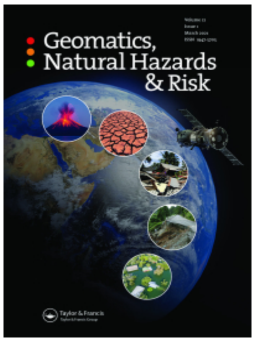

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REVIEW

Mobile 3D scan LiDAR: a literature review

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ABSTRACT

This paper, by critically reviewing different years (from 2010 to 2020) of research activities performed with Mobile Laser Scanning system, aims to review existing systems and how they are exploited in multifaceted domains. To such extent, the work defines five field domains where Mobile Laser Scanning have been used: ***Built and urban environment***, ***Cultural heritage and Archaeology, Underground environment, Environmental monitoring, Forestry and Agriculture.*** Besides, this paper sheds the light on the pros and cons for each domain field, providing useful guidelines for those researchers involved in three-dimensional data collection with innovative systems. To achieve these purposes, research papers, were analysed, mainly considering geosciences related journals. The comparison among them revealed that, despite the incredible potential of Mobile Mapping System, the human intervention is still mandatory, and post-processing actions are needed to achieve the desired results, regardless the domain field. Moreover, our study provides insight into the technical and methodological limitations that raise a general scepticism on Mobile Mapping System for three-dimensional surveying, highlighting that in most of cases supplementary data are required to make the final result trustworthy. Such obstacles, hampering Mobile Laser Scanning diffusion, point towards unexplored areas for further investigations, serving as useful guidelines for future research directions.

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LiDAR; mobile laser scanning; 3D scan technology; performance; test field

1. Introduction

Geomatics experts, researchers and practitioners have witnessed a dramatic change in the way surveying is conducted over the last two decades. Point clouds are the most viable kind of data, to represent, at different scales and with different levels of complexity, every kind of object. Broadly speaking, the problem domain dictates the choice of sensors, processing techniques, computational approaches and resources,

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according to the products in output (e.g. 3 D models, orthoimages, cartography, 2 D drawings) and foremost their quality (resolution, precision vs accuracy) (Konecny 2002).

For this reason, acquisition tools have been developed to provide the user with accurate and geometrically correct 3 D data. Conversely, despite the indisputable value of 3 D point clouds, the choice of the right tool is entrusted on several variables: in other word, the balance between costs, times, accuracy, efficiency, is hard to find. To face this issue, Mobile Mapping System (MMS) proved to be a valuable alternative to the combination of heterogeneous data, assuring benefits in different scenarios. MMS possesses huge potential and its application in several domains has witnessed a growing interest in the latest years. The application of MMS is concerned with several fields of research and examples of this can be found in a variety of engineering and scientific disciplines: urban environment, cultural heritage, environmental monitoring, mapping and modelling, just to mention some. Thus, the combination of several surveying techniques is now a commonly used practice in Geomatic. It is generally agreed that a well-defined pipeline is likely to lead to a suitable product for 3 D representation. However, little systematic work currently exists on how researchers have applied MMS, providing a big picture for different areas.

It is fair to say that there are already a few comprehensive overviews and systematic surveys. For example, the paper of (Yanjun Wang et al. 2019) focuses on MMS in outdoor scenes, given the wide range of possibilities offered for such environments, while (I Puente et al. 2013) emphasizes the application of MMS from the point of view of commercially available tools. Although (Tucci et al. 2018) have a similar focus to this review, which is in terms of pros and cons of delivering 3 D point clouds for mapping outdoor scenes, they are too specific and do not allow practitioners to have a wider overview for other needs. Besides, the aforementioned studies do not examine in detail the performances of the tools in comparison to the large set of possible environments where MMS can be exploited. Therefore, the analysis here presented reports guidelines and best practices following previous works by the authors (Chiappini et al. 2020; Di Stefano, Cabrelles, et al. 2020; Di Stefano, Chiappini, et al. 2020; Paolanti et al. 2019), providing a strong baseline of assessment.

This work is organized as follows: in Section 2, the motivations behind this review are discussed, together with the research questions to be answered. Then, in Section 3, the main definitions and tools broadly adopted in the literature are outlined. Our research design is described in Section 4, including our literature identification search procedure, our filtering process and analysis methods. In Section 5, the results of the literature review are reported. Five application domains are identified (Built and urban environment, Cultural heritage and Archaeology, Underground environment, Environmental monitoring, Forestry and Agriculture). Drawing on this classification, we identify patterns of adopting MLS solutions in different contexts, even considering the research trends in the last decades. Following this analysis, in Section 6 e argue about pros and cons in different domains, based on numerical and statistical analysis of the existing systems. Finally, we draw conclusions in Section 7.

2. Review purposes

Among the Geomatic research community there is growing interest towards the adoption of those surveying methods encompassing all the needs of the domain: ease of use, reliability, efficiency, reduced costs, reduced human effort. It is well-known, in fact, that the integration of heterogeneous data, coming from different source, is somehow unavoidable dealing with complex 3 D surveys.

Mobile Laser Scanner (MLS) are taking over, given the surge of developing all-in-one solutions. State of the art MLS are far from replacing much more consolidated methods, but their expansion is compelling and deserves attention. In the scientific literature, despite the proliferation of papers reporting experiments with MLS, little systematic work currently exists on how researchers have applied MLS, providing a general framework for different areas.

In this paper, we focus on the use of MLS techniques with a multidisciplinary purpose, by identifying manifold features that characterize the existing systems and how they are exploited in multifaceted domains. In particular, the existing literature leave unanswered the following questions:

- Can MLS technologies be considered an all-in-one solution for different domains?
- Given the recent technological advances in point cloud acquisition, where MLS technologies have been mostly applied?
- Is it possible to provide the research community with guidelines, driving practitioners towards the better solution use according to the needs of the survey?
- Which are the advantages and disadvantages of using MLS in different scenario?

3. Mobile laser scanning

3.1. Platform typologies

The expression Mobile Mapping System (MMS) describes a mobile platform that can be either aerial or terrestrial, in which measurement systems and sensors are integrated for the acquisition of geo-referenced metric data. Hence, an MMS is an integration of three main hardware components: optical sensors, navigation/positioning sensors and a control unit (Toschi et al. 2015). This technology, if combined with a Light Detection and Ranging (LiDAR) unit, can be referred as Mobile Laser Scanner (MLS) which is a widely used acronym in recent literature. This approach has the great advantage to be time efficient if compared with the other survey's methods. In this case, the laser scanners have been placed on moving platforms in order to obtain multiple scan positions with artificial targets for high detection rates and avoiding, as much as possible, shadowing effect and non-detection areas. It is a further technology improvement which combines a moving sensor with position estimation to obtain continuous registration and unlimited viewing angles (Westling et al. 2020). For what concerns the quality of the data obtained with the MLS surveys, it depends on the devices used but it generally reaches a centimetric accuracy and a resolution that is related to the data acquisition speed and the distance of the detected objects (Gollob et al. 2020). The MLS are usually categorised according to the mobile platform used.

According to the recent literature reviewed, the mobile terrestrial platforms can be split in human-based, wheel-based, boat-based and sledge-based. With the term ‘human-based’ it is referred to platforms carried by human beings and, normally, they are mentioned as Personal/Portable Laser Scanner (PLS) or Wearable Laser Scanner (WLS). There are few differences between PLS and WLS: the first is usually referred to systems that can be carried manually by the operator (such as a hand-held laser scanner) while the second usually means small devices which can be worn by the operator, like scanners in a backpack. The ‘wheel-based’ platforms can be referred to as trolleys, vehicles on rails, motorbikes, bikes and vehicles. The latter include road vehicle, All-terrain Vehicle (ATV) and Unmanned Ground Vehicle (UGV). Very often UGV coincide with ATV, as they are used where people cannot access easily so a remote-controlled vehicle (in literature may be referred simply as ‘robot’) able to overcome difficult terrains. The ‘boat-based’ and the ‘sledge-based’ platforms are used only in certain domains or conditions, where there is the necessity to use such kinds of platforms (Kaasalainen et al. 2010; Vaaja et al. 2011). Sometimes, the acronym ‘Boat Mobile Mapping System (BoMMS)’ is utilised to denote mobile mapping systems mounted on boats, regardless the boat size. Dealing with airborne mobile systems, in literature they are mainly referred as Airbone Laser Scanner (ALS), but it is possible to find even ‘Aerial Laser Scanner’ and ‘Aircraft Laser Scanner’ and the main difference is due to the laser units equipped, which have different range in the data acquisition. Even in this case, the acronyms UAV and UAS (respectively Unmanned Aerial Vehicle and Unmanned Aircraft System) can be found in literature and they are both referred to the ALS systems. Prior to the scanners installed on mobile platforms, lasers were used on fixed platforms and these systems were named Terrestrial Laser Scanners (TLS). Technological innovation has expanded the use of such stationary laser units which, when bundled with localization and mapping systems, can become mobile laser units and in literature are directly termed either MLS or mobile-TLS (Kukko et al. 2012). As mentioned above, a typical MLS system has the capacity to localize and map itself thanks to both the Global Navigation Satellite System (GNSS) receiver and the Inertial Measurement Unit (IMU), which are sensors that will be better explained in the next review’s section (section 3.2).

3.2. Localization and mapping systems

During the last two decades, the improvement of navigation systems has driven the industrial and scientific community towards the use of several types of sensors which are widely used in the geomatic community. These innovations have contributed to the MLS technologies development, which allows to acquire the surrounding environment in a rapid and efficient way through data localization, with sensors able to perform in all weather conditions (Chang et al. 2019). Commercial MLS instruments are equipped with multiple sensors for the navigation system consisting of GNSS (Global Navigation Satellite System) and IMU (Inertial Measurement Unit). These two components can ensure the correct geo-referenced positioning for the three-dimensional laser scanning data (Kukko et al. 2012). GNSS refers to a group of satellites which provide space signals, delivering positioning and timing information to the GNSS receivers. The latter, subsequently, use these data to establish the position (Groves 2015). Inertial measurement units have acquired a remarkable level of popularity in recent years as a low-cost way to measure motion. An IMU can measure both linear accelerations (three-axis accelerometer) and spin rates (three-axis gyroscope), which can be numerically integrated to provide three-dimensional position and orientation of an object. In combination with the position data, IMU allows to transform the point data obtained by the MLS local frame into the ground-centric-ground-fixed system. Hence, all points are projected into a common framework and any non-compensated error from the IMU will have a direct effect on the geometrical quality of the point cloud (Liu et al. 2019). The level of accuracy of the GNSS/IMU navigation system is related to the signal detection quality of the GNSS, especially if it is composed by low-cost sensors (Chang et al. 2020). To increase location accuracy and remove MLS errors in GNSS-denied environments, previous developers have made significant improvements on data-driven (Mao et al. 2015) and model-driven techniques. Data-driven methods may be directly used to fix point clouds data starting from ground truths and using multiple available correction algorithms. On the other hand, model-driven approaches set up mathematical models for the MLS systems and analyse the error factors to calibrate the biases (Liu et al. 2019). Furthermore, Simultaneous Localization and Mapping (SLAM) algorithms have been investigated in robotics in the past years. SLAM algorithms generate a map of an unfamiliar environment and, in the meantime, it locates the mobile platform. The SLAM system requires a closed loop survey to improve the final precision. Different studies stated that each scan should start and end at a fixed point to ensure a closed loop and locate properly the data collected in the unknown environment, registering the whole points cloud obtained without the GNSS signal (Cabo et al. 2018; Gollob et al. 2020). To localize positions with SLAM, it is possible to apply two major strategies: absolute positioning with feature-matching and relative positioning with scan-matching. The first strategy matches feature detected (such as lines, corners, circles, etc.) with a generated feature map which allows to recognize the position. In the second strategy, two or more scan points frames are matched together by various algorithms to obtain the movement done by the MLS. Therefore, the SLAM algorithm performs better when applied indoors, with regular and repetitive features, while it has been shown to perform poorly when applied outdoors due to the complex and irregular features detected by the laser scanner. These irregularities create abrupt movements or difficulties to detect the whole area, increasing the computation payload and the complexity of the algorithm design (Tang et al. 2015). The combination between the GNSS/IMU navigation system and SLAM will successfully reduce navigation drift whenever the GNSS signal is not clear and will provide absolute navigation information, which are not provided by the SLAM algorithms (Chang et al. 2019).

