Venice: a test field for Urban Historical Centers surveying with SLAM

Caterina Balletti
Dipartimento di Culture del Progetto
Università Iuav di Venezia
Venezia, Italia
balletti@iuav.it

Enrico Breggion
Università Iuav di Venezia
Università degli studi di Trieste,
ebreggion@iuav.it
enrico.breggion@phd.units.it

Federica Gerla
Università Iuav di Venezia
Sapienza Università di Roma
fgerla@iuav.it
federica.gerla@uniroma1.it

Francesco Guerra
Dipartimento di Culture del Progetto
Università Iuav di Venezia
Venezia, Italia
guerra2@iuav.it

Andrea Martino
Università Iuav di Venezia
Università degli studi di Trieste,
amartino@iuav.it
andrea.martino@phd.units.it

***Abstract* - In historical cities, it is often impossible to navigate with traditional MMS, and it is not appropriate to perform photogrammetric flights with drones at very low altitude. Terrestrial photogrammetry is also not feasible since the streets are very narrow and the buildings very tall. In the past, Iuav's Geomatics Laboratory has tested the possible application of spherical photogrammetry, i.e., the use of spherical chambers with which the geometry of taking in narrow spaces is simplified. The results, although promising, proved to be inferior to those achievable with the SLAM technique. The historic center of Venice, in which vehicles are not allowed to circulate and in which the presence of "calli" (streets whose width often does not exceed 2 meters) is numerous, is the ideal field of application for testing SLAM techniques and then applying them in other urban contexts (ancient boroughs) that have an urban morphology similar to that of the lagoon city. In Venice, moreover, SLAM has also been used to survey canals in which buildings face directly without the presence of banks. SLAM in fact can have as carrier not only the operator walking, or in a vehicle, but also in a boat. The paper presents the urban survey in different spatial configurations (calli, canals) using different commercial solutions and a prototype realized in the Geomatics laboratory by the authors.**

Keywords— Urban Cultural Heritage, 3D survey, Mobile Mapping System, SLAM

I. INTRODUCTION

Historic centers represent urban environments of primary importance, due to the high concentration of architectural and Cultural Heritage (CH) they contain, taking on the configuration of areas subject to special management and protection regimes, as a result of the formal and technical variables that define their peculiar characteristics. These are environments which are subject to transformation, and at the current state it is possible to affirm how these areas undergo abrupt transformations, due to both anthropogenic actions and consequences related to climate impacts [1]. Therefore, the need to develop management and adaptation plans, built in a targeted and specific way, assumes an unavoidable aspect [2].

Due to the speed these events can occur, it is possible to state how historic centers need an increase in geo-information technologies as well as mapping having a high degree of precision and accuracy, to allow in-depth urban analysis, to spatialize dynamics, and to monitor any changes [3]. The discipline of urban and spatial planning must therefore take on the task of studying and interpreting the rapid changes taking place and providing solutions: access to the latest and most detailed information is therefore of the utmost importance. Preserving and documenting historic centres, a CH of fundamental importance, is still a research topic addressed in recent years by the Geomatics community by identifying some rapid low-cost mapping solutions.

In particular, 3D modelling and the digital twin emerge as future and useful tools to support decision-making processes in spatial planning [4], as these approaches make it possible to describe variations within urban environments. These are research tools in which the possibility of bringing the physical dimension into dialogue with the virtual dimension, incorporating geospatial data in real time, becomes an added value for understanding the dynamics at work [5]. These technologies make it possible to create detailed and accurate 3D models of sites [6][7], enabling researchers from different backgrounds to study and analyse them in ways that were previously difficult. However, the digital acquisition of CH, even at an urban scale, is a complicated process that requires in-depth knowledge of the peculiarities of the object and the purpose of the investigation: by its very nature, it is often characterised by an articulated conformation, which requires special awareness in the elaboration of the survey project. Identifying the best solution for an adequate reconstruction of the surface that fulfils the intended purpose and final requirements of the survey becomes an indispensable step. Furthermore, it is not unusual for complex environments in the field of CH to suffer from a lack of accessibility: agile and easy-to-use sensors should be preferable to collect the relevant amount of data while avoiding time-consuming procedures [8][9].

