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Robotics for Heritage Surveying: preliminary test on Leica BLK ARC & Spot® toward autonomous 3D mapping

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Abstract

Today, robotics technologies are revolutionizing surveying and construction in AEC fields, enhancing precision, safety, and efficiency and also in the realm of Cultural Heritage knowledge and protection, the integration of cutting-edge technologies is reshaping consolidated surveying methods for documentation, especially in risk scenarios. One such innovation making waves is the use of mobile mapping systems, where automation and expediency are the determining factors in technological development, both in the direction of in indoor positioning (visual/LiDAR SLAM, UWB, etc.) and 3D mapping of known and unknown spaces. The BLK ARC by Leica, equipping the Agile Mobile Robot Spot® by Boston Dynamics, as a dynamic sensing platform, is here presented and discussed. BLK ARC is part of a diverse landscape of mobile mapping systems, each offering unique features and specifications tailored to different surveying needs, from handheld devices and wearable systems, to vehicle-mounted systems, the options vary in dimension, weight, price, and technical capabilities and the recent companies and research are largely focusing on them. A preliminary evaluation takes into consideration the dual dynamic-static 3D data-types, considering local and global accuracy of the 3D data delivered from the first experimental tests in a case study. Different metrics have been considered including acquisition time, precision, resolution, density, accuracy, roughness, and completeness of the acquired data.

1. Introduction

Today, robotics technologies are revolutionizing surveying and mapping in Architecture, Engineering and Construction (AEC) sectors, enhancing precision, safety, and efficiency (Manzoor et al., 2021). Not only the professional AEC world benefit from such innovation but also recent reflections in literature should be considered, conducted in the education and scientific research field of Science, Technology, Engineering, and Mathematics (STEM), emphasizing this process as a circular path (Sipakov, 2022; Simarro & Couso, 2021). The STEM disciplines are constantly observed in re-designing and shaping updated skills of engineers and architects’ curricula. In fact, both the gradual and disruptive innovations in the technological market have great implications, firstly, in the economy for industry developments and market trends expansion, as well as accelerating diffusion and use skill improvements, thanks to research and education innovation.

Particularly in the realm of Cultural Heritage (CH), experts working in knowledge and protection, the integration of cutting-edge technologies in documentation practices is reshaping consolidated surveying methods for measurement, 3D modeling, analysis, and fruition (Calisi et al, 2017). One such innovation making waves is the use of Mobile Mapping Systems (MMS) as a portable and compact solution, where automation and expediency are the determining factors in technological development, both in the direction of integrated 3D mapping and outdoor (GNSS) and indoor positioning (visual/LiDAR SLAM-Simultaneous Localization and Mapping, Ultra-Wide Band-UWB, etc.)

The last MMS are part of a diverse landscape of MMS, each offering unique features and specifications tailored to different surveying needs. The options vary in dimension, weight, price, and technical capabilities and recently, companies and research are largely focusing on them (Di Stefano et al., 2021; Elhashash et al., 2022; Martino et al., 2023). They are designed to be portable devices (Leica BLK2GO, Stonex X120GO, Geoslam Horizon, Kaarta Stencil etc.) and can be mounted on different tools (cars, backpacks, poles, drones, robots, etc.).

The rise of automation processes, with minimal human intervention, especially in survey planning and increasingly avoiding operator active presence on the field, is a prominent trend across various industries. Specifically for industries and AEC sectors, the use of robots for substituting human actions is increasingly disruptive, as the noticeable case of Boston Dynamics R&D. In fact, last mapping sensors developments are pushing forward automation in both data acquisition planning and execution, as well as data capturing and extraction. The use of robots for environment mapping and exploration originates with the prominent scope of cyclic mapping and visual inspection in applications such as carrying various sensors (LiDAR, positioning, cameras for visible/non-visible data, temperature etc.), while the exploration of unknown spaces with the specific scope of 3D survey and delivering 3D point clouds for accurate measurement is a secondary and more recent direction, as in the presented research, exploiting and stressing a hybrid sensor and a robot vehicle for assessing the documentation performance and 3D data quality, especially with the point of view of heritage objects. In fact, in architecture and surveying applications, this trend is increasingly evident with the introduction of autonomous scanning modules equipping different motion systems allowing users to plan suitable paths for adequate scan areas and reducing the manual data collection phases. Leica BLK ARC and FARO Trek 3D are two examples of these tailorable mapping modules. Furthermore, the last MMS technological developments are conceived to perform motion with SLAM or visual algorithms and to work on hybrid acquisition methods as dynamic for 3D mapping and navigation for trajectory estimation, and in static mode to locally increase detail and data accuracy.

Besides, they can operate data capturing in static mode along the trajectory to integrate Terrestrial Laser Scanners (TLS), and potentially and progressively replacing them in the future because they implement increasingly precise sensors as the fully static TLS, but more versatile. This is the case of BLK ARC by Leica Geosystems and FARO Technologies developing Swift

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system (Patrucco et al., 2023) and last FARO Hybrid Reality Capture (Sammartano et al., 2024) integrating point cloud upsampling based on visual-Lidar data, these last two already tested in complex and multi-scale heritage sites.

