Aerial and Terrestrial LiDAR: Comparisons and Accuracies

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Abstract

Based on the availability of data produced during the activities carried out for the creation of the new topographic database [DBT] of the Municipality of Genoa, the integration methods between aerial laser scanner and terrestrial laser scanner surveys are evaluated for a comprehensive modeling of the territory.
In the recent past, methodologies for acquiring territorial data that generate point clouds have become available: aerial and terrestrial laser scanning, SLAM acquisitions, and the production of point clouds obtained through photogrammetric correlation.
The purpose of this paper is to highlight, based on the conducted experiences and available data, the activities carried out that involve the potential for mutual integration between aerial and terrestrial LiDAR surveys.
The mutual accuracies and the merging methods between the available datasets are also assessed.

Keywords (separated by '-'): ALS - TLS - LiDAR

Aerial and Terrestrial LiDAR: Comparisons and Accuracies

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Keywords: ALS · TLS · LiDAR

1 Introduction

Within the National Operational Programme for Metropolitan Cities PON METRO 2014–2020 - Axis 1 "Metropolitan Digital Agenda," co-financed with European Union resources (European Structural and Investment Funds) and national resources (Agency for Territorial Cohesion), the Municipality of Genoa has initiated the modernization of its territorial database, aiming to integrate all the information concerning the entity's territorial objects.

This project involves the implementation of a computerized service system for the exposure/use of the information stored in various subsystems, including management systems, linked through certified unique identifiers based on the properly re-engineered and updated Topographic Database of the entity.

To carry out the aforementioned, it is necessary to have an updated Topographic Database, which is an essential support for activities related to intervention planning, prevention of hydrogeological disasters, and overall knowledge of the territory.

Therefore, the production of the Topographic Database at a scale of 1:1000 for urban areas and 1:2000 for extra-urban territory has been initiated. This entails an update starting from the available database, which was previously converted according to the specifications of the DM 10.11.2011 "Technical rules for defining the content specifications

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of geotopographic databases" (Official Gazette no. 48 of 27/02/2012 - Supplementary ordinary no. 37).

2 Aerial and Terrestrial LiDAR

Aerial LiDAR involves the use of laser sensors mounted on aircraft, typically planes or helicopters. These sensors emit laser pulses towards the ground and measure the time taken for the laser to reflect back. Using this time information, along with the aircraft's position data, it is possible to create a three-dimensional model of the terrain with extensive coverage. Aerial Lidar is particularly suitable for large-scale acquisitions such as land mapping, digital elevation model generation, and identification of topographic features on a large scale. It offers fast coverage and high resolution, but accuracy can vary depending on the point density and the precision of the aircraft's orientation and positioning.

On the other hand, terrestrial lidar involves the use of lidar instruments mounted on tripods or ground vehicles, which are positioned on the ground at regular intervals. These instruments directly measure laser reflection points within their range, creating a high-density point cloud in three dimensions. Terrestrial lidar is particularly suitable for detailed and highly precise acquisitions, such as surveying buildings, monuments, infrastructure, and specific areas of interest. It offers high accuracy due to the close distance between the instrument and the object being measured, but the coverage is limited to the area where the instrument is positioned.

The accuracy of lidar depends on various factors, including the point density, the precision of the positioning and orientation system, the accuracy of point coordinate calculations, and the correction of systematic errors. In general, both aerial and terrestrial lidar can provide high measurement accuracies, with errors ranging from a few centimeters to a few decimeters, depending on the project specifications and operational conditions.

In addition, it should be noted that transitioning from a traditional aerial view to a ground-level view produces a change in the quantity and level of detail of the captured features. Therefore, it is currently appropriate to proceed with a true integration of acquisitions, each capable of capturing specific objects:

- on one hand, aerial LiDAR captures extensive territorial surfaces, roads, and building roofs but lacks details on facades related to capture geometry aspects;
- on the other hand, ground surveys (static or SLAM-based) capture details at eye level, where many specific features necessary for technical applications are present.

3 Characteristics of the Production in the City of Genoa

Within the mentioned specifications, the production in question has distinctive characteristics related to the use of innovative tools and methodologies. It involves the creation of cartographic materials, including unconventional ones, for which it is currently recognized that the City of Genoa has the most up-to-date and innovative database at the national level.