The configuration of historic centres, mainly characterised by narrow environments and tall buildings, therefore makes aerial or drone surveys unsuitable, limiting the possibility of studying and managing these environments effectively [10]. The development of geomatic techniques has led to the creation of a wide variety of sensors that can be used in these contexts. These sensors range from RGB and multispectral cameras in both terrestrial and aerial photogrammetry [11] to terrestrial laser scanners (TLS), aerial LiDAR (Laser Imaging Detection and Ranging) and mobile mapping systems (MMS) based on SLAM (Simultaneous Localization And Mapping) algorithms capable of simultaneously mapping the environment and locating within the generated 3D map [12]. Given the different ways of collecting and producing three-dimensional urban data [13], terrestrial laser scanners embedded in mobile ground-based mapping systems appear to be the most suitable solution for solving the criticalities that the configurations of historic centres possess, as far as their survey is [14][15]. Mobile Mapping Systems (MMS), precisely because of their ease of use, speed of acquisition and lower costs, have assumed an important role in the comparison of these sensors with other established approaches [16][17]. These systems integrate and synchronise mapping sensors, such as the LiDAR (Light Detection And Range) scanner and spherical or hemispherical cameras, as well as navigation/positioning sensors, such as the GNSS (Global Navigation Satellite System) receiver and the IMU (Inertial Measurements Unit) platform, to provide real-time 3D geospatial point clouds obtained from automatic scan-to-scan registration with an accuracy of a few centimetres. One of the main advantages of portable MMSs is that they enable the collection of a significant amount of georeferenced information quickly and efficiently, enabling the rapid and efficient digitisation of even large urban areas and inaccessible locations [18].

The nature of these data, and their possibility to be integrated and used in a GIS environment, proves to be an advantageous aspect for the discipline of spatial planning as it facilitates the presentation and sharing of data that allow the observation and monitoring of the transformations taking place within historic centres and urban landscapes [19]. This has a twofold utility: on the one hand, the production of information assets for cognitive frameworks is increased; on the other hand, the type of data produced becomes a useful decision support tool for the management and protection of the architectural and CH present in historic centres [20] and subject to anthropogenic and climatic impacts.

II. MATERIALS AND METHODS

Based on these considerations, the aim of this work is to evaluate the performance of one of the newest commercial MMSs for urban CH documentation within different external applications [21][22]. In detail, this work evaluates the suitability of SLAM technology for the documentation of complex environments in the built heritage domain characterised by particular urban peculiarities, using the system by walking the streets by hand. Nutcher et al [23], proposed a SLAM/ICP procedure divided in several phases and consisting of estimating the six TLS degrees of freedom using odometry data, heuristic computations based on octree representations to improve the 6D poses, registration using the ICP approach for all scans performed, a phase in which it is necessary to minimise the error, following th equation (1):

$$E = \sum j \rightarrow k \sum i \left| \boldsymbol{R} j \boldsymbol{m} i + \boldsymbol{t} j - (\boldsymbol{R} k \boldsymbol{m} i + \boldsymbol{t} k) \right|^2 \tag{1}$$

The last steps consist of closing the scan cycle to distribute the residual error and global refinement of the ‘simultaneous matching’ model. The degree of accuracy of the final MMS cloud depends on both the accuracy of the instrument (the TLS distance meter) and the INS accelerometers/giroscopes and GNSS receiver. This is especially the case when using low-cost sensors. Different MMSs with similar sensors may provide different results in terms of accuracy: this depends on the software and hardware configurations used. Operational aspects also play a role in influencing the results of the operation [24], such as the way the system is moved, slow or fast (especially when turned). Halving the speed of the walk doubles the resolution of the cloud. Furthermore, although the operations take place under the same instrumental/processing/acquisition conditions, the geometric uniformity and surface texture of the surveyed environment can locally affect the final accuracy. Smooth materials are synonymous with better results than historical materials with irregular and deteriorated stones and bricks.