4. Definition of the research strategy

The systematic literature review presented in these pages was conducted querying international scientific databases. The main repositories used were Scopus, Web of Science (WOS) and Science Direct. In addition, in order to cover a wider spectrum of scientific high-quality papers, even search engines such as Google Scholar and CiteSeerX have been used.[1]

The search strategy adopted includes articles dealing with procedures, study cases and comparison between devices. To obtain an overview in the geomatic sector, the terms referring to Mobile Laser Scanner system have been used. As first search, the terms 'Mobile Laser Scanner' and 'Mobile Mapping System', provided several papers. Being a review based on the Geomatic sector, a first screening was carried out in five different main domains: Built and urban environment, Cultural heritage and Archaeology, Underground environment, Environmental monitoring, Forestry and Agriculture. Then, a further pre-processing was conducted by including other keywords such as 'LiDAR', 'Mapping', 'Localization', '3 D Scan Technology', '3 D Modelling' in association with 'Point Clouds', 'Accuracy', 'Performance', 'Comparison' which are all related to the research field. Thanks to the search filters provided by the repositories and by the search engines, the keywords previously mentioned were searched in the resulting papers' title, abstract text and keywords. These terms ensured that the search conducted was in line with the technologies and outcomes in Geomatics. Moreover, the publication date was a criterion for choosing the articles to be analysed. Nevertheless, there are a few articles submitted in 2020 but published in early 2021 that have been used to submit a complete literature review on MLS. Once that all the papers were collected, at least two authors carefully read each of them, starting from the title and abstract. Thereafter, the next stage of screening, went through the contents reading. A results and discussions comparison among the selected papers was carried out, giving the possibility to reach a total number of 89 papers obtained from these filter operations.