This paper originates from an occasion of experimenting a new 3D mapping technology for Ph.D didactic and research purposes, organized in a workshop demo at Politecnico di Torino, Department of Architecture and Design. The research conducted afterward wants to propose a novelty in the literature by providing a first assessment and evaluation of the 3D metric content of the data collected by means of BLK ARC mapping module (an acronym for Autonomous Reality Capture) by Leica Geosystems, equipping the Agile Mobile Robot Spot® by Boston Dynamics, in a real case scenario belonging to CH application.

BLK ARC is as a dynamic sensing platform, and based on GrandSLAM (Open Source: https://gradslam.github.io/), specified in the next paragraph. As far as the authors' knowledge regarding BLK ARC performances in robotic 3D mapping, at the time of writing, no literature is available. As declared by the Leica company, the BLK ARC represents a paradigm shift in CH surveying, unlocking the potential for rapid and precise data collection in diverse environments. BLK ARC is conceived for mapping and positioning based on LiDAR SLAM, and for monitoring of already-known large environments when mounted on robotic carriers. In particular, the creative alliance between Leica and Boston Dynamics optimized the version of BLK ARC module specifically for the equipment of Spot® robot as presented in this research.

1.1 The Spot® robotic mapping system

The available works regarding testing Spot® as a vehicle for 3D metric survey is partial and mainly limited to indoor mapping applications (e.g., tunnels, industries) and forestry. Gebert (Gebert, 2023) presents personal research developing an autonomous mobile mapping robot with Spot® for the execution of autonomous and recurring mapping missions of harsh and changing environments, for example, construction sites, based on a predefined path. Since the robot can carry up to a 14kg payload, the research proposes the combined use of NavVis VLX sensor with great precision, density, and range performance.

Wetsel (Wetsel et al, 2022) evaluated Spot® with Faro S-350 TLS mounted on it in a building-under-construction environment. The mean error in scans registration for the Faro S-350 with Spot was double the error of the same acquisitions performed with the same scanner in a static mode mounted on a tripod, but in any case, less than 2 mm.

Chirici (Chirici et al, 2023) applied Spot® for tree diameter estimation. Seven different tele-piloted paths (one-way, back-and-forth with low and medium speeds, diamond, zig-zag, spiral, and four-petal) were analyzed with the integrated Velodyne VLP-16 LiDAR, reporting a point density varying between 41 and 152 points/m2 and a Root Mean Square (RMS) error percentage between 40 and 57 in respect to trees diameters measured with total station used as reference. Regarding tree positioning, the absolute error recorded by Spot® varies between 0.002 and 8.1 m. This research reports that trees with a diameter of less than 20 cm were not identified, and authors noticed a high influence on the positioning and density results according to the followed path, pointing at the spiral one as the best.

Spot® (Chirici, 2023) is a quadruped robot developed by Boston Dynamics (now Spot v4.0.0 Release) in order to operate autonomously or with assisted missions based on self-positioning and trajectory execution in the mapped environment and to collect multiple data based on sensors equipment. Thanks to its legs, Spot® is able to walk on steep terrains and stairs and the elevated mobility is surely its promising feature. Through the joysticks of the Spot tablet, the operator can maneuver the robot, otherwise, the robot can autonomously walk thanks to *Auto-walk* where a mission can be planned along a path with actions to undertake (Boston Dynamics, V 4.0.0). Thus, Spot® can be applied alone for inspections based on its own sensors and as a carrier of payloads such as tailored sensors to perform specific missions for acquiring different kinds of data.

The system is featured by reduced dimensions, length of 1.10 m, width of 0.50 m and height between 0.52 and 0.70 m. Its total net weight is 32.7 kg and can carry a payload of a maximum of 14 kg. Spot has a battery duration of 90-180 minutes, and a maximum speed of 1.6 m/s. Various cameras (black-and-white, RBG, infrared, and depth) are mounted on it to enable autonomous movement. Spot® software installed on the Spot®CORE operative system (Figure 1) manages the obstacle detection and avoidance within a 2 m distance. Beside cameras, a Velodyne VLP-16 LiDAR sensor improves depth detection, expanding object detection till a 120 m distance. Spot can manage and coordinate operation with mounted BLK ARC (Figure 1) thanks to the Leica app installed on Spot®CORE OS, in order to really maximize the potential of autonomous mapping and documentation along the surveying missions. However, it is also possible to exploit the robot as a simple vehicle and pilot it independently and launch separately BLK ARC module data acquisition from the dedicated app.