The methodology [25] was applied to a test fields in the historic center of the city of Venice: the urban area of Santa Marta, in Dorsoduro district (Fig. 1), an example of venetian narrow streets leading to wider areas, very similar to many urban contexts, also characterized by canals accessible exclusively by boat. The Santa Marta area occupies the western end of the city, where ancient settlements coexist with popular neighborhoods and buildings built between the 19th and 20th centuries. The area is also characterized by the presence of large industrial archeology buildings and many churches. The area of Santa Marta has lent itself several times to numerous instrumental tests, described in previous works [8][17]. In this work, the focus was on the circular route around the Church of San Nicolò dei Mendicoli, which is one of the oldest churches in Venice.

Fig. 1. The urban area of Santa Marta in Venice.

A. *Instruments overview*

The purpose of this research, as previously stated, is to analyze the performance of some commercial solutions and a prototype still in the testing phase created by the CIRCE Geomatics laboratory in the field of urban CH in order to document or produce an urban analysis. The commercial MMSs used are the well-known STONEX® X120^{GO} *SLAM Laser Scanner*[1], the STONEX® X70^{GO} *SLAM Laser Scanner*[2] and NavVis VLX3 by Dynatech[3].

1) *STONEX® X120^{GO} SLAM Laser Scanner* (Fig. 2)

It is composed by a 360° rotating head Hesai XT16 LiDAR scanner, which can form a 270°x360° point cloud coverage acquiring 320000 pts/s in a 0.5m-120m range. Three 5MP cameras are adopted to form a horizontal 200° field of view (FOV) and a vertical 100° FOV, which can synchronously obtain texture information and to furthermore produce colored point clouds and partial panoramic images. The STONEX® X120GO SLAM Laser Scanner has an integrated structure design with a built-in control and SD storage system and built-in replaceable lithium batteries.

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[1] https://www.stonex.it/it/project/x120go-slam-laser-scanner/

[2] https://www.stonex.it/it/project/x70go-slam-laser-scanner/

[3] https://www.dyna-tech.it/prodotti/navvis-vlx-3/

Fig. 2. The STONEX® X120^{GO} *SLAM Laser Scanner* and the RTK120^{GO} portable GNSS module.

2) *STONEX® X70^{GO} SLAM Laser Scanner* (Fig. 3)

The X70GO is a real-time MMS that combines a processing system, a 512GB internal storage, and inertial navigation module. It includes a Livox LiDAR head that rotates around the vertical axis producing point cloud data. Color is provided to the model using a 12 MP RGB camera, and real-time previews are provided by a SLAM visual camera through the field app.

Fig. 3. The STONEX® X70^{GO} *SLAM Laser Scanner* and the RTK120^{GO} portable GNSS module.

3) *NavVis VLX3 by Dynatech* (Fig. 4)

It captures 3D measurements with two 32-layer lidar sensors in combination with groundbreaking SLAM software to deliver point cloud quality for a wearable device. Four cameras positioned on top of the device take high-resolution, sharp images in every direction for a complete 360º image - all without the operator appearing in the field of view. The accuracy of point cloud is 6mm.

Fig. 4. The NavVis VLX3 by Dynatech.