The production in Genoa has served as inspiration for ongoing productions in other important cities at the national level, such as Milan, Turin, and others.

The production was carried out by a Temporary Grouping of Companies composed of *SIT - Servizi di Informazione Territoriale* S.r.l. (lead company based in Noci - BA, now Mermec), *Corvallis SpA a socio unico* (Padua), *Arcadia Sistemi Informativi Territoriali S.r.l.* (Milan), and *Aerosigma S.r.l. a socio unico* (Grottaglie - TA).

3.1 Aerial Photogrammetric Surveys and Aerial LiDAR

The project specification included an integrated aerial photogrammetric survey combined with an aerial LiDAR survey, with the latter being crucial for accurate terrain modeling in vegetated areas and for generating digital surface models (DSMs) and digital terrain models (DTMs) needed for hydrogeological studies. This was one of the main objectives of the project due to the well-known challenges posed by the municipal territory and the Liguria region as a whole.

The aerial survey was conducted using a *Vexcel UltraCam Eagle Mark 3* photogrammetric camera mounted on a *Vulcanair P68 Victor B* twin-engine aircraft (Fig. 1).

Approximately 5000 RGBN photographs were captured, with a ground sampling distance (GSD) of 5 cm for a scale of 1:1000 and 9 cm for the remaining area. The survey achieved high overlaps, ranging from 80–90% in the longitudinal direction and 60% in the transverse direction, due to the unique geographical features and the presence of a large and densely populated urban core.

The LiDAR survey, on the other hand, was carried out using a *Riegl LMS-Q1560* sensor. The point density was set at 55 points per square meter for urban areas and 40 points per square meter for the rest of the territory.

Fig. 1. Main devices used for the photogrammetric and LiDAR acquisitions: *Vexcel UltraCam Eagle Mark 3* and *Riegl LMS-Q1560*

The high quality of the employed sensors allowed for achieving accuracies on the checkpoints of less than 10 cm for photogrammetry and residuals in the Z-axis (vertical) of approximately 5 cm for the LiDAR strips. These values are entirely compatible with the requirements of the project specifications and align with the standards stated in international literature (Fig. 2).

The achieved accuracies demonstrate the effectiveness and precision of the data acquisition process. The photogrammetric outputs, with accuracies below 10 cm on the checkpoints, indicate the reliability of the generated orthophotos, digital surface models (DSMs), and digital terrain models (DTMs). Similarly, the LiDAR residuals in the Z-axis within the range of 5 cm affirm the accuracy and vertical precision of the captured LiDAR point clouds.

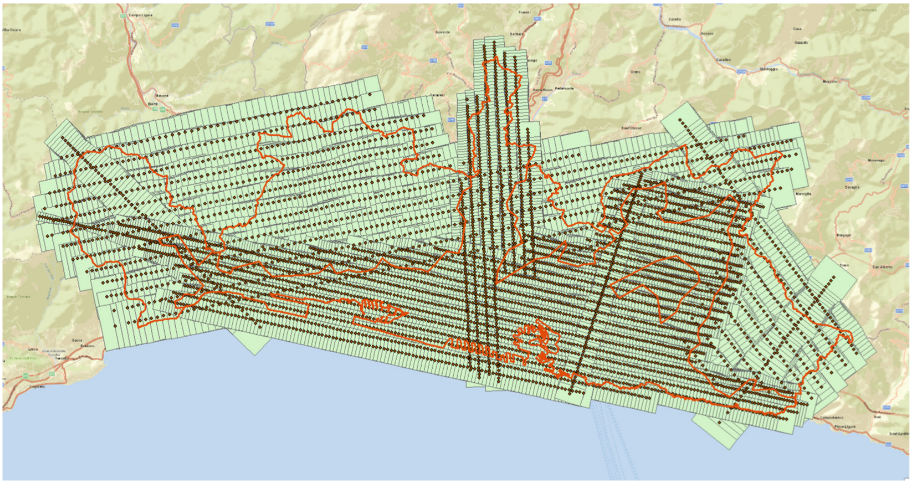

Fig. 2. Index of aerial shots taken in the territory of the Municipality of Genoa: capture centers and frame overlaps

These accuracies are in line with the industry standards and reflect the adherence to the specified requirements, ensuring the reliability and usability of the acquired data for various applications and analyses.