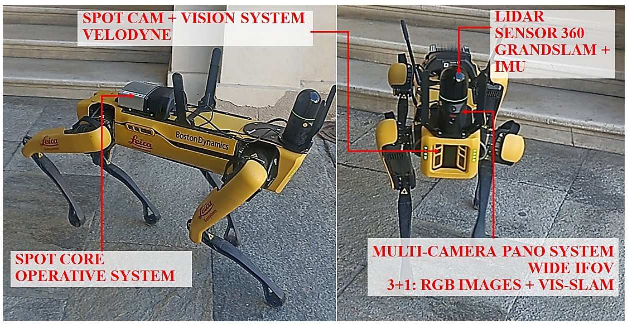


Figure 1. BLK ARC mounted on Spot®

2. The hybrid robotic mapping system overview

The BLK ARC system is a low-weight hybrid device (<1kg) equipped with LiDAR and imaging sensors. In particular, the Leica BLK ARC Autonomous Laser Scanning Module integrates with autonomous robots, enabling high-precision 3D laser scanning of complex environments, such as CH ones, risk scenarios for 3D metric surveys and video-visual inspections.

The visual devices equipped with the system are based on 1+3 cameras. A camera for detail acquisition and visual SLAM, and a panoramic system combining 3 cameras for a 360° view with 12MP. The LiDAR module has a declared indoor accuracy of +/- 10mm, post-processed range noise of +/- 3 mm for dynamic mode and +/- 2 mm for static mode, and 0.5-25m range limits.

For mission planning, data acquisition models and parameters can be set, according to the dynamic mode only, or integrating static points acquisition along the trajectory. Points density can be set up with a maximum point rate of 420.000 pts/s, and static scans can be set at 30, 60 or 120 sec.

The system precision is declared as environment-dependent and thus needs to be evaluated and stressed in different capturing conditions, especially in this case for heritage scenario.

Basically, the BLK ARC is an improvement (especially in light weight, capture speed, accuracy, and noise) of the previous BLK sensors, such as BLK360 static scanner and BLK2GO SLAM portable scanner, as visible in Table 1.

Specs	Sensors		
	BLK ARC	BLK2GO	BLK360
Operative range (m)	0.5-25	0.5-10	0.6-60
Post-processed range noise (mm)	+/- 3 (dynamic) +/- 2 (static)	+/- 5	n.a.
Accuracy (mm)	+/- 10	+/- 20	n.a.
Capture speed (points/s)	420,000	420,000	360,000
Size (height x d)	18.3 x 0.8	28.2 x 0.8	16.5 x 10
Weight (g)	690	850	1000

Table 1. Comparative analysis of BLK-family sensors specs by Leica Geosystems

The BLK ARC uses SLAM for positioning and orienting and, therefore, navigates itself through 3D spaces, capturing images and dimensionally accurate point clouds in real-time. In addition, the BLK ARC leverages the SLAM features to enhance the robot navigation. Since SPOT® Robot uses its close-range perception system to walk spaces and overcome obstacles on its path, BLK ARC extends the robot's capability of avoiding obstacles and, with real-time scanning, enhances navigation accuracy in a larger and more challenging environment if the mission exploits the integrated software capabilities of Leica App on Spot®CORE OS, as previously introduced.
BLK ARC provides the capability for offline planning missions and incorporates static and mobile scanning modes within a single mission. Static scanning mirrors a traditional tripod setup (naturally, the height is very limited). In contrast, mobile scanning aligns with SLAM-based devices, similar to an operator moving through a site with a handheld scanner. According to this approach, it is possible to gain speed and confidence when capturing outdoor, large indoor, underground, complex, and multi-level spaces.

2.1 Specifics on BLK ARC SLAM-mapping module.

BLK ARC is based on the GrandSLAM (Open Source: https://gradslam.github.io/), a method that facilitates the automatic alignment of static scans within a unified coordinate system. GrandSLAM technology combines LiDAR SLAM, Visual SLAM, and an Inertial Measurement Unit (IMU) to deliver very accurate mobile mapping performance. More in detail the BLK ARC combines the BLK2GO’s dual-axis lidar (Del Duca & Machado, 2023), IMU, and a multi-camera system with a high-resolution camera for detailed images, as well as three panoramic cameras for visual navigation, point cloud colorization, and panoramic images capture. Specifically, the LiDAR SLAM allows the identification of different surfaces and unique geometry in the LiDAR data, which it analyzes to calculate its 3D position. LiDAR sensors allow the creation of detailed 3D maps of the environment while simultaneously tracking the device's location. As it is well-recognized (Zou, et al.,2021, Abdelaziz & El-Rabbanym, 2022), this technology is crucial for autonomous vehicles, robotics, and mapping applications, offering precise navigation and object detection capabilities in real-time. LiDAR SLAM can accurately model and navigate complex surroundings by analyzing the time-of-flight of laser beams, making it a cornerstone of modern automation and spatial analysis. The visual SLAM performed by the three panoramic cameras identifies similarities between consecutive images to calculate the scanner’s movement through 3D space. This approach uses camera imagery to construct a map of an unknown environment while simultaneously determining the camera's location within that space. The visual SLAM approach can provide the possibility of navigating and understanding complex environments without GNSS. This technology identifies features and land-marks, enabling precise positioning and movement through real-world spaces. Finally, thanks to the IMU sensor, it is possible to evaluate and calculate the device's change of position in 3D space.