4) *Low-cost MMS Prototype*

The fourth MMS (Fig. 5) is an experimental low-cost device developed using a Livox Mid-360 sensor, which includes a LiDAR with a 360°*59° field of view, a range of 70 meters, and a precision of ±2 cm at 10 meters. Additionally, the sensor features an integrated IMU system1. The sensor is connected to a computer running Ubuntu operating system, powered by an Intel Core i7 processor and 32 GB of RAM. Both the computer and the sensor are powered by an external battery, with power consumption of 19 V for the computer and 9 V for the sensor. The real-time data processing is managed using ROS (Robot Operating System) and the SDK provided by Livox. Input data is processed using the open-source FAST-LIO22 (Fast LiDAR-Inertial Odometry) package, which allows fusion of LiDAR feature points with IMU data using a tightly-coupled iterated extended Kalman filter to enable robust navigation in fast-motion, noisy, or cluttered environments where degeneration occurs. To further enhance system efficiency by enabling loop identification, the SC-PGO3 (Loop detection and Pose-graph Optimization) package is also used alongside FAST-LIO2. The system has been tested both as a handheld system, with the sensor mounted on a pole, and as an autonomous MMS, assembling the SLAM system on a rover capable of moving freely within the environments to be mapped.

Fig. 5. Low-cost MMS Prototype.

The choice of using the same closed path (Fig. 6) for all instruments makes it possible to compare different systems in an environment with similar characteristics. Furthermore, the route was defined with the aim of simulating conditions as close as possible to real surveys. The analytical prediction of the accuracy of the final position from the MMS components of the instrumental error is a rather complex operation. For this reason, the data evaluation presented in this paper was produced by comparing each mapping performed with the 'ground truth'. The scan alignment was performed by topographic survey measurements based on a control network of 7 vertices. The network accuracy is +/- 0.003 m and the GCPs accuracy is +/- 0.005 m. A cloud of approximately 1250 million points was therefore available as ground truth. First, a rough alignment of the clouds was obtained and appropriately defining some corresponding points in all datasets. As a result, the clouds were pre-aligned. The final refinement was obtained using the ICP algorithm, using the CloudCompare[4] software.

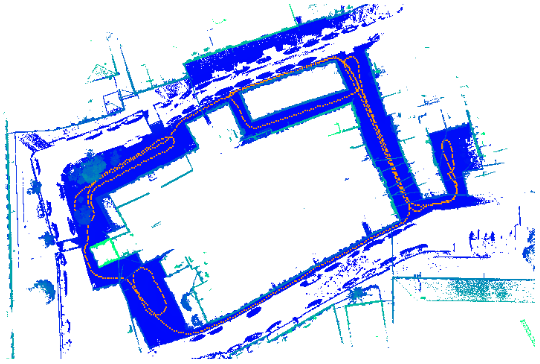

Fig. 6. The test-field path within the urban area of Santa Marta in Venice.

B. *Quantitative Criteria for Evaluation*

As previously mentioned, generating final point clouds is a complex operation. This translates into a difficulty regarding the prediction of accuracy but also with regards to the definition of general and objective procedures for the evaluation. In any case, the phase of setting some operational procedures for data acquisition becomes important: aspects such as walking speed and the way in which the handheld systems are held, the regularity of the path, all aspects that influence the completeness of the model. The raw data is stored in proprietary format depending on the instrument, for this reason the comparison between them is not possible. The same data were post-processed with dedicated software. As is known, the evaluation of the accuracy of point clouds can be carried out using different approaches: cloud to cloud, point to point and cloud to feature.

In this study, the cloud to cloud (C2C) approach was used comparing two specific sub-datasets area (Fig. 7) within the whole test-field.

Fig. 7. The sub-datasets within the ground truth point cloud.

C. *Cloud to feature comparison*

The cloud to feature approach was also used, which consists in comparing the real geometric characteristics with the geometries of the generated clouds. This comparison is useful because it allows you to obtain an in-depth analysis of the performance of the devices. It is important to point out that the comparison must take into consideration the dimensions of the scene, together with the presence of systematic errors resulting from the alignment of the frames of the same point cloud. Using an identifiable object to make the comparison becomes necessary. The use of both longitudinal and vertical sections and the comparison of point cloud thicknesses is useful for quantitative verification of device characteristics. Using a small environment allows you to minimize the impact of position estimate drift on the analysis. This allows to obtain data relating to the recognizability of geometric features rather than tracking errors which are considered more fully with the comparison between cloud and cloister cloud mesh.