3.2 MMS Survey

MMS (Mobile Mapping System) surveys refer to a geospatial data acquisition system carried out using vehicles equipped with advanced sensors and positioning technologies. These vehicles are equipped with high-resolution cameras, LiDAR systems, and GPS/IMU to accurately record the 3D geometry of the surrounding environment as the vehicle moves along a designated trajectory.

During MMS surveys, the vehicle collects data from multiple sources simultaneously. The cameras capture high-resolution images that can be used to generate orthophotos and detect objects and details in the environment. LiDAR sensors emit laser pulses to measure the distance to surrounding objects and create high-density three-dimensional point clouds. The GPS/IMU system records the real-time position and orientation of the vehicle, allowing for georeferencing of the collected data.

MMS surveys are widely used for mapping roads, urban areas, infrastructure, and other complex environments in an efficient and accurate manner. This data acquisition approach enables extensive and detailed coverage, facilitating in-depth analysis and the creation of precise three-dimensional models of the surrounding environment.

The dense nature of the urban territory led the Municipal Administration to request an MMS (Mobile Mapping System) survey using a vehicle (*Videocar*) equipped with a *Riegl Vux1* LiDAR sensor integrated with GNSS/IMU apparatus (Fig. 3).

The acquisition density on the facades of urban buildings reached approximately 4,000 to 5,000 points per square meter. Additionally, a *Ladybug* spherical camera (with an 8,000 × 3,000 pixel sensor) was used for 360° panoramic photography, covering all city road sections (Figs. 4 and 6).

During the survey production, these devices were supplemented with more manageable equipment to account for the unique morphology of the territory, such as pedestrian areas and narrow alleys ("*caruggi*"):

- the narrowest alleys were surveyed using backpack-mounted equipment provided by Gexcel. Leveraging SLAM (Simultaneous Localization and Mapping) technology, laser data was acquired using a *Velodyne* sensor, resulting in point densities of approximately 3,000 to 4,000 points per square meter;
- in areas inaccessible to the Videocar, where SLAM technology would not yield optimal results due to the distance from the details to be surveyed, a static Leica scanner was employed. The scanner stations were repeated every 20–30 m, resulting in point densities reaching 20,000 to 30,000 points per square meter, which were subsequently thinned out for final delivery. A high-resolution reflex camera (20,000 × 10,000 pixels) was used to acquire information for coloring the point cloud.

Fig. 3. Main devices used for MMS (Mobile Mapping System) acquisitions: Videocar equipped with the *Vux1* LiDAR sensor and the *Ladybug* camera (on the left) and the *Gexcel Backpack* with the *Velodyne* LiDAR sensor (on the right)