Thus, accordingly to the search instruction, an example of code used in the Scopus repository was as follows:

```
(TITLE-ABS-KEY (lidar, AND mobile AND laser AND scanner) ) AND (point AND clouds, AND performance) AND (LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010) )
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To assure quality, the majority of the papers selected were based on the reference journals within the Geomatic research community, according to their level of Scimago Quality index and Impact Factor as scientific soundness indicators. However, even international conferences papers were considered because of their relevance in the disclosure of MLS technologies.

Finally, it is worthwhile to underline that, given the multidisciplinary nature of MLS, it would be restrictive to limit the research only to those journals who deal strictly with the Geomatic, so that the research was extended to a wider set of disciplines (even if close to the Geosciences). The articles that were considered incoherent with the research topic and published before the year 2010 were discarded.

5. Results

The goal of this paper is to add awareness to the body of knowledge, highlighting pros and cons of a solution that, despite its proven reliability, might bring to

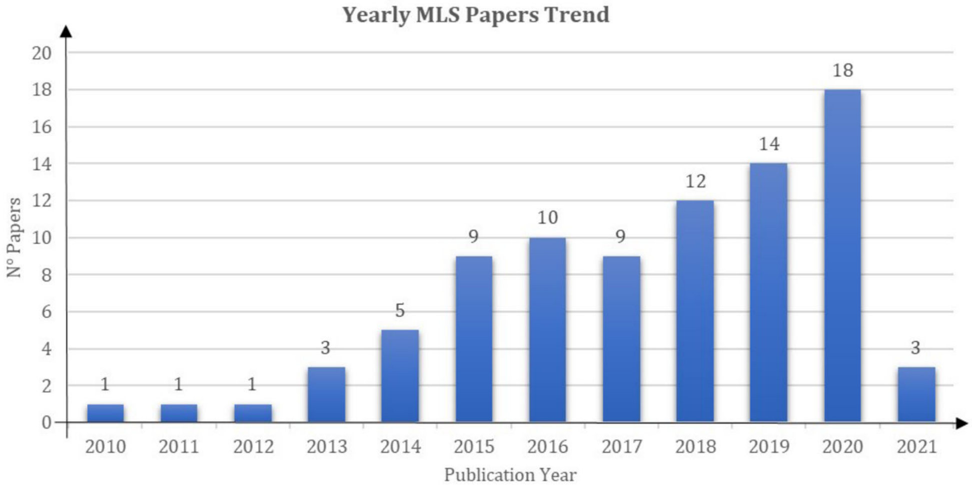

Figure 1. MLS papers annual trend in all the review's domains.

incorrect evaluations. The paper is also aimed at facilitating a more conscious use of the different available MLS systems, thanks to a thorough quantitative comparison made over the published papers and based on the tests conducted by the research group in charge of this review.

Our contributions in this paper are concluded as follows:

- A comprehensive review of existing MLS tools. The classification has been performed according to the support and methodology of field survey. The purpose is to reorder and unify definition and taxonomies which are somehow misleading and in contrast to one another.
- Various scenarios in which MLS have been used. Classification of MLS according to the environment in which they have been used, with the purpose of providing the big picture of the possibilities offered by the systems.
- Analysis of the experimental results. According to some evaluation indicators (e.g. accuracy achieved), the aim is to summarize the results of the obtained data using the different case studies reported in the literature.
- Discussion regarding the disadvantages of existing MLS and future directions. We thoroughly analyse several problems for model design, which need to improve for future research.

5.1. Statistical data

Existing MLS platforms, application domains, accuracy requirements and limitations were examined in the recent literature, considering the period from 2010 to early 2021 which highlights a growing trend on MLS applications (Figure 1). The reasons are attributable to more than one factor. The interest of using MLS in some application fields is growing in the last years as explained in paragraph 5.3. Another important aspect is linked to the cost, which tends to decrease over the years, but mainly the interest increased since MLS is suitable for different scenarios where millimetric

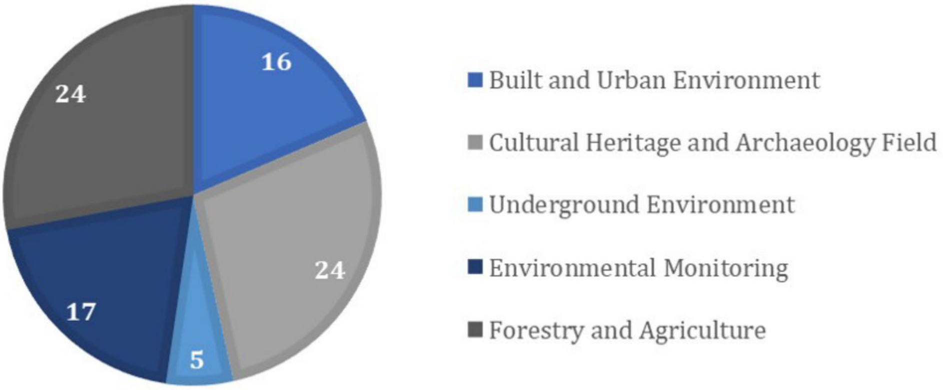

Figure 2. Number of selected papers identified in the 10-year time span within a given domain.

accuracy is not required while the demand for data is always higher in the shortest possible time.

After the selection of the articles based on the keywords search and the time period mentioned above, the next step was to operate a sort of cataloguing by identifying the possible parameters that could help to make subgroups.

Geomatics and therefore the instruments related to this discipline range over different fields of application, so a first classification of the articles was based on the definition of domains. Five domain fields have been identified, namely built and urban environment, cultural heritage and archaeology, underground environment, environmental monitoring, forestry and agriculture (Figure 2).

The terminology *mobile* in the abbreviation MLS alludes to the dynamic mode of use of the LiDAR device, whose movement is guaranteed by the type of platform on which it is installed (Section 3.1). Therefore, a second cataloguing of the same articles was carried out on the definition of the various types of platforms, achieving a categorization as: human-based (hand-held and backpack solutions), wheel-based (trolley-based, devices mounted on road and rail vehicles), boat-based, sledge-based e aerial or airborne (Figure 3). The sum of total number of MLS platforms used in all articles is greater than the total amount of papers since some authors mentioned more than one platform typology.

5.2. Test field domains

Here is a brief definition of the five identified domains within which the articles describing the various MLS applications are grouped:

- ***Built and urban environment***: a broad domain, which includes several applications related to the urban context. Being a domain strongly linked to human activities and human relations, the research carried out were specific to the relative activity and/or relation, focusing especially on buildings indoor, outdoor urban spaces and infrastructures.

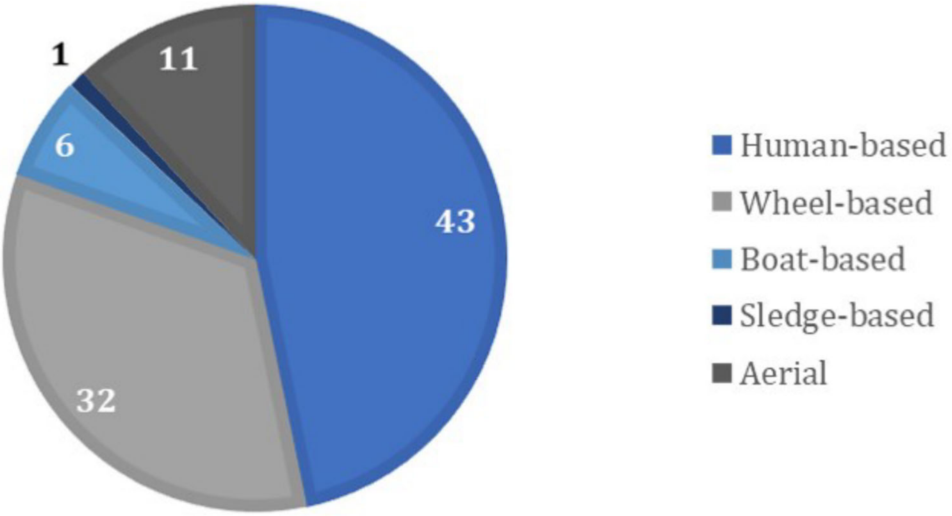

Figure 3. Number of papers attributed to MLS platform typologies.

- ***Cultural heritage and Archaeology field***: a domain facing with 3D documentation and virtual reconstruction of indoor and outdoor environments of historical buildings or complex of buildings, underground built heritage and archaeological sites.
- ***Underground environment***: types of emptied environment by geological processes or anthropogenic actions.
- ***Environmental monitoring***: various types of natural landscapes in which the major natural processes are monitored with the geomatic technologies.
- ***Forestry and Agriculture***: tree metric extraction in both managed or natural forests and smart farming applications (orchards yields).

5.2.1. Built and urban environment

All over the world, urban environments have increased in recent years and nowadays people are moving from rural areas or small villages to cities. The management, conservation and safe use of urban environments are topics of increasingly interest from many points of view. Researchers are studying technologies, systems and services which concern urban environments, both on a large map scale, considering urban elements, and on a small one, studying entire areas of a city. The use of laser scanners, thanks to theirs high precision, responds well to the different needs in urban areas and smart cities, bringing multiple advantages. Three-dimensional analyses can be made, starting from point clouds, which allow a faithful rendering of reality. These data, with an accuracy down to the millimetre-level and a point density of thousands points/m^2, can be used in different city applications, such as urban planning and management (Yanjun Wang et al. 2019), recognition, segmentation of point clouds (Li et al. 2019; H. Wang et al. 2015), classification of urban elements (Balado et al. 2018) and much more. All of these are possible thanks to the rapid data acquisition of the modern MMS tools. By the way, the instrumentation varies according to the application and the main scope since there is no suitable tool for all the needs at the same time for which they are chosen according to performance, cost, conditions of use etc. In this paragraph both the advantages and disadvantages of the MLS tools are considered.

In the last decade, several researchers have developed their own prototype MMSs starting from the lidars available on the market, such as Velodyne VLP-16 or Hokuyo UTM-30LX, to build their own prototypes scanning or mapping system, thus breaking down the economic barriers that are still high for many companies and researchers.

Scanned elements, in urban environment, may vary greatly in size and this is due to the different application areas present. In urban planning, there are rather extensive areas, for example roads or group of buildings. In the majorities of the cases, the systems used are wheel-based and ALS which allow to cover such areas in the shortest time, while 'human-based' cases are rare but still significant. Another example of laser scanner application in urban environment concerns infrastructures (such as roads, bridges or tunnels). In these cases, the detail level required must be very high to study anomalies, such as cracks or structural elements bending (Y. Yan and Hajjar 2021) or damage to the road surface. In the latter, an accurate extraction of roads from MLS is therefore necessary (H. Wang et al. 2015). TLS would be the best choice thanks to its accuracy, but its applicability is not always easy. In sites where MSL with TLS cannot be performed, for safety reasons or just time consuming, the ALS or MLS are proved to be the best solutions.

The applications in urban areas are potentially endless. Indeed, the application can be extended further when dealing with the smart cities paradigm: to collect information on advertising signals in the city (Chiappini et al. 2020), parking monitoring (Bock et al. 2015), evaluation of emergency cases for infrastructures such as tunnels (Leingartner et al. 2016) and much more. In literature there are already a few cases of comparisons of laser scanner tools, specific to the urban environment (C. Wang et al. 2020; Yanjun Wang et al. 2019) and more generally reviews by MLS (I Puente et al. 2013; Servières et al. 2021).

Regarding the urban environment, different MLS applications are carried out in the indoor context. Indeed, several studies have been made in spaces most used by the human being activities and new technologies are focused on studying these structures. The interest in the use of laser scanners in these areas is constantly increasing, especially in case of lack of data or where it is necessary to carry out massive inspections (Otero et al. 2020). Big data acquisition is getting importance for storing, studying and evaluating the state of conservation in the cultural field, but also to study a more innovative nature of semantic mapping for Artificial Intelligence (AI) use (Paolanti et al. 2019) or Building Information Modelling (BIM) (Xiong et al. 2013). Even social studies can be carried out on strategic buildings, supporting schools reopening due to the ongoing global pandemic (Comai et al. 2020).The main MLS tools on the market are almost always usable both indoors and outdoors with their own advantages and disadvantages (Kaijaluoto et al. 2015). Among the major disadvantages there is the impossibility of using those systems provided with GNSS (Shamseldin et al. 2018) and, for this reason, many researchers have worked to develop their own systems capable of operating indoor which are mainly based on methods that involve the use of inertial measurement units (IMU). Different

Table 1. Built and urban environment MLS applications.

Typology	Platform	MLS system	Context	Purposes	Application
Human-based	Hand-held	Kaarta Stencil 2	Industrial zone	Collecting data in urban environment	(Chiappini et al. 2020)
Human-based	Hand-held	GeoSLAM ZEB REVO RT	Building indoor	Automate the reconstruction of building indoors	(Díaz-Vilariño et al. 2017)
Human-based	Hand-held	GeoSLAM ZEB1	Building indoor	Algorithms for the interpretation of interior space using MLS	(Nikoohemat et al. 2018)
Wheel-based	Trolley	NavVis M3			
Human-based	Backpack	GeoSLAM ZEB1	College indoor	Comparison of two systems against a traditional survey workflow	(Thomson et al. 2013)
Wheel-based	Trolley	Viametris i-MMS			
Human-based	Backpack	HERON MS Twin	School indoor	MLS for re-opening of an educational building	(Comai et al. 2020)
Human-based	Backpack	Riegl VZ400	University indoor and outdoor	Evaluation of a backpack MMS	(Lauterbach et al. 2015)
Wheel-based	Road vehicle	Riegl VMX-250	Urban environment	Parking statistics	(Bock et al. 2015)
Wheel-based	Road vehicle	Riegl VMX-450 Trimble MX2 MLS	Infrastructures	Road detection	(Yang et al. 2017)