D. *Qualitative Criteria for the Evaluation*

In addition to the quantitative evaluation, a qualitative analysis was carried out in order to obtain a more detailed overview of information for the comparison covered by this work. In particular, the completeness and quality of the data, the degree of recognisability of the details and the double surface errors and outliers were investigated. An analysis of the number of points in the clouds becomes a useful evaluation to highlight the quality and usability level of the data. it is good to remember that although the area analyzed is the same, the number of points between scans varies considerably based on the tools used. There are many elements that contribute to defining these differences, such as the operator's movements, the path taken during acquisition, the scanning speed. All these aspects actively influence the final number of points. Using the CloudCompare software, a roughness filter was applied, which determines a roughness value for each point in the cloud. In this way it is possible to visualize the local geometric variations in the point cloud, which then allow the quality of the details to be verified. The data obtained were represented through and consequently visually compared with the reference cloud. Repetition of the scanning surface can be critical as errors such as double surfaces can negatively affect the result. In order to prevent and evaluate this type of error, it can be useful to assess the approach used by the software for acquisition and processing. The extraction of the horizontal and vertical profiles of the various parts of the clouds is indispensable for assessing the presence of double surfaces. Particular attention must be paid to the thickness of the point cloud, which is due in part to general noise related to the characteristics of the sensor and in part to the incorrect recording of the individual frames acquired.[FG2]

III. RESULTS

Alongside the results of a quantitative nature (Tab. 1)(Tab. 2), aspects emerge from the results obtained that are not easily quantifiable as they can only be described from a qualitative point of view (Tab. 3)(Tab. 4). These aspects are related to the level of noise and the resolution of the model, which influence the 'level of detail' (LoD) of the models that have been processed. It should be remembered that the level of noise depends mainly on the TLS system, together with the algorithms applied in post-processing, while the resolution depends strongly on the speed of acquisition.

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[4] https://www.danielgm.net/cc/

Sub-dataset A	ICP RMSe	C2C distance	
		Mean	*Std. dev.*
Stonex X120^{Go}	0.0154510m	0.004709m	0.008281m
Stonex X70^{Go}	0.0186157m	0.006914m	0.011090m
NavVis VLX3	0.0180837m	0.007971m	0.015313
Low-cost Prototype	0.0216103m	0.015534m	0.018129m

Tab. 1. The first test-field sub-Dataset ICP and C2C distance computation results.

Sub-dataset B	ICP RMSe	C2C distance	
		Mean	*Std. dev.*
Stonex X120^{Go}	0.0137598m	0.007760m	0.017915m
NavVis VLX3	0.0138952m	0.008105m	0.019303m
Low-cost Prototype	0.0250514m	0.033628m	0.032065m

Tab. 2. The second test-field sub-Dataset ICP and C2C distance computation results.

Sub-dataset A	N. of points	Density	Roughness
Ground Truth	**169723128**	**80359pts/m^2**	**0.001924m**
Stonex X120^{Go}	4320941	4268pts/m^2	0.003021m
Stonex X70^{Go}	5874785	6671pts/m^2	0.003987m
NavVis VLX3	41423997	31245pts/m^2	0.003936m
Low-cost Prototype	1795677	1904pts/m^2	0.010305m

Tab. 3. The first test-field sub-Dataset consistency indices.

Sub-dataset B	N. of points	Density	Roughness
Ground Truth	**116999543**	**58967pts/m^2**	**0.002638m**
Stonex X120^{Go}	3650632	4865pts/m^2	0.003567m
NavVis VLX3	20839176	28018pts/m^2	0.003873m
Low-cost Prototype	1935571	3644pts/m^2	0.012892m

Tab. 2. The second test-field sub-Dataset consistency indices.

