrammetric flight plan on the urban square block, with the integration of nadir and oblique images.

2.2.2 Data analysis. As far as the processed data have bene optimized and co-registered on the UAV DSM, the analysis is returning a global and local value of deviation which surely needs further investigation for the systems implementation.

The mean deviation distance in a *cloud-to-cloud* comparison approach on the whole area is 0.13m with a Std.dev of 0.17m. Instead, a set of local length distance misures distributed in the building block resurns an differences of approximately 2-5cm according to the length of distances distribution.

This measurement instead is connected with the global registration of the *anchor scans* clouds, which are not an actual continuous SLAM data but can still suffer from a drift with respect to the reciprocal registration. Also in this case further investigations are needed.

A first evaluation of point cloud features is reported in Figure 11-Table1, where it is possible to assess the surface density of 1 m^2 sample located in different positions. They are distributed at different elevation on the building facades, from 5m to 30m heigh, and ad various radial distances from the sensor trajectory. In closed configuration the system returns a density of less than 10000pt per m^2, where at the farthest configuration, a value of less than 100pt per m^2.

In Figure 12 and Figure 13, visual evaluation of Swift point cloud detail and density in Intensity map in comparison to the close-range image. Specifically for Figure 13, the architectural element of the balcony in connection with the building wall, in a comparison between the intensity-map and the RGB image of the building. As for the previous example, in section 2.1, the nature of the Swift SLAM data demonstrate the capability to be suitable for a multi-scale mapping and modelling.

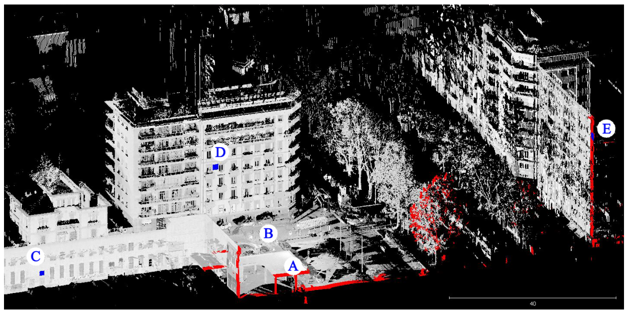
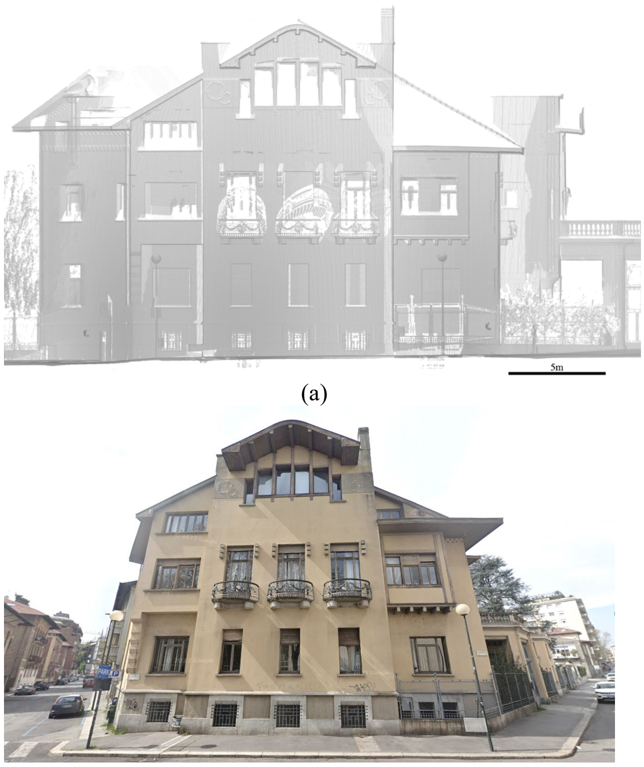


Figure 11. The indication of the five samples (1mq) selected on the urban scene, and the visualization thanks to the transverse section across the boulevard in red colour.