3. Methodology

As highlighted before, the documentation and modeling of CH objects is recognized as an intricate process based on different integrated workflow, and influenced by various factors. This complexity is evidenced by the wide range of standards and benchmarks dedicated to CH artifacts (Argyridou et al., 2023). For those reasons is very important to define validation criteria focusing on quality metrics and other aspects concerning the usability of the datasets.
Moreover, the utilization of these datasets should be examined through a set of samples that reflects the distinct features of cultural complexes. Authors are aware that the research progress need further evaluation on different application contexts as different and multi-scale heritage scenarios.
Mounted on the agile Spot®, the Leica BLK ARC was remotely piloted by an operator effortlessly through different challenging environments of the Castello del Valentino (better described in the next section) such as the narrow stairs and corridors, uneven pavements, decorated and furniture-crowded rooms, and long underground corridors with artificial light. The 3D point cloud generated with the system presented in this article has subsequently been subjected to both quantitative and qualitative evaluations.

3.1 The case-study

To showcase the capabilities of the hybrid robotic mapping system, a demo event has been organized and a survey of the Castello del in Turin (Figure 2), a UNESCO World Heritage site, has been designed.

Figure 2. Leica BLK ARC mounted on Spot®, during the data acquisition at the Valentino Castle

It has been directed both at research experimentation and training experience making didactic practice for Ph.D. students experience on technology developments as part of the STEM programs. As a result of the many uses the castle has had over the years, as well as the subsequent modifications it has undergone, Castello del Valentino now resembles an articulated and extremely complex architecture, shaped around a central court. It consists essentially of two main floors, the first floor hosts the secretary rooms and classrooms of the Polytechnic University of Turin and is simply covered in white plaster, while the Noble Floor on the second level has numerous decorated and frescoed chambers. Besides, other portions complete the Castle: an attic with a pitched roof made of intricate wooden warping, an underground floor that houses the castle's basement, and four towers, one for each corner (https://castellodelvalentino.polito.it/). Comprising multiple levels, including underground areas, ground floors, and royal rooms on the main floor, navigating the castle presents a formidable challenge for traditional surveying methods, recently investigated also in Chiabrando et al, 2018 and other literature from our research group.

3.2 The assessment method

With the aim of assessing the efficiency of the Leica BLK ARC and the reliability of the 3D data, the acquired information has been analyzed and validated with that obtained from traditional static TLS. Different metrics have been considered, including acquisition time, precision, resolution, density, accuracy, roughness, and completeness of the acquired data.

Beyond the analysis of the ground floor and the main floor of the castle, special attention was given to the castle's underground level in order to stress the sensors performance according to different reasons: it presents the greatest complexity in terms of access and poses the most significant challenges for documentation methods. This area is poorly documented and explored, yet it holds crucial insights into the castle's history and evolution. Finally, this underused part of the building offers potential for future valorization and enhancement. The basement area features various rooms, corridors, stairways, narrow passageways, and utility rooms, creating a complex environment to evaluate in a complex scenario the performance of Spot® and Leica BLK ARC. In order to compare the data acquired with the BLK ARC with a more accurate reference survey, several static TLS scans have been used as ground truth. The scans were acquired with Faro Focus x330 (ground floor and noble floor) and Leica RTC360 scanners (courtyard and basement). A total of 141 scans have been acquired in around 21 hours. Both the TLS scans have been registered using the consolidated workflow for LiDAR processing Iterative Closest Point (ICP)- and target-based. The final report of the registration process shows a mean value on the ICP algorithm less than 4mm, and the mean value and standard deviation on targets are less than 2 cm (Chiabrando et al., 2018; Tanduo et al., 2023). In the next sections, the preliminary evaluation that considers the local and global accuracy of the 3D data delivered from the first experimental tests in the case study are reported.

3.3 Data acquisition and processing

The scan planning has been setup with the max point density of 420.000 pts/s for both dynamic and static scans, and the last were set up at the minimum time of 30 seconds. No loop closure is necessary to test the system so the operator didn't perform starting-ending in the same point. Static scans work like the TLS scans, Spot® is guided manually to the desired point, stopped, and the static scan is registered.

Two types of acquisition have been tested, static and dynamic: dynamic scans are acquired during Spot® walks. Static scans are acquired along the trajectories in the Castle rooms. In Figure 4 there is an example of the difference between the dynamic acquisition and the static one in the courtyard area. The two types of scans also have great differences in point distribution and density, as visible in Figure 4 and in Table 2. Once the property raw files (**.b2g*) have been downloaded from the BLK ARC sensor, the data processing follows the workflow implemented into Cyclone Register by Leica Geosystem. Here the operator has only a partial disposal of actions on SLAM reprocessing according to parameters related to the number and wideness of the observation area. The data import itself requires the data re-computation and extensive processing, in addition to the fast calculation performed in the fieldwork.