In order to assess the real usability of the MMS data in an urban/architectural environment, some comparisons were made with respect to the possibility of recognising not only the main built volumes (Fig. 8), but also some typical architectural details (Fig. 9). In this work, the focus was on the details of a window of the church under study. With regard to the type of processing, there is a clear difference between the instruments used. While the NavVis VLX3 Dynatech processes data in a cloud environment, reducing the possibility of having raw data, this is not the case with data obtained using the STONEX® X120GO and Livox Mid-360 instruments. The Livox Mid-360 in its current state and at the local level is suitable for expeditious surveys, reaching representation scales of the order of 1:100 and 1:200 while at the global level there are aspects to be modified and improved. The NavVis VLX3 is as the best tool, among those tested in this work, for architectural representation (1:50).

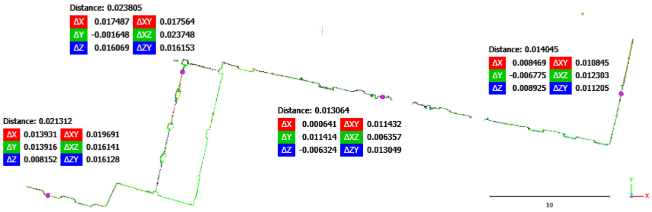
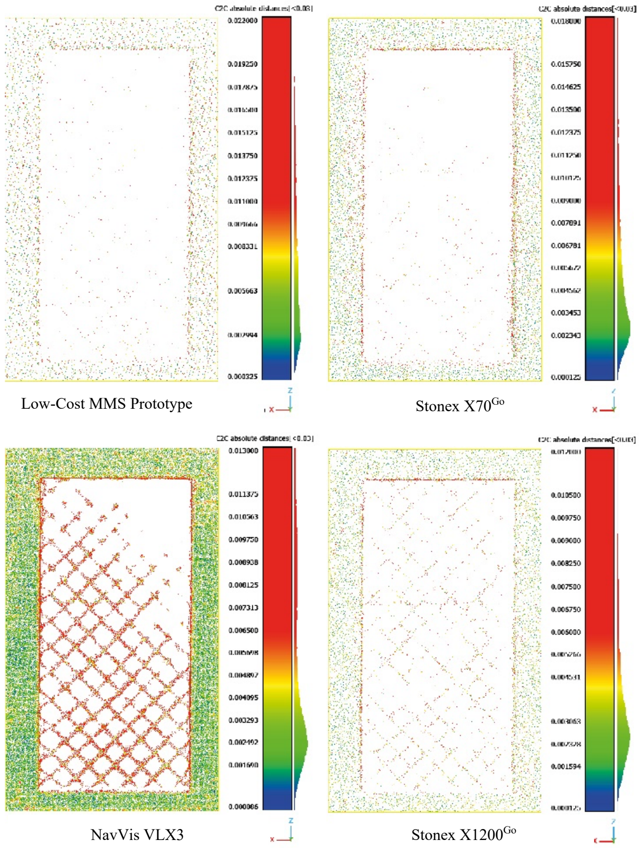


Fig. 8. Sub-Dataset A horizontal profiles.



Low-Cost MMS Prototype

Stonex X70^{Go}

NavVis VLX3

Stonex X1200^{Go}

Fig. 9. Window detail visual and C2C distance analysis.

IV. CONCLUSION

The methodology tested in this study proves to be valuable for monitoring and mapping the transformations involving the CH of our cities. Historic centres represent urban environments of primary importance, given their high concentration of architectural and cultural heritage, subject to specific assessment and protection regimes. These areas, susceptible to sudden changes due to human actions and climatic impacts, require targeted and specific management and adaptation plans. Thinking about new integrated approaches for producing innovative data for the discipline of urban planning, expanding the knowledge possessed so far becomes an issue to be explored in depth. This results in the need to increase the use of of geo-informative technologies as well as mapping techniques characterised by a high degree of precision and accuracy, in order to enable in-depth urban analyses, spatialisation of dynamics and monitoring of possible changes. The aim of this work is to compare four instruments for mobile mapping. The instruments compared are: STONEX® X120GO, STONEX® X70GO, NavVis VLX3 Dynatech and a low cost prototype still in the testing phase created by the CIRCE Geomatics laboratory. The test area is a part of the Santa Marta district, in Venice. It is a very special urban configuration, as it is characterised by calli and canals. The urban characteristics of Santa Marta make it excellent for the experimentation that is the subject of this paper. A closed route was defined, used with all four instruments to allow a comparison of performance. In particular, attention was focused on an area characterised by a series of calli and a church, San Nicolò dei Mendicoli.