Swift MMS samples					
	A	**B**	**C**	**D**	**E**
	Porch ceiling	Street	Façade	Façade	Façade
Elevation	4.5 (*m*)	~1.5(*m*)	~5(*m*)	~15(*m*)	~30(*m*)
Scanner distance	~3 (*m*)	1.5(*m*)	~10(*m*)	~20(*m*)	~70(*m*)
Pt. density (*pt/mq*)	88000	24000	11000	6350	620

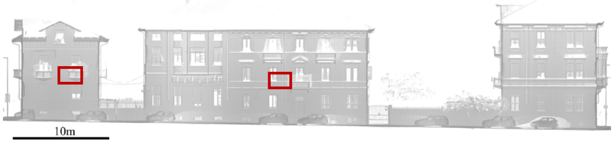
Table 1. The characteristics of the different samples: the density values and the relative average position from the trajectory



(a)

(b)

Figure 12. The Villa Javelli façade, from Swift data with orthogonal projection,, and from Google street.



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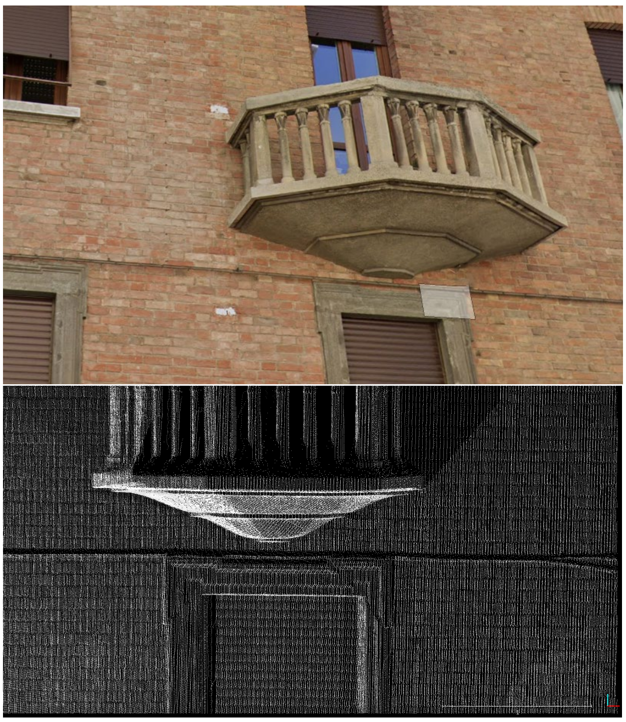


(c)

Figure 13. Southern facade of the block (a), with indication of two architectural details in balcony element and masonry, in (b) and (c), from RGB image and from Swift anchor scans.

3. DISCUSSION

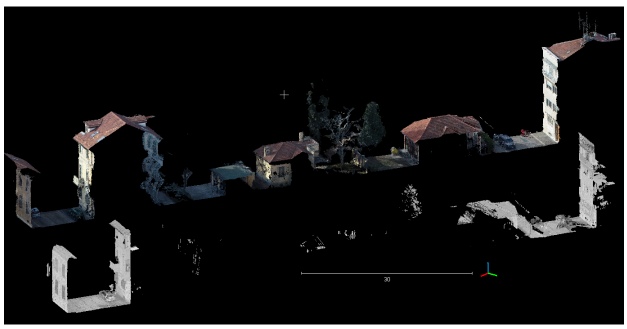
From the preliminary assessing tests carried out in the framework of the presented research, both the scales and the instances connected with them have been considered and many issues still remain open to further investigation, following the development of the Swift system implementation. From this first evaluation it emerges that the tested MMS system can efficiently acquire data satisfying different level of detail and enabling to manage the quality of almost static scan data in a SLAM-based system of pre-positioning, suitable for subsequent analyses from architectural to urban scale.

From an architectural scale point of view, the possibility of acquiring façades of complex built heritage assets with a high level of detail should be stressed, enabling the recognition of the architectural characters and the constructive morphology of the analysed buildings.