Wheel-based	Road vehicle	Optech Lynx Mobile Mapper	Infrastructures	Detect and classify urban ground elements	(Balado et al. 2018)
Wheel-based	Road vehicle	RIEGL VUX-1HA	Infrastructures	Detect road furniture	(Li et al. 2019)
Wheel-based	Road vehicle	RIEGL VMX-450	Infrastructures	Accurate extraction of roads	(H. Wang et al. 2015)
Wheel-based	Road vehicle	FARO Photon 120	Urban environment	Urban and geomorphology mapping	(Kukko et al. 2012)
	Trolley	FARO Photon 120			
Boat-based	Boat	FARO Photon 80			
Wheel-based	Robot	Velodyne HDL-64E	Infrastructures	MLS in disaster situation	(Leingartner et al. 2016)
Wheel-based	Trolley	FARO Focus3D X330 FARO Focus3D 120S	Building indoor	Level of trajectory accuracies with high quality sensors	(Kaijaluoto et al. 2015)
Wheel-based	Trolley	Kaarta Stencil 2	Retail indoor	Semantic 3 D object recognition	(Paolanti et al. 2019)
Aerial	ALS	Velodyne VLP-16	Infrastructures	Detection and extraction of bridge elements	(Y. Yan and Hajjar 2021)

Table 2. Built and Urban Environment MLS accuracies.

Application	Context	MLS system	Ground Truth	Point cloud evaluation	Accuracy assessment
(Chiappini et al. 2020)	Industrial area of Brescia	Kaarta Stencil 2	Photogrammetry	Cloud-To-Cloud	RMSE = 34 cm
(Thomson et al. 2013)	UCL college indoor	GeoSLAM ZEB1	TLS FARO Focus3D	ICP alignment	Mean = 3.2 cm
		Viametris i-MMS			Mean = 2.6 cm
(Lauterbach et al. 2015)	University of Wurzburg indoor and outdoor	RIEGL VZ400	iSpace positioning system	Modified ICP algorithm	Up to 2.9 cm
(Bock et al. 2015)	Urban environment	RIEGL VMX-250	Camera	Object based alignment	15 cm
(Kukko et al. 2012)	Urban and environmental	FARO Photon 120	Target surveyed by GNSS antenna	Distance between target surveyed and MLS	RMSE = 20 mm
(Kaijaluoto et al. 2015	Building indoor	FARO Focus 3 D X330 FARO Focus 3 D 120S	TLS FARO Focus X330	Cloud-To-Cloud	RMSE = 17mm
Y. Yan and Hajjar 2021	Infrastructures	Velodyne VLP-16 on UAV	TLS	ICP	0.08 m

List of abbreviations: TLS = Terrestrial Laser Scanner; GNSS = Global Navigation Satellite System; ICP = Iterative Closest Point; RMSE = Root Mean Square Error.

prototype applications can be found in the modern literature, such as: (Fu et al. 2012; Nüchter et al. 2015; Filgueira et al. 2016; Zhao et al. 2018; Karam et al. 2019). The indoor MMS, often referred in literature as iMMS or i-MMS (Thomson et al. 2013), or Indoor Mobile Laser scanner (IMLS) (Nikoohemat et al. 2018) is mostly human-based. The latter can be split into hand-held, backpack, or trolley. Wheel-based are also defined as those systems mounted on robots or remotely controlled vehicles. ALS systems are almost impossible to use in indoor while TLS systems, which are among the most performing laser scanners but also the most expensive, are integrated with trolleys.

Based on these statements concerning the built and urban environment, it is easy to understand that there is not a standard solution for all the case studies but the MLS, technology and use method, must be chosen according to the specific requirements of the environment and needs. In the Table 1, some significant MLS applications in this domain are listed.

In the Table 2, it is possible to observe the accuracies values obtained by the different researchers in their studies. The Build and Urban Environment accuracies are obtained from the experimental use of an MLS instrument compared to the point cloud obtained from TLS or from known points identified in the surrounding environment through manual measurement. The algorithm employed to minimize the difference between two point clouds is known as Iterative Closest Point (ICP), while the distance between the points is calculated by the Cloud to Cloud distance computation. Both can be processed in CloudCompare, the most widespread software cited in the literature. The accuracy required in built and urban domain may vary a lot. Whether the point cloud required is intended for research activities at urban scale, there are no doubt that MLS fulfils its task even when the errors are 'big' of the order of 0,5 m. Instead, a high accuracy is required when monitoring infrastructures, for instance, inspection or management purposes of bridges and its elements. In this case the use of TLS guarantees an accuracy level up to 2 mm which will be used in combination of MLS. The examples below give a clear idea of how much the accuracy may vary according to the scope of application and the instruments in use.

5.2.2. Cultural heritage and archaeology field

Historic artefacts and archaeological sites, belonging to the cultural heritage domain, should be preserved as cultural legacy and common heritage. The Charter of Krakow is the most recent document defining the principles for conservation and restoration of built heritage (ICOMOS 2000). Considering the definition of the Outstanding Universal Value (UNESCO 1972), all the information available about a historical artefact are useful to allow a widespread reconstruction, interpretation, conservation and dissemination for future generations. Tangible cultural heritage, particularly immovable assets, is the main subject of application in the new methodological approaches. Furthermore, cultural heritage is threatened by various factors such as natural hazards, vandalism, development of cities, and aging, which in a pragmatic view means that their eternity cannot be guaranteed, and the possibility of their loss always exists (Hassani 2015).

Table 3. Cultural heritage and archaeology field MLS applications.

Typology	Platform	MLS system	Context	Purposes	Application
Human-based	Hand-held	CSIRO Zebedee	Indoor and outdoor of building complex (old lazaret)	Conservation monitoring and documentation	(Zlot et al. 2014)
Human-based	Backpack	Leica-Geosystem Pegasus	Roman Circus	historical and archeological urban studies	(Macias Solé et al. 2017)
Human-based	Hand-held	GeoSLAM ZEB REVO RT	Indoor of medieval castle	Hybrid 3 D model	(Chiabrando et al. 2019)
Human-based	Backpack	GeoSLAM ZEB REVO RT	Indoor of XV century palace	Mapping and digitalization heritage site	(di Filippo et al. 2018)
Human-based	Hand-held	GeoSLAM ZEB 1 GeoSLAM ZEB REVO	Indoor of cylindrical tower; old mining cave; castle courtyard	Evaluation and effectiveness of SLAM-based MMS	(Sammartano and Spanò 2018)
Human-based	Hand-held	GeoSLAM ZEB 1	Indoor of cathedral	Test field in narrow spaces	(Mandelli et al. 2017)
Human-based	Hand-held	GeoSLAM ZEB 1	Underground built environment	3D documentation and modeling	(Farella et al. 2016)
Human-based	Hand-held	Kaarta Stencil 2	Ancient city walls	3D documentation and reconstruction for HBIM	(Di Stefano, Chiappini, et al. 2020)
Human-based	Backpack	Leica-Geosystem Pegasus	Indoor and outdoor of a historical hydro technical development	3D documentation, restoration and renovation activities	(Șmuleac et al. 2020)
Human-based	Backpack	Leica-Geosystem Pegasus	Indoor and outdoor of fort defensive structures	3D reconstruction, conservation interventions	(Fassi and Perfetti 2019)
Human-based	Hand-held	Kaarta Stencil 2	Indoor of church and cloister	3D reconstruction for VR-AR and HBIM modelling	(Bronzino et al. 2019)
Human-based	Hand-held	GeoSLAM ZEB REVO	Indoor of a baroque chapel	3D documentation through integration of active sensors	(Barba et al. 2019)
Human-based	Hand-held	GeoSLAM ZEB REVO	Outdoor of historical building complex	3D documentation	(Patrucco et al. 2019)
Human-based	Backpack	Leica-Geosystem Pegasus	Indoor of a Reinassance palace	3D digital model for CH management and fruition	(Nespeca 2018)
Human-based	Hand-held Backpack Hand-held	Kaarta Stencil 2 Leica-Geosystem Pegasus GeoSLAM ZEB REVO	Indoor and outdoor in a fortress and a chapel	A comparative procedure of three commercial MMS	(Tucci et al. 2018)
Human-based	Hand-held	Kaarta Stencil 2	Roman amphitheatre	3D documentation, test field	(Malinverni et al. 2018)

(*continued*)

Table 3. Continued.

Typology	Platform	MLS system	Context	Purposes	Application
Wheel-based	Rail vehicle	Z + F Imager 5010c	Bas-reliefs	historical analysis, decay analysis, preservation, VR tour	(Zheng et al. 2015)
Wheel-based	Road vehicle	GeoTracker	Ring-fort	3D digital documentation	(Viberg and Larson 2015)
Wheel- based	Road vehicle	RIEGL VMX-450	Old door in a Roman city	3d reconstruction; comparison with other geomatics techniques	(Studnicka et al. 2013)
Wheel- based	Road vehicle	RIEGL VZ-400	Archeological site	Robotic mapping	(Borrmann et al. 2015)
Wheel- based	Road vehicle	Optech Lynx Mobile Mapper	Roman bridge	NDT (non-destructive testing) documentation	(Puente et al. 2015)
Wheel- based	Road vehicle	Optech Lynx Mobile Mapper	City walls	3D recording and reconstruction	(Rodríguez-Gonzálvez et al. 2017)
Aerial	ALS	Leica ALS50II	pre-Columbian settlement	3D mapping topography	(Vilbig et al. 2020)
Aerial	UAV	RIEGL VUX-1	Mound villages	3D mapping topography	(Iriarte et al. 2020)

Table 4. Cultural Heritage and Archaeology field MLS accuracies.

Application	Context	MLS system	Ground Truth	Point Cloud evaluation	Accuracy assessment
(Chiabrando et al. 2019)	Indoor of medieval castle	GeoSLAM ZEB REVO RT	TLS FARO Focus 120	Cloud-To-Cloud	MAE $<$ 2 cm, no filter MAE $<$ 1 cm, noise filter
(Farella et al. 2016)	Underground built environment	GeoSLAM ZEB 1	Total Station TOPCON GPT 7001i	Topographic network	Mean RMSE = 1.3 cm segmented point cloud
(Di Stefano, Chiappini, et al. 2020)	Ancient city walls	KAARTA Stencil 2	UAV CRP DJI Spark MMA1	Cloud-To-Cloud	Mean RMSE = 10 cm
(Bronzino et al. 2019)	Indoor of church	KAARTA Stencil 2	TLS FAROCam2 Focus 3 D	Cloud-To-Cloud	RMSE = 7.4 cm real-time RMSE = 5.9 cm post-processed
(Barba et al. 2019)	Chapel	GeoSLAM ZEB REVO	TLS Faro Focus S350	Cloud-To-Cloud	MAE $<$ 2 cm
(Patrucco et al. 2019)	Outdoor of historical building complex	GeoSLAM ZEB REVO	UAV CRP DJI Mavic Pro	ICP alignment	MAE = 3.7 cm
			TLS Faro Focus3D S 120	Cloud-To-Cloud	MAE = 2.2 cm
(Tucci et al. 2018)	Indoor and outdoor in a fortress (path 1)	KAARTA Stencil 2	TLS Z + F 5010 C	ICP alignment	RMSE = 5 cm
		Leica-Geosystem Pegasus Backpack			RMSE = 6 cm
		GeoSLAM ZEB REVO			RMSE = 4 cm

List of abbreviations: TLS = Terrestrial Laser Scanner; UAV = Unmanned Aerial Vehicle; CRP = Close-Range Photogrammetry; ICP = Iterative Closest Point; MAE = Mean Absolute Error; RMSE = Root Mean Square Error.

A structured digital 3 D model as part of the architectural heritage improvement process is an urgent need, nowadays. Moreover, the digital 3 D model must be converted into a crucial reference frame for the understanding and monitoring of documentation (Penttila et al. 2007).

Over the last decades, innovative 3 D digitisations and geomatics techniques, as non-invasive technologies, has entered the field of cultural heritage, mainly to meet the needs of documentation, management and protection. The aim is to ensure that the information regarding the significant historical characteristics (shape, appearance) of a cultural heritage entity will be reserved in case of natural or other damages (Gomes et al. 2014).

Specifically, carrying out a three-dimensional survey of cultural heritage objects with geomatic instruments, in particular range sensors, makes it possible to achieve the following objectives (3D *Laser Scanning for Heritage* 2011):

- 3D reconstruction, documentation, data source for restoration, conservation and preservation interventions and activities;
- design of 3D parametric surfaces and meshes through reverse modelling, direct modelling or generative modelling operations;
- spatial analysis and management through information system of the achieved 3D geometrical models for further applications (HBIM or 3DGIS);
- detailed archivable record, condition analysis and structural monitoring in case of changes over time due to forms of degradation or damage resulting from risk situations by anthropological and natural actions;
- digital inventories and sharing for education, research or tourism purposes and also improving accessibility, knowledge and understanding.