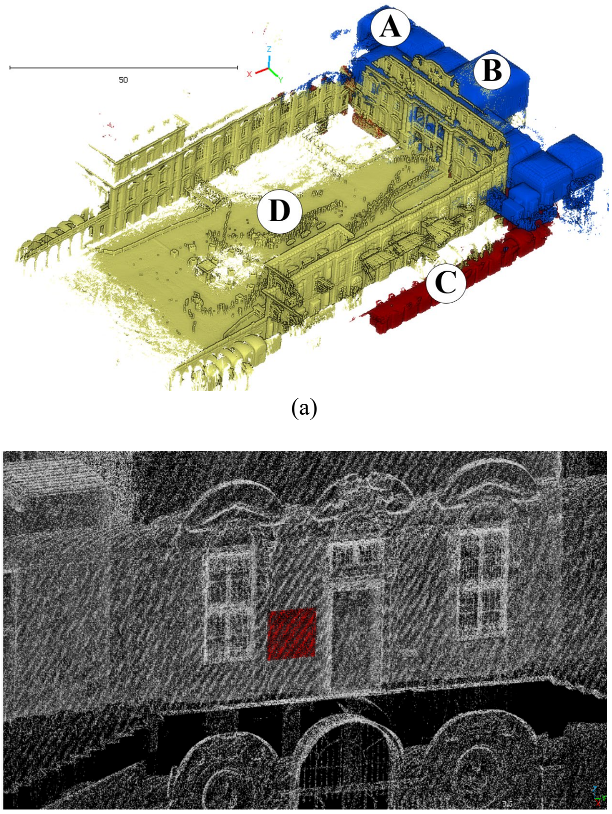
Final point clouds dimensions are very dense with big file dimensions (Figure 3a and Table 2) hard to manage, and a downsampling is needed to manage the 3D data. However, the authors specify that the local accuracy analysis has been performed on the original raw datasets. The specific metric assessment is planned for 3 main areas and some samples have been selected in order to analyze typical features and challenging details related to heritage assets (Figure 3a).

The analysis refers to four areas: (A) a small plaster-decorated room, (B) a large frescoes-vaulted room, (C) in the underground, and (D) courtyard. Specifications of the acquired scans are reported in Table 2. The dynamic scans have been acquired with BLK ARC mounted on Spot® and manually maneuvered by an operator in three environments:

(I) ***Noble floor*** (blue) with aulic rooms has been selected for the complex and detailed decorative apparatus, as well as for the succession of rooms, crowded of furniture, with different material and dimension (*static scans A and B*). Also, the ancient narrow staircase (1m) has been tested but the trajectory had to be interrupted. (From ~221.7mln to ~38.7mln points)

(II) ***Underground*** (red) corridors have been selected due to the huge length (>60m), articulation of different sections of the spaces, for the large stairs to access them and the vertical level executed by the robot (*static scan C*). (From ~192.3mln to ~25.9mln points)

(III) The ***Courtyard*** (yellow) has been selected for evaluating outdoor performance of the robotic system in a wider area with high decorative apparatus of the façade in a vertical extension. (*Static scan D*) (From ~177mln to ~36.7mln points)



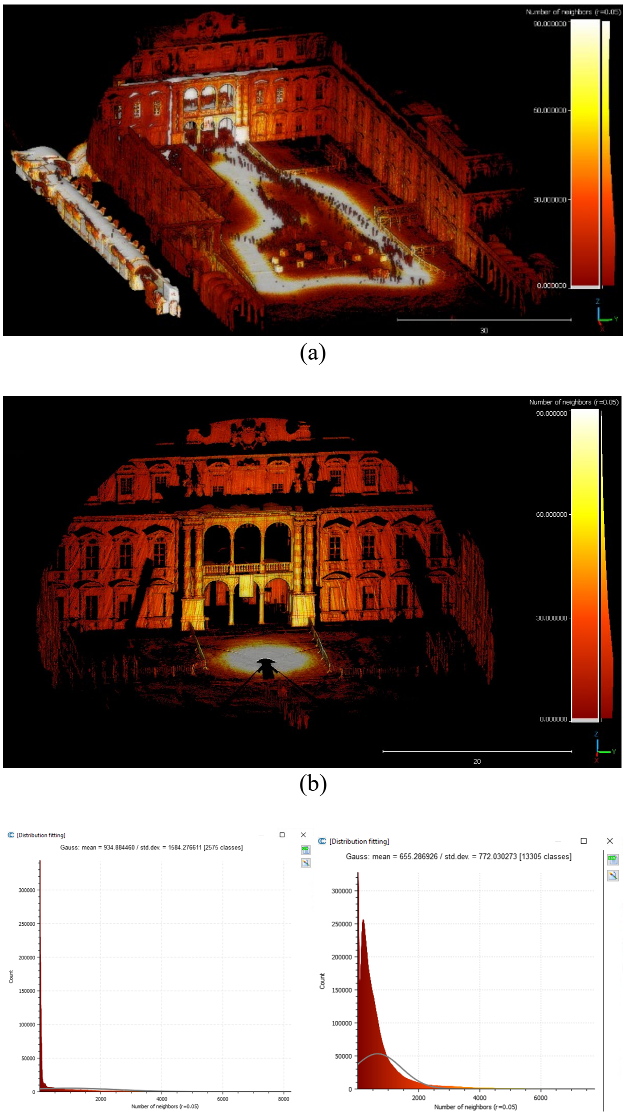
(a)