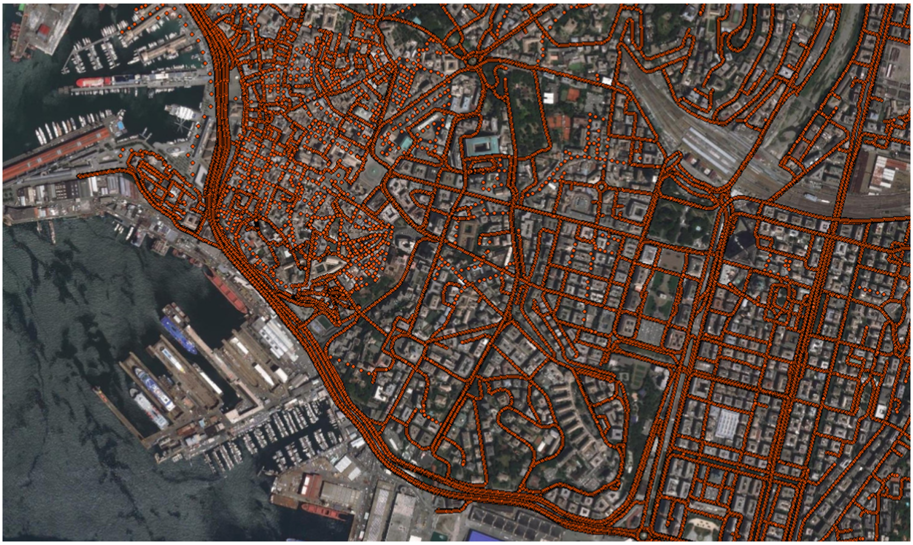

Fig. 4. Tracks of acquisition trajectories from Videocar

4 Cartographic Products

The elaborations have led to the creation of traditional cartographic outputs:

- Digital Base Map (DBT) according to the shared specifications of the ex D.M. 10/11/2011;
- Digital Surface Model (DSM) level 6 for extra-urban areas and level 7 for urbanized areas (Fig. 5);
- True orthophoto.

The focus of this document is not so much the description of traditional products but the analysis of innovative supports that are not yet widely used in the national territory, except for prototypical implementations. However, these innovative supports are extensively applied throughout the entire municipal territory.

4.1 Integration Between Aerial and Terrestrial LiDAR Point Clouds

The integration of aerial and terrestrial LiDAR point clouds is a process that combines data acquired from LiDAR sensors mounted on aircraft and ground-based devices. This integration allows for extensive and detailed coverage of the terrain by combining three-dimensional information from different sources.

In the integration process, aerial and terrestrial LiDAR point clouds are registered and aligned in a common reference coordinate system. This involves correcting systematic errors, processing positioning data, and identifying common reference points between the two data sources.

Once the point clouds have been integrated, the combined data can be used to create a comprehensive and accurate three-dimensional model of the terrain. This model can

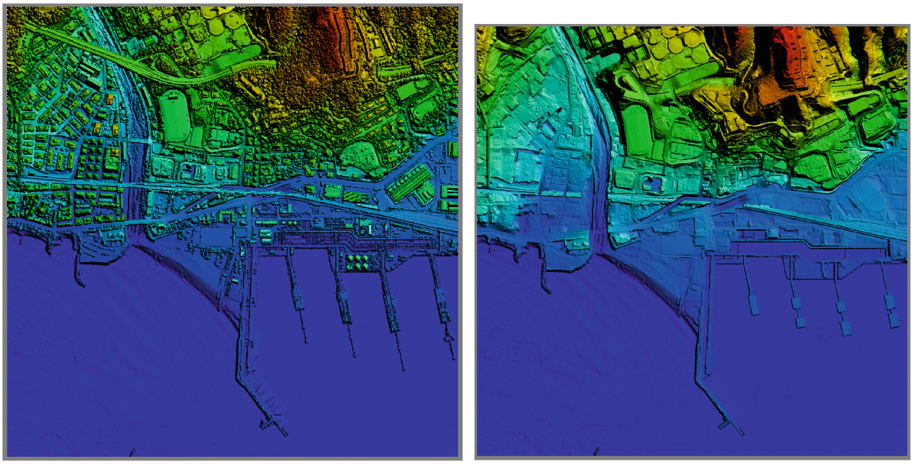

Fig. 5. DSM (Digital Surface Model) e DTM (Digital Terrain Model)

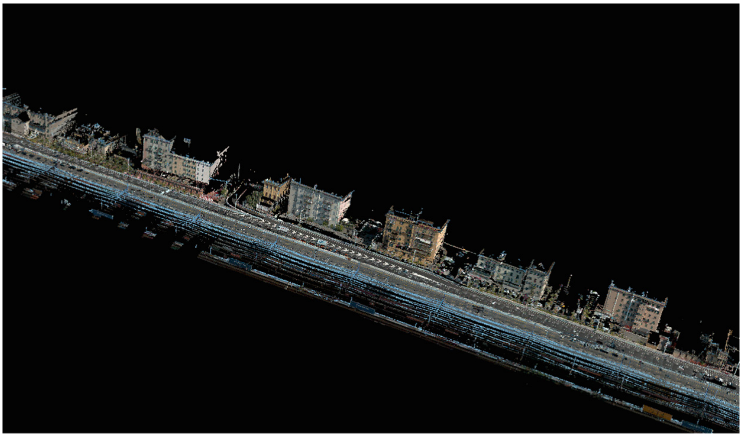

Fig. 6. Example of acquisition from Videocar

be applied in various ways, such as urban planning, land management, terrain analysis, and 3D visualization.