The comparison performed shows how the use of SLAM-based MMSs in digitising urban CH has great potential for documenting, monitoring and preserving cities and urban landscapes. Although MMSs drastically reduce the data collection process, they still require a lot of time and resources to reconstruct optimised and filtered data [26]. However, the challenges associated with the use of MMS must be carefully addressed to ensure that the data collected is accurate, useful and can be used for its intended purpose. With proper planning and management, MMSs can play a key role in the preservation and documentation of CH becoming a useful support tool for spatial planning that investigates climate and urban issues.

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REFERENCES

[1] D. Hu, & J. Minner, "UAVs and 3D City Modeling to Aid Urban Planning and Historic Preservation: A Systematic Review" in Remote Sensing, 15(23), **2023,** 5507.

[2] E. Cantatore, M. Lasorella, & F. Fatiguso, "Resilient Improvement of Historic Districts via Digital Tools. The Virtualization of Energy Retrofit Actions Using Simplified CityGML-Based Plans. In International Conference on Computational Science and Its Applications, **2021**, pp. 155-172.

[3] E. Abbate, G. Sammartano, & A. Spanò, "Prospective upon multi-source urban-scale data for 3d documentation and monitoring of urban legacies" in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, **2019**, 42, pp. 11-19.

[4] R. Tan, P. Li, W. Lin, C. Pan, "Improvement of 3D Urban Modeling Method Based on Unmanned Aerial Vehicle Oblique Photography" Bull. Surv. Mapp. **2016**, 11, 39–42.

[5] N. Kikuchi., T. Fukuda, & N. Yabuki, "Future landscape visualization using a city digital twin: Integration of augmented reality and drones with implementation of 3D model-based occlusion handling" in Journal of Computational Design and Engineering, 9(2), **2022**, 837-856.

[6] S. Barba, C. Ferreyra, V.A. Cotella, A. di Filippo, S. Amalfitano, "A SLAM Integrated Approach for Digital Heritage Documentation" in Rauterberg, M. (Ed.), Culture and Computing. Interactive Cultural Heritage and Arts, Lecture Notes in Computer Science. Springer International Publishing, Cham, **2021**, pp. 27–39.

[7] F. Chiabrando, G. Patrucco, F. Rinaudo, G. Sammartano, V. Scolamiero, O. Vileikis, M. Hasaltun Wosinski, "3D documentation towards heritage conservation: a rapid mapping approach applied to bahrain forts" in Arch. Photogramm. Remote sens. Spatial inf. Sci., xliii-b2-**2022**, 769–776.

[8] B. Tanduo, A. Martino, C. Balletti, F. Guerra, "New Tools for Urban Analysis: A SLAM-Based Research in Venice" in Remote Sens. **2022**, 14, 4325.

[9] F. Di Stefano, A. Torresani, E.M. Farella, R. Pierdicca, F. Menna, F. Remondino, "3D Surveying of Underground Built Heritage: Opportunities and Challenges of Mobile Technologies" in Sustainability **2021**, 13, 13289.

[10] T. Deng, K. Zhang & Z. J. M. Shen, "A systematic review of a digital twin city: A new pattern of urban governance toward smart cities" in Journal of Management Science and Engineering, 6(2), **2021**, pp 125–134.