MLS point clouds may represent a base material for professional figures working in the field of cultural heritage such as conservators, architects, restorers, archaeologists and so on. This is the reason why laser scanners have become common in the heritage field (Remondino 2011). Despite the millimetric accuracy achieved using stationary TLSs, they do not always guarantee speed or completeness of survey and so cannot always operate in an efficient way, particularly in critical or difficult-to-access environments. This is where the MLS comes in, which, thanks to its use in dynamic mode can be defined as a fast and agile survey solution.

In CH, depending on the type of context, the degree of accuracy and the level of detail, mobile devices are used in different ways. Thanks to the versatility and handiness of portable devices such as hand-held and backpack, it is possible to survey any type of environment in a very short time by making short and closed paths. These are mainly used in indoor environments of historical buildings, underground built heritage or to detect outdoor environments where it is not possible to operate with wheel-based Laser Scanner for different factors such as restricted access for reasons of cultural heritage safeguard or the presence of narrow passages to cross. When it is necessary to detect objects along a long perimeter such as bas-reliefs or large-scale cultural heritage sites or objects such as the ancient walls of a city or artefacts in archaeological sites, the wheel-based solution is more likely to be adopted with MLS system, composed by TLS used in kinematic manner, on rails or mounted on trolley or vehicles that travel long or medium distances in the vicinity of the object of interest.

Aerial or airborne laser scanners are used here to survey very large areas of land at various altitudes where remains of ancient cities, mound complex or archaeological sites can be identified, allowing the possibility of creating a topographic and semantic mapping of the identified objects (Campana 2017).

The different typologies of use based on the platform of the mobile device are classified according to the type of context and thus the environment in which it is adopted. Environments have been identified as those indoor and outdoor of a historical building or complex of buildings, underground sites with an anthropogenic nature of historical value (Underground Built Heritage – UBH), and mostly open-air archaeological sites. The Table 3 summarizes the most relevant case studies where MLS was chosen for survey purposes in the cultural heritage field.

In the previous table, only MLSs applied in the various contexts are reported, but in the field of cultural heritage, in order to have a completeness of data of the cultural object or context to be acquired, techniques of integration of geomatic instruments are often used. In addition to MLS, TLS and photogrammetry, mainly aerial, are also managed, whose data are then combined to enrich the level of detail and information of the final three-dimensional model. The degree of accuracy of MLS-generated point clouds is often compared with TLS-generated point clouds. The difference between TLS and MLS is also found in the final accuracy value. While TLS guarantees millimetre-scale accuracy, the point clouds generated by mobile scanners have a mean value up to one centimetre. This value is then confirmed after the Cloud-To-Cloud or Iterative Closest Point (ICP) analysis operations between TLS and MLS point clouds, which report an average accuracy value of the latter generally lower than 10 cm. In addition to the TLS, point clouds processed after an aerial photogrammetry survey or by comparing the distance between points with targets detected with a topographic survey can be used as ground truth for verifying the accuracy of MLS-generated point clouds. Table 4 below reports some case studies where the accuracy analysis of point clouds from MLS is listed in the field of cultural heritage.

5.2.3. Underground environment

This section is devoted to that type of underground environment which has been emptied by natural processes (caves) or anthropogenic actions (mines, quarries, tunnels). Three-dimensional survey of cavities created by geological and geo-mechanical phenomena are objects of both research and monitoring study, e.g. collapse hazard (Zlot and Bosse 2014; Dewez et al. 2017). The need for accurate spatial data is also essential in underground space utilization to ensure the safety, void control, and efficiency of extraction operations (Eyre et al. 2016). Mapping large-scale underground environments, such as caves, mines and tunnels is typically a time consuming and challenging benchmark. Existing techniques utilizing 3 D terrestrial scanners mounted on tripods rely on accurate surveyed sensor positions and are relatively expensive and inefficient. Mobile mapping solutions have the potential to achieve coverage and

Table 5. Underground environment MLS applications.

Typology	Platform	MLS system	Context	Purposes	Application
Human-based	Hand-held	CSIRO Zebedee	Cave	3D mobile mapping and surface reconstruction	(Zlot and Bosse 2014)
Human-based	Hand-held	NavVis-3D	Coal Mine	3D mineral environment modeling and positioning	(Chen et al. 2017)
Human-based	Hand-held	CSIRO Zebedee	Quarry	3D mobile mapping	(Dewez et al. 2016)
Human-based	Hand-held	GeoSLAM ZEB 1 GeoSLAM ZEB REVO GeoSLAM ZEB 40-Hz REVO	Mining	Evaluation of automated underground mapping solutions	(Eyre et al. 2016)
Human-based	Hand-held	GeoSLAM ZEB REVO	Quarry	Cavity-collapse hazard maps	(Dewez et al. 2017)

Table 6. Underground environment MLS accuracies. List of abbreviations: *TLS = Terrestrial Laser Scanner.*

Application	Context	MLS system	Ground Truth	Point Cloud evaluation	Accuracy assessment
(Chen et al. 2017)	Coal mine	NavVis-3D	Field measurement	Comparison of distance measurement	Approx. 5 cm (difference)
(Eyre et al. 2016)	Mining	GeoSLAM ZEB 1 GeoSLAM ZEB REVO GeoSLAM ZEB 40-Hz REVO	TLS Leica HDS6000	Cloud-To-Cloud under deviation comparison	50% of the data <15.6 mm 50% of the data < 16.8 mm 50% of the data < 19.7 mm
(Dewez et al. 2017)	Quarry	CSIRO Zebedee	electronic distance meter Leica Disto D210 electronic distance meter Bosch PLR-30	Distance measurement validation	Distance accuracy better than 3 mm over a 30 m distance (that is, 1/10 000 relative accuracy)

mapping more accurately and completely (Table 5). Handheld laser scanners enable faster complete dimensioning of cavities with gallery width, height, volume of voids, location of voids with respect to assets above ground and thickness of the overburden.

Underground contexts are typically challenging environments for 3D mapping, because they are dark, wet, dusty, have limited lines of sight. They are also GPS-denied areas. As the Table 6 resumes, the accuracies of survey in underground environment are evaluated under distance computation trough Cloud-To-Cloud algorithm comparing with TLS point cloud or taking as ground truth geometric dimensions manually measured.

5.2.4. Environmental monitoring

In recent decades, advanced monitoring technologies have spread and increasingly been used for the study and management of geological hazard and risk, which may

Table 7. Environmental monitoring MLS applications.

Typology	Platform	MLS system	Context	Purposes	Application
Human-based	Hand-held	GeoSLAM ZEB 1	Coastal cliff, gullies	cliffs erosion	(James and Quinton 2014)
Human-based	Backpack	ROAMER – AkhkaMMS – FARO Photon 120	Fluvial sediment	3D Modelling of Coarse Fluvial Sediments	(Yunsheng Wang et al. 2013)
Human-based	Backpack	ROAMER – AkhkaMMS – FARO Photon 120	Riverine topography	erosion change dectection mapping	(Vaaja et al. 2011)
Wheel-based	cart	ROAMER – CartMMS – FARO Photon 80			
Boat-based	boat	ROAMER – BoMMS - FARO Photon 80			
Human-based	Backpack	Leica-Geosystem Pegasus	Fluvial sediment	3D reconstruction of fluvial surface sedimentology and topography	(Williams et al. 2020)
Human-based	Hand-held	KAARTA Stencil 2	Landslide	deformation monitoring of slope stability	(Di Stefano, Cabrelles, et al. 2020)
Human-based	Hand-held	CSIRO Zebedee	Land	landform mapping and slope investigation	(So et al. 2015)
Human-based Wheel-based	Hand-held Road vehicle	Phoenix AL3-32	Landslide	slope monitoring in urban area	(Ahmad Fuad et al. 2018)
Wheel-based	UGV	LMS511-10100	Coast	monitoring coastal zones	(Kurkin et al. 2016)
Wheel-based	road vehicle	Optech ILRIS 3DMC	Coast	sandy coastal foredune monitoring	(Lim et al. 2013)
Wheel-based	road vehicle	SITECO Road-Scanner3 – FARO Focus S 70, FARO Focus S 150	Coast	mapping of sandy coastal foredunes	(Nahon et al. 2019)
Wheel-based	road vehicle	RIEGL VZ-400	Coast	dune erosion; foredune recovery	(Donker et al. 2018)
Boat-based	motorboat	MDL DYNASCAN M150	River	erosion hydroelectric reservoirs	(De Moraes et al. 2016)
Boat-based	boat	RIEGL VMZ-400	Coast	Erosion, landslide of coastal cliff	(Ossowski and Tysiąc 2018)
Boat-based	boat	Optech Ilris Long Range	Coast	rockfall detection, landslide of coastal cliff	(Michoud et al. 2014)
Wheel-based	road vehicle	Leica-Geosystem Pegasus SM70; RIEGL MSLVZ400; TOPCON IP-S2.	Coast	surveying of complex coastal sites	(Liuzzo et al. 2019)

(*continued*)

Table 7. Continued.

Typology	Platform	MLS system	Context	Purposes	Application
Boat-based	boat	Leica Pegasus SM70 RIEGL VZ400 TOPCON IP-S2			
Sledge-based	sledge	ROAMER – FARO Photon 120	Snowed environment	snow cover profiling	(Kaasalainen et al. 2010)
Aerial	UAV	Velodyne VLP-32C	Coast	mapping coastal environment	(Lin et al. 2019)

compromise, in some cases, the state of preservation of civil infrastructure (James and Quinton 2014). Monitoring actions are necessary to guarantee health and safety conditions by controlling the evolution of deformation patterns or detecting significant instabilities. Geological applications, for example, geo-hydrological risk assessment, rockfall runout modelling, or slope stability analysis, can have a great benefit through non-destructive investigation (Kukko et al. 2012). In terms of spatial and temporal resolution, the improvement of range-based techniques represents a significant achievement. These methods provide innovative tools in supporting mapping products and geological and geo-mechanical analysis required for assessment and evaluation.

Accurate mapping and monitoring of different natural environment analysis are critical tasks to which several techniques have been used, from aerial photographs, remote sensing, land surveying, Close-Range Photogrammetry and, more recently, Terrestrial Laser Scanning (TLS) and Mobile Laser Scanning (MLS). These latter technologies are in principle advantageous because of their good accuracy, easiness of use and lower time of response (Jaboyedoff et al. 2012). For the completion of existing surveys in particular, MLS was considered the most suitable alternative for the challenges established in the project requirements, concerning productivity, sample density and final costs. In particular, Mobile Mapping System technology allows users to reach complex, enclosed spaces by scanning by hand or by attaching a scanner to a trolley, a drone or by mounting it on a pole. As a result, the variety of diffuse environments to be detected becomes wider. In addition, the MLS's SLAM technology solves the problem associated with GNSS-based systems where it does not work well in complex natural environments, where tree canopies hamper the signal to be received.

In places with complex topography, the use of MLS, following a continuous path, is more advantageous than a tripod-based laser scanner that requires multiple scan positions to cover all the areas of the survey (Tommaselli et al. 2014). MLS data processed allow giving an added value and greater richness of the acquired data providing a high detailed Digital Elevation Model (DEM) or Digital Terrain Model (DTM) of the selected area (Lindenbergh and Pietrzyk 2015).

Alternative purposes to use mobile LiDAR technologies, in addition to the assessment of the geometrical state, concern change detection, deformation analysis (D'Aranno et al. 2019), hazard assessment and structural and infrastructural health monitoring (Francioni et al. 2015) in different types of natural environment. In technical terms, mobile mapping solutions contemporaneously allow users to acquire geometrical aspects for geological studies and geomorphological analysis, to operate mapping of all the elements present in the detected area (e.g. vegetation, road, etc.), and to define basic modelling for monitoring operations (e.g. rockfalls, coastal erosion, river dynamics, etc.). Mobile laser scanning could also provide validation for satellite analysis snow covered area estimation, especially in forested areas, where the snow forest interaction is increasingly important for hydrological and climate models (Kaasalainen et al. 2010).