The integration of aerial and terrestrial LiDAR point clouds leverages the strengths of both acquisition techniques, providing a more complete and detailed view of the surrounding environment (Fig. 7).

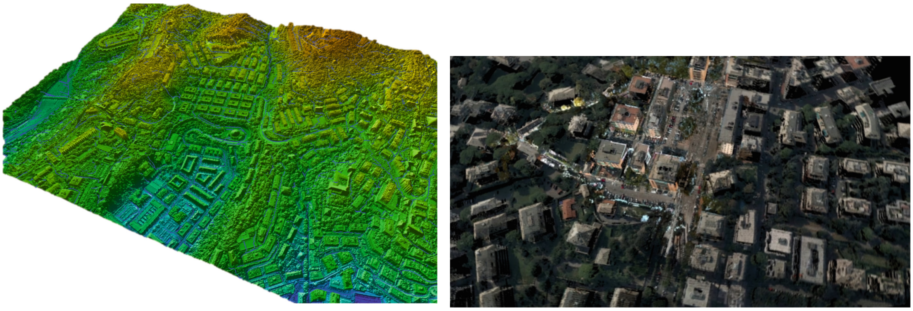

Fig. 7. Overall point cloud

The availability of point clouds acquired from both aerial and mobile vehicle means allows for a highly detailed geometric description, but only for areas where acquisition was possible or for roads and public areas. This description incorporates the characteristics of the different acquisition points:

- on one hand, aerial LIDAR enables optimal acquisition of road surfaces and coverings.
- on the other hand, mobile LIDAR, in addition to road surfaces, provides significant coverage of building facades facing streets and public spaces, excluding private areas and roof coverings (Figs. 8, 9 and 10). AQ1

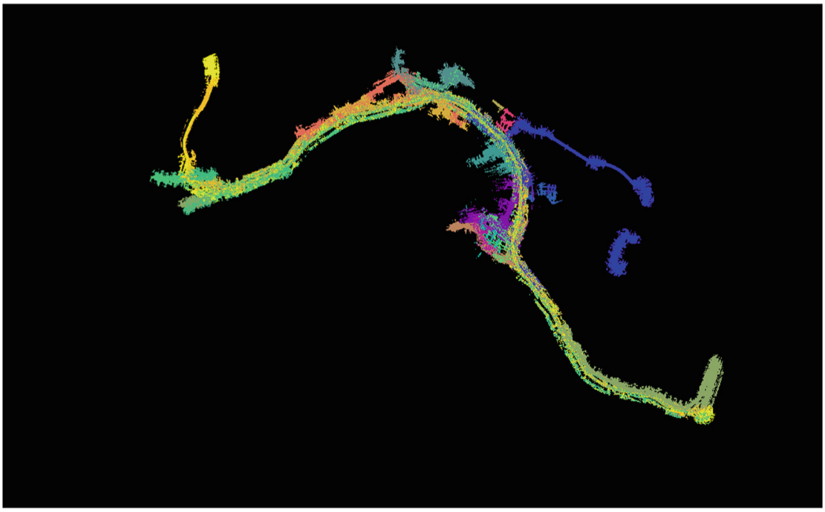

Fig. 8. Set of colored ground runs for acquisition mission: total of 21 runs - Porto Antico area.