(b)

Figure 3. The BLK ARC 3D acquisitions: (a) the datasets – dynamic mode and (b) zoomed view of the decorated wall of the main entrance (red area: 16200 pt/m^2)

		Specifications		
		N° of points (millions)	Time	Size
Dynamic	Noble floor	221.7	~25min	4.12Gb
	Underground	192.3	~20min	2.39Gb
	Courtyard	177.0	~30min	3.30Gb
Static	A – small room	15.9	30sec	298Mb
	B – large room	16.5	30sec	310Mb
	C - underground	16.0	30sec	300Mb
	D - courtyard	6.6	30sec	125Mb

Table 2. Specifications of the BLK dynamic scans and the four samples static scans selected, according to Figure 3



(a)

(b)

(c) (d)

Figure 4. Points quality distribution using the density analysis, normalization 0-90 in the colour ramp for improving visualization): (a) dynamic acquisition dataset and (b) the static acquisition, (c) and (d) the respective gaussian distribution

4. Results & discussion

This section reports the assessment of the double-type data derived from the 3D mapping: the dynamic scans and a selection of static acquisitions extracted in the test areas. Firstly, a global evaluation of accuracies is introduced (4.1), based on a global performance with ground truth. Then the global trajectory drifts are evaluated and measured, and a prelaminar set of localized measures are systematically extracted and compared with the ground truth surface. Finally, the local performance of the sensor is proposed (4.2), and conceived as a combination of two selected parameters: local density and roughness evaluation.

4.1 Global accuracy

The global accuracy of the obtained dataset has been assessed by an ICP-mean deviation and a C2C (Cloud to Cloud) analysis (C2C algorithm implemented in CloudCompare).

After performing the ICP, the final RMS error between the global SLAM dataset and the ground truth is 0.04m. Within the C2C analysis, which resulted in a mean value of 0.0388m with a standard deviation (st.Dev) of 0.0368m. Some discrepancies have been found in the most peripheric areas in the underground and the noble floor. Excluding an error in the co-registration of the scans, these differences can be interpreted as drift errors on the trajectory computing. In particular, horizontal and vertical drift errors can be measured on the different areas and summarized as follows:

- Underground $0.2< XY<0.02$m; $0.13<Z<0.015$m
- Noble floor $0.13< XY<0.01$m; $0.02<Z<0.015$m
- Courtyard $0.04< XY<0.01$m; $0.02<Z<0.01$m

Considering the preliminary evaluation of the global accuracy and the drift occurrences, a specific punctual accuracy check is preliminary performed on length distances between ground truth and ARC dataset. Residual Δ errors and st.Dev are analyzed and reported in Table 3, based on distances located in the building, considering both short and long distances and longitudinal, transvers and vertical directions.

	Mean D (m)	St. Dev (m)
Courtyard	0.042	0.0338
Noble floor rooms	0.016	0.0122
Underground	0.018	0.0277

Table 3. Punctual distance measures extraction from BLK ARC data and compared with ground truth

4.2 Local accuracy

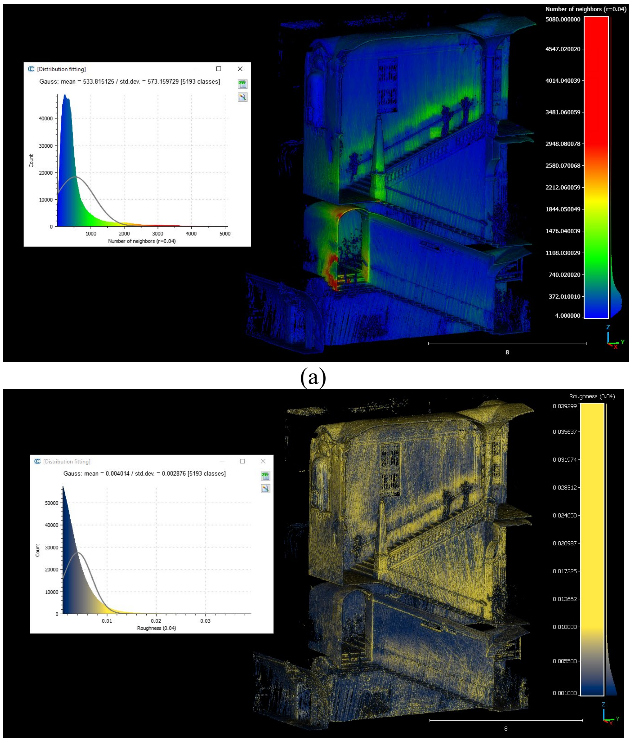
This analysis was conducted to assess the quality and geometric characteristics of the BLK ARC data from a local-scale perspective. The set of parameters have been examined in this phase, with a specific focus on the presented sample areas. The quality and completeness of the Leica BLK ARC dataset have been evaluated locally. To assess the system's ability to accurately reconstruct the recorded spaces' geometric features, density and roughness values have been locally computed for the test areas (implemented in CloudCompare software).