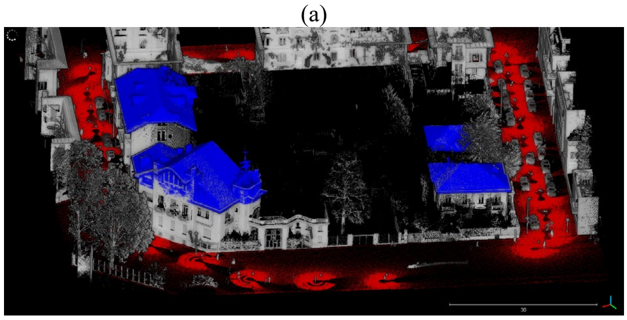
In the cases presented in this paper, considering the time required from each scan (approximately 15 seconds) and from the movement of the operator, the point clouds collection operations have been carried out in 15-30 minutes, acquiring a significant amount of data with trajectories that reach several hundreds of meters. Additionally, the implementation of the radiometry acquisition during the point clouds capturing represents a significant advantage in the framework of rapid surveying operations since it allows the users to consider crucial aspects hardly noticeable without the contribution of radiometry.

- architectural elements interpretation
- material consistency and patterns
- radiometric anomalies and degradation

Additionally, despite the significantly lower density – compared to traditional static TLS systems – the point clouds derived from the tested MMS enable the possibility to appreciate small architectural details and material features (e.g., bricks, like in the case of the residential building of the "Quartiere Bellavista" in Ivrea, section 2.1.1 but also the building facades in 2.1.2).



(a)



(b)

Figure 14. The comparison of two point cloud sections from UAV photogrammetry and Swift ground-based (a) and the simulation of the integrated point cloud.

On the other hand, it is also possible to underline the possibility of acquiring and documenting the characteristics of the public urban environment with a high level of geometric resolution in a cartographic mapping and updating perspective following urban transformation (Section 2.1.2).
In this first step, the UAV data on the urban block have been used for a preliminary comparison evaluation, considering the nature and accuracy and continuity of surface and scale of this aerial datum, relative to the Swift data. In further research progress the intention is to continue with an evaluation of multi-source data for multiscale urban modelling in the context of historical areas, based on data integration (Figure 14).

4. CONCLUSIONS AND PERSPECTIVES

The future of these systems and their forthcoming sensors development will be increasingly competitive and significant for a rapid mapping surveying perspective, and it is worth mentioning that the time required for a complete data acquisition is significantly short. The final data is certainly lighter and more manageable than a set of static scans, but extremely denser than a consolidated urban mapping system.
Surely it is necessary to highlight that, considering the technological nature of the analysed MMS mounted on a trolley, the use of this device is limited to the acquisition of only a few urban blocks, or particularly inaccessible area of historical centres. On the contrary of numerous MMS developed for urban surveying (usually equipped by GNSS-IMU on vehicles) capable of covering large areas in a short time, but it should be emphasized that the majority of these systems acquire data with a significantly lower density and level of detail. This is crucial if the tailored consideration pertains the use of this type of data in the context of documenting built heritage.

Figure 15. Level of detail of the point cloud derived from the anchor scans for the urban block referred morphologically complex building manufacts

From the historical urban modelling point of view, the research developed on these type of hybrid system advances, in the direction of investigating the applicability issue, is effective for urban documentation and multi-scale Digital Twinning modeling and mapping of urban transformation. It can support also the research in the perspective of exploit the extracted features in the harmonizing multi-scale heritage data and their semantics in the CityGML LODs specification (Figure 16). The characteristics of this fusion-based sensor enables the collection of high quality data in a competitive sustainable approach in terms of time expense (Figure 15) for the generation of high-scale models characterised by higher LoDs and, thanks to the possibility of collecting the radiometry of the acquired urban areas, also featured by increasingly rich LoI (Level of Information).

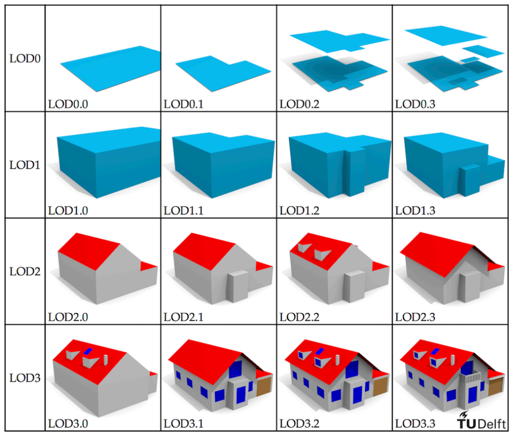


Figure 16. The CityGML LOD specification and the 16 LODs (Biljecki, 2016).

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