Direct topographic, bathymetric reconstruction and large spatial coverage are ensured with aerial or airborne laser scanner.

Table 8. Environmental monitoring MLS accuracies.

Application	Context	MLS system	Ground Truth	Point Cloud evaluation	Accuracy assessment
(James and Quinton 2014)	Coastal cliff	GeoSLAM ZEB 1	TLS Riegl VZ-1000	Cloud-To-Cloud	MAE = 20.2 mm
(Yunsheng Wang et al. 2013)	Fluvial sediment	ROAMER – AkhkaMMS - FARO Photon 120	Field Measurement	Measurement of Sediment Particles	Good achievement in boulders and cobbles modelling (particle size above 63 mm); Not so good achievement for medium gravels (particle size 10-20 mm)
(Vaaja et al. 2011)	Riverine topography	ROAMER – AkhkaMMS - FARO Photon 120	TLS Leica HDS6000	DEM comparison	Std. Dev. Error = 3.4 cm
(Williams et al. 2020)	Fluvial sediment	Leica-Geosystem Pegasus	GNSS system Leica GS10	Topographic verification	MAE = 7.1 cm RMSE = 7.5 cm
			TLS Riegl VZ-1000	Cloud-To-Cloud	MAE = 7.95 cm
(Di Stefano, Cabrelles, et al. 2020)	Landslide	KAARTA Stencil 2	CRP Canon EOS D5 Mark II	ICP Cloud-To-Cloud	MAE = 5.6 cm Std.dev.= ±2.3 cm
(Lim et al. 2013)	Coast	Optech ILRIS 3DMC	GNSS system (not defined)	Topographic network	Distances: 6 cm east 9.5 m north 5.3 m height
(Donker et al. 2018)	Coast	RIEGL VZ-400	GNSS system (not defined)	Topographic network	RMSD = 3 cm <1m distance RMSD = 8 cm >70m distance
(Lin et al. 2019)	Coast	Velodyne VLP-32C	UAV Photogrammetry Sony Alpha 7R	Cloud-To-Cloud (elevation difference)	MAE = 2 cm Std.dev.= ±6.5 cm

List of abbreviations: TLS = Terrestrial Laser Scanner; UAV = Unmanned Aerial Vehicle; CRP = Close-Range Photogrammetry; DEM = Digital Elevation Model; ICP = Iterative Closest Point; MAE = Mean Absolute Error; Std.Dev = Standard Deviation; RMSE = Root Mean Square Error; RMSD = Root Mean Square Difference.

Table 9. Forestry and agriculture MLS applications.

Typology	Platform	MLS system	Context	Purposes	Application
Human-based	Backpack	GeoSLAM ZEB REVO RT	Coniferous forest	Inventory	(Shilin et al. 2019)
Human-based	Backpack	GeoSLAM ZEB REVO RT	Coniferous forest (urban area vs rural area)	Inventory	(Cabo et al. 2018)
Human-based	Backpack	GeoSLAM ZEB1	Coniferous forest	Inventory	(Bauwens et al. 2016)
Human-based	Hand-held	GeoSLAM ZEB1	Pure sweet chestnut stand	Inventory and monitoring	(Perugia et al. 2019)
Human-based	Backpack	Velodyne VLP-16	Forest	Mapping	(J. Shao et al. 2020)
Human-based	Hand-held	GeoSLAM ZEB HORIZON	Forests	Inventory	(Gollob et al. 2020)
Human-based	Backpack	LiBackpack DG50	Apple trees orchard	Tree branch info	(Zhang et al. 2020)
Human based	Hand-held	Velodyne VLP-16	Coniferous forest	Inventory	(Jie Shao et al. 2020)
Human-based	Hand-held	CSIRO Zebedee	Mango orchard	Measuring light interception	(Westling et al. 2020)
Wheel-based	ATV	FARO Focus 3D X330	Coniferous forest	Inventory	(Qian et al. 2016)
Wheel-based	ATV	FARO Focus 3D X330	Coniferous forest	Modeling and inventory	(Kukko et al. 2017)
Wheel-based	Robot	Velodyne VLP-16	Coniferous forest	Monitoring	(Pierzchała et al. 2018)
Wheel-based	Road vehicle	SICK LMS 511	Coniferous Forest	Mapping	(Forsman et al. 2016)
Wheel-based	Robot	Sick LMS 511	Olive trees	Inventory	(Auat Cheein and Guivant 2014)
Wheel-based	Utility vehicle	Velodyne VLP-16	Apple trees orchard	Precise Spray Application	(Sultan Mahmud et al. 2021)
Wheel-based	Robot	Velodyne VLP-16	Begonia fruit tree orchard	Tree branch and tree metric info	(Zhou et al. 2021)
Wheel-based	Motorbike	FARO Focus X130	Urban Trees	Inventory, crown volume	(Z. Yan et al. 2019)
Aerial	Helicopter	Optech ALTM Orion M300	Coniferous forest	Inventory	(Moe et al. 2020)
Aerial	Airplane	Trimble Harrier 68i/G1	Forest plantation	Estimation of canopy volume	(Verma et al. 2016)
Aerial	Airplane	RIEGL VQ-1560i-DW	Dense Uneven-Aged	Fire management	(Stefanidou et al. 2020)
Aerial		Optech ALTM 3100	Old growth forest	Inventory	(Ferraz et al. 2016)
Aerial	UAV	Velodyne Ultra Puck	Forest plantation	Inventory	(Corte et al. 2020)
Aerial	UAV	KAARTA Stencil 2	Boreal forest	Inventory	(Hyyppä et al. 2020)
Aerial	UAV	RIEGL LMS-Q560	Tropical forest	Inventory	(Jörg et al. 2020)

The examples described by the literature (Table 7) are various, depending on natural effects as geological and atmospheric actions or anthropogenic consequences of the built environment which compromise the stability of the natural landscape.

Table 10. Forestry and agriculture MLS accuracies.

					Accuracy Assessment		
Application	Context	MLS System	Ground Truth	Point Cloud Evaluation	Point Cloud Features	RMSE	BIAS
(Shilin et al. 2019)	Coniferous forest	GeoSLAM ZEB REVO RT	Field Measurement	Statistical analysis	DBH (cm)	1.62	−1.19
(Cabo et al. 2018)	Coniferous forest (urban area vs rural area)	GeoSLAM ZEB REVO RT	TLS FARO Focus3D	Statistical analysis	DBH (m) Tree Height (m)	0.011 1.340	– –
(Bauwens et al. 2016)	Coniferous forest	GeoSLAM ZEB1	TLS FARO Focus 3D 120	Statistical analysis	DBH (cm)	1.11	−0.08
(Perugia et al. 2019)	Pure sweet chestnut stand	GeoSLAM ZEB1	Field Measurement	Statistical analysis	DBH (cm) Tree Height (m)	1.28 2.15	2.06 −4.61
(Gollob et al. 2020)	Forests	GeoSLAM ZEB HORIZON	Field Measurement	Statistical analysis	DBH (cm)	2.87	−0.48
(Jie Shao et al. 2020)	Coniferous forest	Velodyne VLP-16	TLS RIEGL VZ-1000	Statistical analysis	DBH (m)	0.01	0.001
(Pierzchała et al. 2018)	Coniferous forest	Velodyne VLP-16	Field Measurement	Statistical analysis	DBH (cm)	2.38	–
(Zhou et al. 2021)	Begonia fruit tree orchard	Velodyne VLP-16	Field Measurement	Statistical analysis	DBH (m) Tree Height (m)	0.004 0.028	0.013 0.038
(Moe et al. 2020)	Coniferous forest	Optech ALTM Orion M300	Field Measurement	Statistical analysis	Tree Height (m)	1.35	−0.05
(Verma et al. 2016)	Forest plantation	Trimble Harrier 68i/G1	Field Measurement	Statistical analysis	Tree Height (m)	1.44	–
(Corte et al. 2020)	Forest plantation	Velodyne Ultra Puck	Field Measurement	Statistical analysis	DBH (cm) Tree Height (m)	3.46 1.51	−0.39 −0.69
(Hyyppä et al. 2020)	Boreal forest	KAARTA Stencil 2	TLS	Statistical analysis	DBH (%)	2.3	1.3

List of abbreviations: TLS = Terrestrial Laser Scanner; DBH = Diameter at Breast Height; RMSE = Root Mean Square Error.

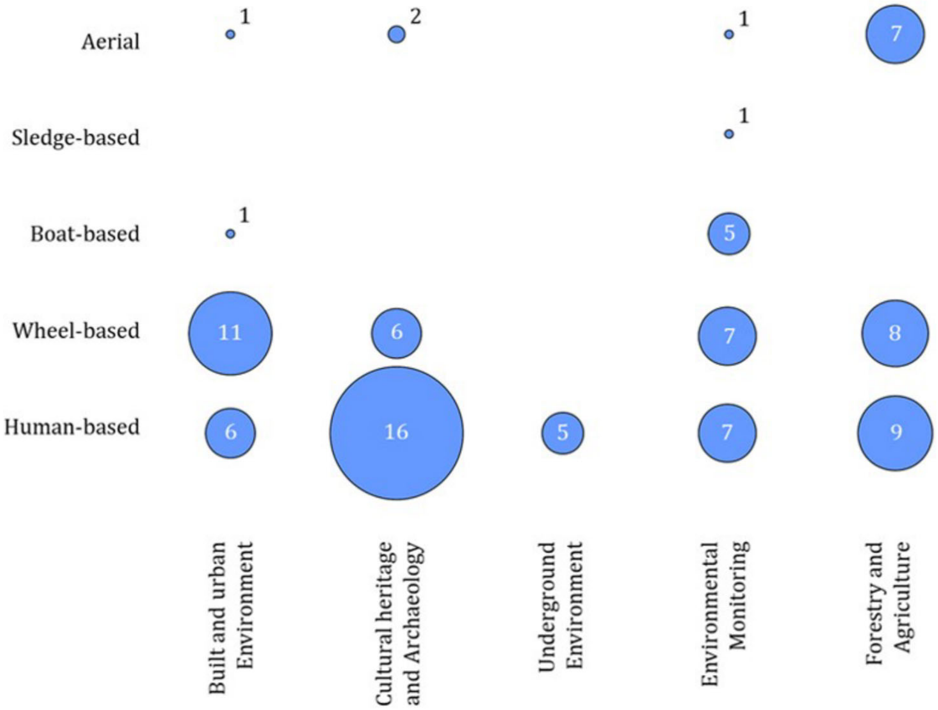

Figure 4. Relation between the platform's typologies and the test field domains.

In the field of environmental monitoring, MLS systems are representing an advantageous surveying technique due to the topographical complexity, the difficulty of access, and the characterisation of very large areas of the contexts examined. A quick survey method is often convenient for geological, geomechanical, geotechnical and geomorphological studies due to both versatility of use of MLS and its adaptability to any support platform. When centimetre-level topographic data is required over distances of the order of tens or hundreds of metres, MLS is a valid tool for such surveying purposes for environmental monitoring. This final accuracy value is then compared with a ground truth represented by a TLS point cloud or aerial photogrammetry or by computation of the distance to points in the topographic network. In some cases, when the lower degree of accuracy of the MLS is to be tested, a comparison analysis with measurements made in the field or in the laboratory is used, such as the case of sediment classification of water basins. In the latter case the degree of accuracy of the MLS does not fully satisfy the identification of the different particle size components of the sediment, but it does recognise those with a diameter greater than 20 mm.

The Table 8 describes the degree of accuracy of MLS relative to examples of environmental monitoring and it can be seen how the value varies from case to case.

5.2.5. Forestry and agriculture

Nowadays, ecosystems and natural resources have a priceless value for human beings. The major issues of the modern world are related with the climate change, with the food scarcity and with the demographic growth. The urban areas are expanding year by year and the green ones need to be managed properly. Continuous technological

Table 11. Technical specification of mobile laser scanner (MLS).

	Laser Unit									Added Components		
MLS system	Scanner	N. Sensors	Measuring Principle	Maximum range [m]	Range precision [mm]	Range accuracy [mm]	Scan rate [points/s]	Laser wave-length	FOV	IMU	Processor	Camera [Image resolution]
KAARTA Stencil 2-16	Velodyne VLP-16	16	ToF	100	N/A	30	300,000	NIR	360° H 30° (±15°) V	MEMS	Intel NUC i7 Quad Core	feature tracker [640 × 360]
CSIRO ZEBEDEE	Hokuyo UTM-30LX	1	ToF	30 indoor 15 outdoor	N/A	30	43,000	NIR	360° H 270° V	MEMS	N/A	GoPro
GeoSLAM ZEB1	Hokuyo UTM-30LX	1	ToF	30 indoor 15 outdoor	30 @10m 50 @30m	30	43,000	NIR	360° H 270° V	MEMS	N/A	N/A
GeoSLAM ZEB REVO	Hokuyo UTM-30LX	1	ToF	30 indoor 15 outdoor	30 @10m 50 @30m	30	43,000	NIR	360° H 270° V	MEMS	N/A	ZEB Cam GitUp G3 Duo [1920 × 1440]
GeoSLAM ZEB REVO - RT	Hokuyo UTM-30LX	1	ToF	30 indoor 15 outdoor	30 @10m 50 @30m	30	43,000	NIR	360° H 270° V	MEMS	APP on tablet or cell phone	ZEB Cam GitUp G3 Duo [1920 × 1440] ZEB Pano Ricoh Theta V [14 MP]
GeoSLAM ZEB HORIZON	Velodyne VLP-16	16	ToF	100	N/A	30	300,000	NIR	360° H 30° (±15°) V	MEMS	N/A	ZEB Cam GitUp G3 Duo [1920 × 1440]
Leica-Geosystem Pegasus (Backpack)	Dual Velodyne VLP-16	16 + 16	ToF	100	N/A	20–30 indoor 50 outdoor	600,000	NIR	270° H 30° (±15°) V	SBAS	N/A	5 cameras [2046 × 2046]
NavVis 3D	Hokuyo UTM-30EW	2	ToF	60	30 @10m 50 @30m	N/A	43,000	NIR	360° H 270° V	Xsens MTi-G 710	N/A	N/A
NavVis M3	Hokuyo UTM-30LX	3	ToF	30 indoor 15 outdoor	30 @10m 50 @30m	30	300,000	NIR	360° H 270° V	MEMS	Intel Core i7	6 cameras [4592 × 3448]
HERON MS Twin	Dual Velodyne Puck	16 + 16	ToF	100	N/A	30	600,000	NIR	360° H 360° V	MEMS	N/A	Panoramic camera [1920 × 1080]
–	Velodyne HDL-64E	64	ToF	120	N/A	± 5 mm	up to 2,200,000	NIR	360° H 30° V	MEMS	N/A	–

List of abbreviations: ToF = Time-of-Flight; NIR = near-infrared; FOV = Field Of View; IMU = Inertial Measurement Unit; MEMS = Micro Electro-Mechanical Systems; SBAS = Satellite-based Augmentation Systems.