4.2.1 Surface density to evaluate points distribution.

For the density analysis, we considered the number of neighbors around each point in the dataset in a sphere with a radius of 0.04m. The data displays various local surface average densities: 15000-25000 pt/m^2, between floor, walls, and vaults, as introduced in Figure 3b, performing a very suitable reconstruction of the decorative apparatus.

Table 4 shows the computed values on the scan's samples, both dynamic acquisition and single static scans.

The ground truth TLS has an average density of 1000-5000 pt/4 cm sphere (st.dev. 2900-10000) according to the environment considered.



(a)

(a)

Figure 5. 3D visualization of the main stairs entrance points: (a) density and (b) points roughness, in range colors

Number of neighbors (pt/sphere)			
ARC dynamic	Mean/st.dev	ARC Static	Mean/st.dev
indoor	390-520/	A	850/771
	350-490	B	475/851
underground	555/790	C	1,185/1161
courtyard	421/490	D	603/1024

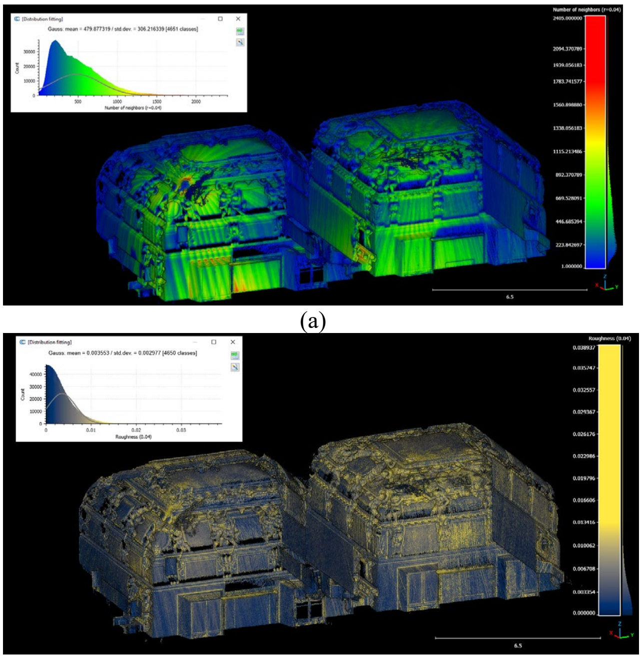
Table 4. The table reports the density analysis on the study areas

The BLK ARC dataset shows considerably irregular points distribution as visible in Figure 5a and Figure 6a, not only in relation to the outdoor-indoor scene but in relation to the scanner position on the robot and relative height from the ground.

4.2.2 Roughness to evaluate data precision. Using the "roughness" mathematical algorithm, the noise level was locally analyzed: it is defined as the mean deviation of each point from the estimated plane. In this case, a sphere with a radius of 0.04m has also been considered coherently with recognizability of detail for the architectural scale requirements.

For each point, the nearest neighbors are taken into account while computing the best-fitting plane. The radius of the observed sphere is compatible with the precision (4 cm) and accuracy (8 cm) of the representation scale 1:200 that is hypostatized suitable for BLK ARC data. The results reported in Table 5 show a mean around 3.5 mm and a standard deviation around 3.4 mm, for the dynamic, and lower for the static data, as expected. Ground truth TLS data has 0.9-1.7 mm/4cm sphere (2.1-2.7 st.dev.) according to the environment and type of motion.

Generally, a considerably regular roughness is visible in Figure 5b and Figure 6b with medium values, and mainly associated with the profile pattern.



(a)

(a)

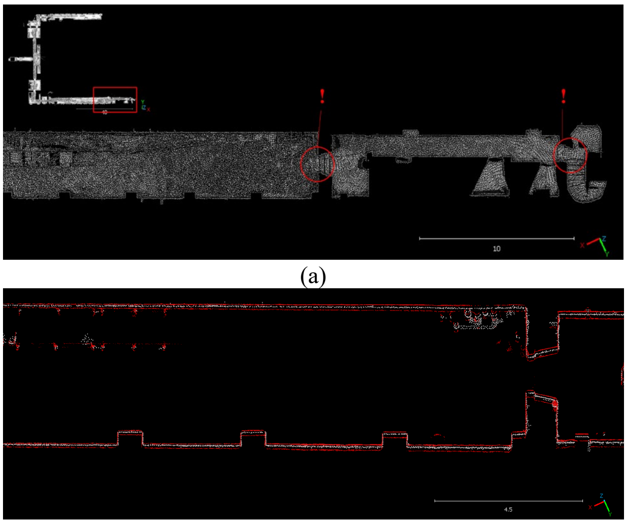
Figure 6. 3D visualization of the decorated vaults of the aulic rooms of the Castle: (a) density and (b) points roughness.