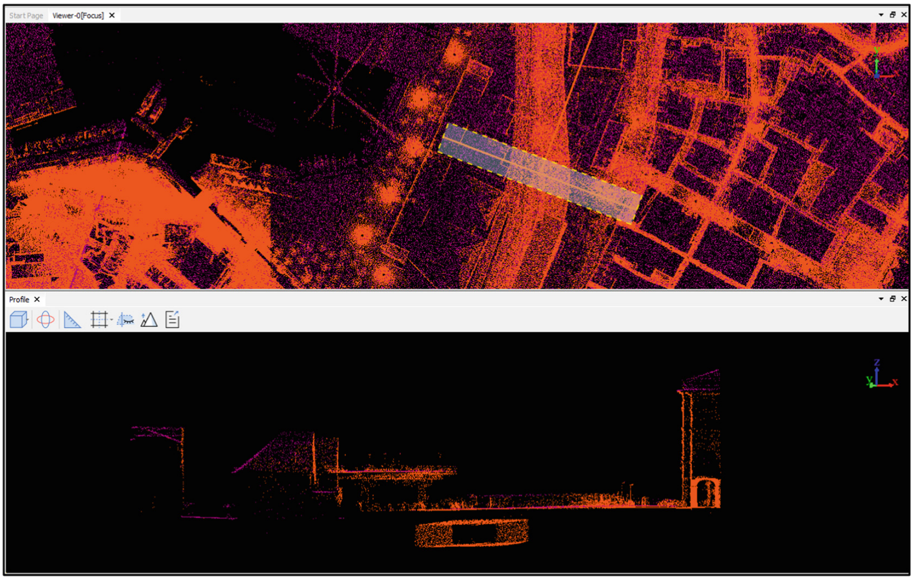

Fig. 9. Overlap between aerial (purple) and ground (orange) point clouds. (Color figure online)

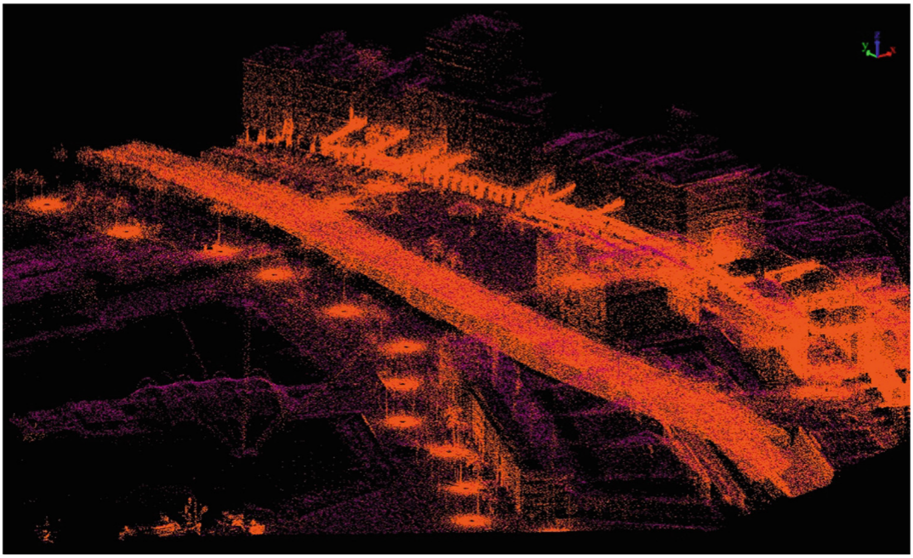

Fig. 10. Overlap between aerial (purple) and ground (orange) point clouds - area of the elevated road in front of the "Bigo". (Color figure online)

5 Evaluation of Accuracies and Possibility of Simultaneous Use

The simultaneous use of different acquisitions is clearly possible only after appropriate verification activities regarding their correct georeferencing and the resulting residuals following their merging (Figs. 6 and 7).

Therefore, a significant precision analysis activity has been initiated, based on which the production of tiles obtained from the merge of different acquisitions was possible.

The accuracy analysis was performed using the dedicated tools of the Trimble RealWorks environment (version 12.4), which allowed evaluating "cloud to cloud" distances using standardized procedures.

The validation of integration possibilities between point clouds led to the following results, assessed on a significant sample across different territorial areas:

- mean planimetric residuals between different *Videocar* acquisitions: ±2 cm
- mean altimetric residuals between different *Videocar* acquisitions: ±2 cm
- mean altimetric residuals between *Videocar* acquisitions and aerial LiDAR acquisitions: ±6 cm

These accuracies are highly compatible with the usual cartographic tolerances of large scales (1:1000/1:2000) and are therefore suitable for use in territorial information systems at those scales.

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