innovation combined with the traditional methods techniques are increasing the practicable paths to follow and manage properly green areas, such as artificial environments or natural forests. The management of the latter, being complex ecosystems, requires a big amount of information and data to make right future decisions (Gollob et al. 2020). In the forestry sector, the forest inventory has a relevant role in the management choices and this process is gradually becoming more and more automated. Spatial distribution information, trees and crowns volume and the diameter at breast height (DBH) are among the most popular forestry parameters calculated automatically. This automation of processes has underlined the reduction in time and labour required to obtain a big and useful quantity of tree metric data (Shilin et al. 2019). However, traditional methods are still used as reference values for the quality assessment of the automatically detected forest inventories (Gollob et al. 2020). The accuracy of the results obtained with the different automated methods depends on the type of forest, species distribution, density, stand structure, past management and current conditions (Kaartinen et al. 2012). As far as the smart farming is concerned, in the orchards mainly, the canopy volume has been shown to be related to fruit yield and this information is used for decision making in precision farming. Internal crown gaps are difficult to be detected with traditional methods, and this can cause volume overestimation (Westling et al. 2020). Even branches information like typology, length and number are utilized as indicators in productive orchards, giving an indication about trees growth and yields (Zhang et al. 2020). In the last decade, the laser scanner technologies had, and still has, an important role in the automatization of these processes. Thanks to these instruments is possible to reconstruct a three-dimensional (3 D) model of the analysed forest or orchard, in a fast and accurate way. The Light Detection and Ranging (LiDAR) instruments can be equipped on different platforms which could be fixed, aerial or mobile, according to the different survey and resulting pulse cloud needed (Perugia et al. 2019). In the last decade, the Terrestrial Laser Scanning (TLS) survey has been used for the creation of 3 D point clouds which are dense enough to permit the spatial location of each tree, combining with an accurate trees' geometry extraction. Notwithstanding these advantages, the TLS survey is not always the best one due to its static nature (Cabo et al. 2018). Forest inventories or orchards 3 D reconstruction over wide areas can be achieved with the help of Airborne Laser Scanner (ALS) data. This kind of survey, combined with field sampling, can reach good results even if certain algorithms developed in the last years permit the individual tree crown segmentation starting from only ALS data. One of the most common limitation of the ALS survey is the low-density points cloud acquired and, to overcome this, multi-data source approaches have been developed, combining different survey's typologies (such as ALS with photogrammetry). The airborne laser scanning surveys are generally unsuitable for single tree measurements because, although they cover large areas, they cannot accurately detect single tree information due to their inability (or partial inability) to scan what is present below the tree foliage (Gollob et al. 2020). However, if detailed data collection is needed, data should be collected at plot level or even at individual tree level utilizing traditional survey's methods (Cabo et al. 2018). A further improvement in green areas data collection method has been obtained using Mobile Laser Scanning (MLS) surveys, with moving platforms. The latter have made improvements in many fields, but limitations in the forestry sector remain evident: the tree crown cover does not permit a spatially continuous mapping (due to the low GNSS/IMU signal detection) and the relative 3 D point cloud does not match properly, leading to a reduction in instrument accuracy (Perugia et al. 2019). Even using a high quality and expensive IMU system, if the crowns obstruct the satellite visibility, the positioning error grows rapidly to tens of centimetres or metres which creates multiple copies of the same scanned object in the points cloud. This is due to the repeated acquisition of the same feature by the laser scanner, leading to a deterioration in the quality of the points cloud obtained as final output (Kukko et al. 2017). However, with good GNSS signal the accuracy reported for MLS data is 2-4 cm and, with the use of the best laser system, a ranging error of 2 mm (Tang et al. 2015). Such limitations can be overcome thanks to the Simultaneous Localization and Mapping (SLAM) algorithm. Scientific results demonstrated that the positioning accuracy is improved if compared with the one obtained by the traditional tactical grade GNSS/IMU positioning system in a forest (Tang et al. 2015). Recent algorithm developments have been proposed in the forestry sector to improve trunk estimation, but its performance is always hardware-dependent and the accuracy level in the forestry sector is still not well-known (Tang et al. 2015).

In according with the MLS surveying experiences in forestry and agriculture, we can state that the recognition of constant, similar and homogeneous features (as in the case of stems in managed forests) can be easily associated with the geometric primitives' shapes which help the camera to avoid trajectory loss. The latter gets mainly lost when inhomogeneous features (such as shrubs or low-lying crowns) are present in the understory or in the trees surrounding areas. This trajectory, which initially had an accuracy of tens of cm, can be deviated by metres if there are features that are generating noise and outliers in the point cloud obtained.

The following table (Table 9) indicates some studies where MLS was chosen to obtain different tree characteristics or tree metric data, both in the forestry and in the agriculture sector:

In the subsequent Table 10, it is possible to examine the evaluation of the accuracy obtained in different surveys in the Forestry and Agriculture domain. This evaluation is associated to statistical analysis of tree metric data extracted from the point cloud obtained with MLS system, exploiting both the GNSS antenna and the SLAM algorithm. Diameter at Breast Height (DBH) and Tree height are the two most frequently tree metric evaluated. This is due to the fact that both are used for the extraction of further morphological parameters, such as the crown volume, the canopy cover and the stem volume.

The statistical results reported in this section, the Root Mean Square Error (RMSE) and the BIAS, are estimated by comparing the values obtained from the MLS experimental survey with the dataset acquired with the traditional methods.

5.3. Research trend over the time span analysed

All the different domains have been analysed in a certain time span but, accordingly to the research carried out, it is possible to note in Tables 1, 3, 5, 7 and 9 that each domain started to involve MLS techniques in their research activity in a certain year.

‘Built and urban environment’ and ‘Environmental monitoring’ domains are those with the oldest publications, starting in 2012 and 2010 respectively. The other three domains, on the other hand, show several publications that has increased exponentially over the years, but with 2014 as starting year. This trend could be explained due to the representation scale, wider for the formers. MLS surveys started to be carried out in such broad domains and, once the potential of such surveys was understood, research started to be done in more specific domains as well.

6. Discussion

6.1. Relationship between domains and MLS platforms

In Section 5 different MLS platforms have been distinguished, accordingly to the research carried out: human-based, wheel-based, boat-based, sledge-based and aerial. Among them, it is possible to observe differences depending on the survey’s configuration, albeit the first two are the ones most frequently used. Indeed, as shown in Figure 4, human-based and wheel-based platforms are adopted in all the field domains. The Built and Urban Environment domain shows a tendency towards the wheel-based platform and it is due both to the good accessibility of the survey sites and to the rapid movement necessity within urban areas. On the other hand, the Environmental Monitoring domain is one of the wider one and, indeed, the literature showed that even the platforms used in compliance with the survey which can be terrestrial, aerial or boat-based. The Cultural Heritage and Archaeology Field shows the highest number of MLS technologies held by a human and this is due to the presence of restricted access for safeguard reasons or due to narrow passages. The Underground Environment, being an environment that requires certain condition for a correct survey, is the one with the lowest platform variation. The aerial platforms are more used in the Forestry and Agriculture domain where, in some cases, it is not possible to reach the survey’s fields due to the complexity of accessing certain places which may have a steep slope or which may have rough terrain.

6.2. MLS technical specifications comparison

Table 11 summarizes the detailed laser units’ characteristics which compose the MLSs listed in the references. The last three columns indicate the additional components which complete the system.

Table 12 summarizes some detailed commercial mobile TLS laser units’ characteristics which compose the MMSs listed in the references. The last two columns indicate the additional components which complete the system.

Table 13 summarizes the detailed laser units’ characteristics which compose the ALSs listed in the references.

6.3. Survey performance analysis

This section is dedicated to the analysis of survey performance by comparing the various MLS previously summarised based on what emerged from the literature

Table 12. Technical specification of commercial mobile terrestrial laser scanner (TLS).

	TLS								Added Components	
MMS System	Scanner	Measuring Principle	Maximum range [m]	Range precision [mm]	Range accuracy [±mm]	Scan rate [points/s]	Laser wavelength	FOV	IMU	GNSS
FGI ROAMER R2	FARO Focus3D 120S	Phase shift	up to 120	2 @10m	2	976,000	NIR	360° H 305° V	NovAtel UIMU-LCI	NovAtel Flexpak6
	FARO Focus3D X330	Phase shift	up to 330	1.5 @10m	2	from 122,000 to 976,000	NIR	360° H 300° V	–	–
ROAMER	FARO Photon 80	Phase shift	76	2 @25m	N/A	700,000	NIR	360° H 320°V	HG1700 AG58	NovAtel SPAN
SITECO Road-Scanner3	FARO Focus S 70	Phase shift	150	1	2 @10m 3.5 @25m	from 122,000 to 976,000	NIR	360° H 300° V	–	LANDINS, Zephyr Trimble
	FARO Focus S 150	Phase shift	150	1	2 @10m 3.5 @25m	from 122,000 to 976,000	NIR	360° H 300° V		
	Z + F Imager 5010C	Phase shift	187	1	3.5	up to 1,016,000 *pixel/sec*	NIR	360° H 320° V	–	–
Teledyne Optech	Lynx HS300	ToF	250	5 mm	2	up to 600 *lines/sec*	NIR	360°	–	–
Trimble MX2	SLM 250	ToF	up to 250	10 @50m	N/A	Single laser head: 36,000 Dual laser head: 72,000	NIR	360°	Applanix IMU-4	Trimble AP20
–	RIEGL VMX 250	ToF	200	5 @150m	10 @150m	300,000	NIR	360°	–	–
–	RIEGL VMX 450	ToF	220	8	5	550,000	NIR	360°	–	–
–	RIEGL VQ 250	ToF	220	10	5	300,000	NIR	360°	–	–
–	RIEGL VZ 400	ToF	up to 600	3 @100m	3 @100m	from 42,000 to 122,000	NIR	360° H 100° V	–	–
–	RIEGL VZ 400i	ToF	250	5	3	500,000	NIR	360° H 100° V	–	–
–	RIEGL VUX 1HA	ToF	420	3	5	1,000,000	NIR	360°	–	–
–	RIEGL LMS Z210ii	ToF	100	10	10-15	up to 10,000 @low scan up to 8,000 @high scan	NIR	95° (±45°)	–	–
–	TOPCON IP-S2	ToF	up to 80	± 25 @10m ± 35 @10 - 20m ± 50 @20-30m	N/A	N/A	NIR	190° H 360° V	Honeywell HG1700	–
–	Dynascan M150	ToF	up to 500	1	50	36,000	NIR	360°	INS MDL 5000	–

List of abbreviations: ToF = Time-of-Flight; NIR = near-infrared; FOV = Field Of View; IMU = Inertial Measurement Unit; GNSS = Global Navigation Satellite System.

Table 13. Technical specification of laser unit for aerial laser scanner (ASL).

	LiDAR Unit								
ALS	Measuring Principle	Minimum Range [m]	Maximum range [m]	Range precision [mm]	Range accuracy [mm]	Scan rate [points/sec]	Laser wavelength	FOV	Typical platform
RIEGL LMS Q560	ToF	30	1,800	20	10	240,000	NIR	45° (up to 60°)	airplane
RIEGL VQ 480i	ToF	10	1,050	20	2	275,000	NIR	60°	airplane
RIEGL VUX 1UAV	ToF	3	1,050	10	5	500,000	NIR	330°	airplane
Optech ORION M300	ToF	N/A	2,500	N/A	<30–100	N/A	NIR	50°	airplane
Leica - Geosystem ALS50-II	ToF	N/A	6,000	N/A	N/A	N/A	NIR	75°	airplane
Phoenix Alpha AL3-32	ToF	1	107	N/A	25	700,000	NIR	360°	Airplane, UAV, Vehicle, Backpack

List of abbreviations: ToF = Time-of-Flight; NIR = near-infrared; FOV = Field Of View; UAV = Unmanned Aerial Vehicle.

examined for this review and on the expertise and knowledge acquired by the authors. The factors that determine the quality of acquired data, in terms of level of accuracy, precision, resolution, completeness and cleanliness, are listed below:

- *technical specifications of laser unit*

It is referred to the characteristics related to the type of laser unit, distance measurement mode, acquisition range, field of view. In some MLS there is a relationship between the axis of the rotation system of the laser beam (therefore its exposure) and the point cloud direction of the detected object. A pseudo-vertical rotation around the x-axis corresponds to almost horizontal profile traces, a pseudo-horizontal rotation around the y-axis results in almost vertical or oblique profile tracks (depending on the speed of the survey). In other MLS, thanks to the rotating acquisition system (e.g. GeoSLAM devices), the resolution of the surveyed surfaces is more homogeneous, but at the same time does not always guarantee the recognition of the features of the surface itself or targets shapes (Tucci et al. 2018).