Roughness (m/sphere)			
ARC dynamic	Mean/st.dev	ARC Static	Mean/st.dev
indoor	0.003/ 0.003	A	0.024 / 0.024
		B	0.027 / 0.026
underground	0.003 / 0.003	C	0.026 / 0.029
courtyard	0.004 / 0.004	D	0.037 / 0.038

Table 5. The table reports roughness analysis on the study areas

4.3 Bottlenecks overview and research planning

In order to summarize the results of the assessment, some bottlenecks points are listed. The research requires more testing and comparative datasets for trajectories types for context-related evaluations. Firstly, some failure points and profile misalignments occurred during the trajectories due to the environmental features as narrow stairs and tunnel-like spaces in the underground Figure 7.



(a)

(b)

Figure 7. Indication of failure points during the mapping trajectory in the urderground. The 3D data visualized on plan is related to the ground truth, RCT Leica TLS scans.

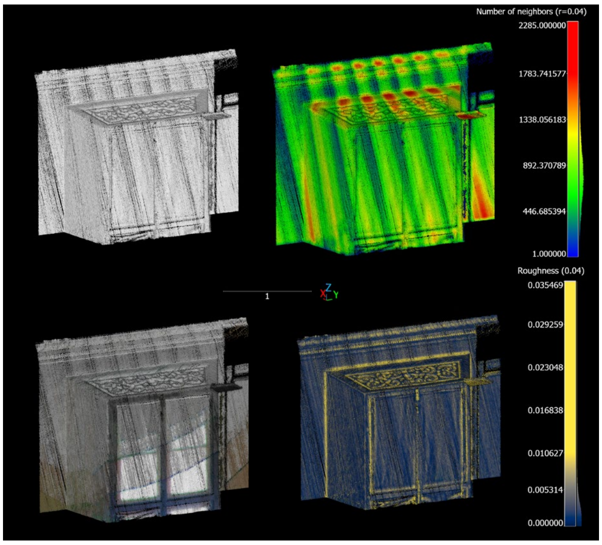


Figure 8. A detail on a window in the aulic rooms

It is possible to synthetize the assessment of the 3D mapping capabilities in surface reconstruction of the BLK ARC sensor used as mobile mapping survey technology in heritage scenario, as shown in Figure 8, where the small plaster details are visible, as well as the limited radiometric association and the pattern-related points distribution. In fact, the optimization of color association is still an open issue due to possible camera calibration errors for exposure and color balancing as reported in Figure 9a, and for the presence of RGB pixels related to the robot volume in the radiometric content of the point cloud. Wherever the color calibration performs well, as visible in Figure 9b, it is possible to appreciate an acceptable radiometric content of the 3D data fitting for architectural shapes analysis and material interpretation.

(a)

(b)

Figure 9. A couple of occurrences related to radiometric inaccuracies: (a) the 3-camera system color calibration, (b) acceptable radiometric content of the 3D data.

Finally, the authors consider the influence of the robot height on the points distribution and 3D reconstruction of irregular pavements for the static scan mode (Figure 10), and it was possible due to the particular topographic characterization of courtyard of the Castello (https://castellodelvalentino.polito.it/?page_id=2337).
In both cases of central and lateral trajectories, the sensor's position on the robot limits the wideness of points distribution on the ground. This means that in large spaces, closer trajectories should be performed.

(b)

Figure 10. A transverse section of the courtyard point cloud, showing the capability of surveying the court pavement according to the sensor height for (a) TLS ground truth and the BLK ARC static dataset (b) side-trajectory and center trajectory.

5. Conclusion and perspectives

The preliminary results of our analysis deliver satisfactory performances of the robotic sensor used as a MMS for surveying and delivering radiometrically enriched point clouds. The first step of the research confirms the proficiency of the Leica BLK ARC in terms of efficiency in data capturing and accuracy in geometric results, even if the particularly challenging context shows some limitations of the system maneuverability. Further tests are strictly required to stress different trajectories in variable environments and perform a fully automated mission with Spot®. The radiometric information quality still requires analysis and improvement since the performance of the results is not entirely adequate in terms of exposure, uniformity, and variety of colors distribution. The Leica BLK ARC Autonomous Laser Scanning Module mounted on Spot® stands at the forefront of innovation in autonomous 3D mapping, and can greatly impact CH documentation. Unlike conventional surveying techniques that require surveyors to physically enter hazardous or uneasy-to-reach areas, the autonomous capabilities of the BLK ARC equipping Spot® enable operators to capture comprehensive data without compromising safety.

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