[11] A. Mathys, R. Jadinon, P. Hallot, in "Exploiting 3d multispectral texture for a better feature identification for cultural heritage", Isprs ann. Photogramm. Remote sens. Spatial inf. Sci. Iv-2/w6, **2021**, pp 91–97.

[12] P. Rodríguez-Gonzálvez, B. Jiménez Fernández-Palacios, A. Muñoz-Nieto, P. Arias-Sanchez, D. Gonzalez-Aguilera, "Mobile LiDAR System: New Possibilities for the Documentation and Dissemination of Large Cultural Heritage Sites" in Remote Sensing 9, **2017**, p189.

[13] G. Vosselman & H. G. Maas, "Airborne and terrestrial laser scanning" in CRC Press (Taylor & Francis), **2010**.

[14] D. Grejner-Brzezinska, R. Li, N. Haala & C. Toth, "From Mobile Mapping to Telegeoinformatics: Paradigm Shift in Geospatial Data Acquisition" in Processing, and Management. PE&RS 70(2), **2004** pp.197-210.

[15] N. Haala, M. Peter, J. Kremer & G. Hunter, "Mobile LiDAR mapping for 3D point cloud collection in urban areas: A performance test" in Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci, 37, **2008**, pp 1119-1127.

[16] B. Tanduo, L. Teppati Losè, F. Chiabrando "Documentation of complex environments in cultural heritage sites. A slam-based survey in the Castello del Valentino basement, in int. Arch. Photogramm. Remote sens. Spatial inf. Sci., xlviii-1/w1-**2023**, 489–496.

[17] A. Martino, E Breggion, C. Balletti, F. Guerra, G. Renghini and P. Centanni, "Digitization approaches for urban cultural heritage: last generation mms within venice outdoor scenarios" in int. arch. photogramm. remote sens. spatial inf. sci., xlviii-1/w1-**2023**, 265–272,

[18] S. Li, G. Li, L. Wang, Y. Qin, "SLAM integrated mobile mapping system in complex urban environments in ISPRS J. Photogramm. Remote. Sens. **2020**, 166, 316–332

[19] E. Nocerino, F. Menna, F. Remondino, "Multitemporal analysis of landscapes and urban areas" in Int. Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 39(4), **2012**, pp. 85-90.

[20] A. Turek, A. Salach, J.S. Markiewicz, A. Maciejewska & D. Zawieska, "An Example of Multitemporal Photogrammetric Documentation and Spatial Analysis in Process Revitalisation and Urban Planning", in GISTAM, **2018** pp. 223-230.

[21] E. Maset, S. Cucchiaro, F. Cazorzi, F. Crosilla, A. Fusiello, A. Beinat, "Investigating the performance of a handheld mobile mapping system in different outdoor scenarios" in Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLIII-B1-**2021**, pp 103–109.

[22] E. Nocerino, F. Menna, F. Remondino, I. Toschi, P. Rodriguez-Gonzalvez, P, "Investigation of indoor and outdoor peromance of two portable mobile mapping systems" inVideometrics, Range Imaging, and Applications International Society for Optics and Photonics, 103320I, **2018**

[23] Nüchter, A.; Lingemann, K.; Hertzberg, J.; Surmann, H. 6D SLAM-3D Mapping Outdoor Environments. J. Field Robot. **2007**, 24, 699–722.

[24] Tucci, G., Visintini, D., Bonora, V., & Parisi, E. I. Examination of indoor mobile mapping systems in a diversified internal/external test field. Applied Sciences, 8(3), **2018**, 401.

[25] Breggion, E., Balletti, C., Vernier, P., & Guerra, F. A Low-Cost MMS Approach to the Simultaneous Localization and Mapping Problem. In the Italian Conference on Geomatics and Geospatial Technologies (**2022**, June) (pp. 15-47). Cham: Springer International Publishing.

[26] N. Sairam, S. Nagarajan, S. Ornitz, "Development of Mobile Mapping System for 3D Road Asset Inventory" in Sensors 16, **2016**, p 367.