Furthermore, in the ground-based mode, knowing *a priori* the width of the field of view makes it possible to understand the coverage of the laser beam of the acquired surface on both the horizontal and vertical planes, especially in small, narrow, indoor or underground environments. The same applies to the three-dimensional representation of a wooded area, where it is not possible to detect the entire canopy based on the height of the vegetation present. In this domain, indeed, it is useful to combine terrestrial detection with the aerial one, which allows to obtain a 3 D representation of the crowns top.

- *setting of the system configuration parameters*

Configuration parameters are often set in the default mode by the developers of commercial laser scanner systems. It is good practice to consider the characteristics of the parameters according to the type of environment being surveyed. The setting can be made either by guided and automatic selection or by manual input of the values by experts in that laser scanner, supported by scientific documentation (Di Stefano, Chiappini, et al. 2020). This operation must be carried out before starting the acquisition operations.

- *method of carrying out the survey*

The resolution and the completeness of the surveyed data are also strongly dependent on the ability of the operator and the acquisition forward speed (Nocerino et al. 2017). These tips are recommended both in case of human-based platforms and constant speed motion of terrestrial (wheel-based, boat-based) and aerial devices. In the case of environments characterised by variations in the spaces to be surveyed, such as indoor environments, considering the small scale of the survey, the path should be even and regular to avoid sudden turns and large differences in the ground.

Passageways, such as the doorway between two rooms, represent a weak point of MLS systems.

In case the localization of the acquired data is not guaranteed by the GNSS system, it is recommended to perform closed loops at the same position as the starting point and roundtrips during the mapping operation. This facilitates the SLAM algorithm and the IMU data to process the transitions and rotation, in order to guarantee the best alignment by minimising or ensuring an appropriate redistribution of the accumulated errors along the trajectory (e.g. drift).

- *intrinsic characteristics of the acquisition context*

The performance of these instruments differs depending on the acquisition context (indoor and outdoor). It is always suggested to inspect the scene or the site of interest in order to identify critical situations and the presence of obstacles that may compromise the correct execution of the acquisition operations (di Filippo et al. 2018). Poor lighting for visual-based feature trackers, the presence of moving objects (such as vehicles, tree canopies) or people, and the presence of smooth or reflective surfaces can cause loss of orientation or increase noise effects of registration, which is clearly visible when analysing the point cloud. On the contrary, in the case of sunny and clear days, this condition prejudices the laser range of MLS (Cabo et al. 2018). As mentioned before, it should be remembered that IMU-based and SLAM-based systems, especially in GNSS-denied environment, loop-closure path must be guaranteed and it is also advisable to plan routes with several self-intersections.

Moreover, for SLAM-based systems, the environment to be surveyed should be feature-rich (better if regular in shapes) because such a localization and mapping algorithm exploits geometries to generate the 3 D final models.

It is therefore required special attention when planning surveys, so some operative tricks and rules for the data acquisition should be set in advance.

6.4. Survey results analysis

Due to the complexity and big data collected and comparison of information from different fields the results cannot be entirely generalized, as they are strongly influenced, not only by the characteristics of the environment, but also by technical specifications and system configuration of laser scanner used, as well as by the operator's ability to correctly manoeuvre the instrument. The aspects to be considered when evaluating the results obtained from a survey are:

- *acquired data – saved data*

Generally, with MLSs, a large number of points can be acquired for any type of environment: indoor, outdoor, underground, articulated, multi-level, narrow or wide, where TLS sensors cannot be employed or would be very time-consuming.

At the end of each survey operation, a project folder is created in the recording unit of the MLS containing various data output. In addition to the point cloud file which contains also its properties (e.g. number of points, scalar fields such as time and intensity), there are files relating to the definition of the characteristics and the graphic representation of the trajectory made, a text file with the set configuration parameters and finally data relating to localisation, either acquired by GNSS system and therefore attributed to a geographical reference system or by IMU and SLAM systems which instead geo-reference the points in a local reference system. Depending on the camera type of the tracker, either RGB or black and white images, can also be found in the same folder. Sometimes, if the purpose is to obtain also such images, you have to activate the image saving configuration in the system parameters. Therefore, for the amount of data saved an MLS requires a lot of memory space.

- *data processing and elaboration*

The final point clouds are directly downloaded from the instrument as soon as the measurements were made. In other instruments, the point clouds are available after the post-processing phase through dedicated software implemented by the laser scanner companies. Hence, in the case of point clouds ready to be downloaded and processed, they can be visualised in open-source programs (e.g. Cloud Compare), otherwise if post-processing is needed, specialist knowledge and expertise of the software provided in the laser scanner system package is required. The subsequent processing phase of the acquired data includes alignment in a geographical reference system, where necessary, and cleaning operations of redundant points or existing noise forms.

- *real-time control during acquisition operations*

It is possible to connect a tablet or a screen, via cables or through wi-fi connection, for real-time view and checks of the acquired data. This gives more assurance for the correct acquisition operations and in case of erroneous results the survey can be repeated immediately before noticing the error being processed by software in the laboratory.

- *presence of errors*

As mentioned before, there may be forms of error, such as drift and wrong double surfaces, due to various causes: loss of orientation, incorrect use or sudden movement of the instrument, incorrect repeatability of the survey, moving elements during the survey, sudden change in the type of environment detected, mismatch of the starting and ending points of the loop-closure.

- *level of detail and tolerance*

Based on the accuracy value of the scanner system, the mode and direction of exposure of the laser beam and the speed of execution of the survey, a different level of detail is obtained which is evaluated basing on the recognition of various types of targets (e.g. planar, spherical) arranged in the detected environment and the identification of the elements characterizing the scene such as: structural details of the buildings, description of architectural elements, definition of surfaces in natural contexts, definition of tree trunks. Therefore, an improved working mode in order to enhance the obtainable level of detail can simply be to slow the walking speed, in case of human-based laser scanner, in the proximity of objects of special interest.

Once the level of detail has been identified, the tolerance of the acquired data can then be estimated. For example, in the case of a survey carried out in an architectural or structural context (building scale), a centimetric or decimetric precision corresponds to a graphical representation scale 1:100-1:200 (Bronzino et al. 2019).

- *expected results*

The degree of compliance with project aims specifications depends on the accuracy achieved by the final 3D representation and on cost-benefit ratio of the survey. A MLS can guarantee a complete survey of the scene but at the same time does not always satisfy the identification of features or the level of detail relevant to the purpose of the survey, or vice versa. On the other hand, the speed rate of the point cloud data collection allows to save time in doing fast survey, which can then be invested in the point cloud post-processing operations.

7. Conclusion

In this article, a systematic literature review was carried out, focusing on the employment of MLS for Geomatic applications. Existing MLS platforms, application domains, accuracy requirements and limitations were examined in the recent literature, considering the last decade.

Looking at the international panorama of the most recent applicative research papers, five domain fields have been selected, namely urban environment, cultural heritage and archaeology, underground environment, environmental monitoring, forestry and agriculture.

With the intent of providing the reader with useful hints, as well as for the sake of clearness among an unprecedented spreading of MLS among practitioners, terminology and type of existing MLS have been systematized. From the analysis conducted in this paper, it emerges that MLS can be considered as a technology applicable to the different domains listed above. In fact, it represents a fast, versatile, customizable solution that can be adapted to different types of platforms (human-based, wheel-based, boat-based, sledge-based, aerial).

Considering the variety of research domain in which this technology has been applied, our results show a growing interest. The positive characteristic that joins all the domains field is the rapidity of data collection and the ease of use, especially human-based platforms. The use of MLS requires a limited number of technical staff on site, thus saving time and survey costs. The navigation and processor components in MLS system offer the possibility to localize and map the scene at the same time and sometimes it's possible to control in real-time the data acquisition operations.

However, the maturity of the system can be considered to some extent questionable. Indeed, the accuracy and resolution requirements change substantially from one domain to another, so the specifications should be carefully considered *a priori*, depending on the intended application.

The tolerance is strictly a consequence of the final output to be created, and this represents the main limitation which is hampering a straightforward adoption; the noise introduced by ready-to-use platforms need filtering operation, and mostly the lack of RGB information is not compliant with those domains where this information is essential. It is recommended to use ground truth data for both verification and orientation of the 3 D model. Definitively, MLS should be considered in its experimental phase and its usage is not systematic or based on best practices, since it generally requires an integration from other sources of data.

As final remark, we can state that main gaps found in this paper should provide the baseline for future improvements, especially strengthening ventures between companies and research centres.

Notes

1. The chosen repositories are the most well-known databases in the scientific sector and they cover the majority of the application fields. Moreover, thanks to the quick expansion of the World Wide Web, even search engines became fundamental tools for research activities. Both have grown rapidly in recent years, evolving and bringing benefits to the research community (Chirici, 2012)(Gizzi & Potenza, 2020), and now their use is fundamental, if not essential, to reach new frontiers within the research sector.

Disclosure statement

No potential conflict of interest was reported by the authors.

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