UAV-Based LiDAR System for Urban Mapping and Modelling Applications

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Keywords: UAV, LiDAR, Mapping, Urban, Modelling, Classification

Abstract

This paper presents urban mapping and modelling utilizing a low-cost Unmanned Aerial Vehicle (UAV) mounted Light Detection and Ranging (LiDAR) systems. Urban environments pose unique challenges for traditional mapping techniques due to their complex and dynamic nature. The integration of UAVs and LiDAR technology offers a versatile solution capable of capturing highly detailed and accurate 3D data in urban settings. The proposed system combines state-of-the-art UAV platforms with advanced LiDAR sensors to acquire high-resolution point cloud data over urban areas. The UAV platform provides the necessary flexibility and agility to navigate densely populated areas while capturing data from various perspectives. The LiDAR sensor, with its ability to accurately measure distances and capture fine details, enables the creation of detailed 3D models with precise geometric information. This research demonstrates the effectiveness of the urban modelling approach through UAV-based LiDAR mobile surveying and mapping conducted in urban environments of a case study area in Sultan Qaboos University. The results show the ability of the system to accurately map complex urban structures, including buildings, roads, and vegetation, with high levels of detail and accuracy. Overall, this research contributes to the advancement of UAV-based remote sensing technologies for urban mapping and modelling, offering new opportunities for capturing comprehensive and actionable data for various applications in urban environments.

1. Introduction

Cities are growing and changing rapidly, creating complex issues for urban planners, infrastructure managers, and environmental researchers. Currently rapid urbanization process is taking place at an unprecedented scale in many parts of the world and is expected to reach about 70% by 2050 (Parveen , Kamruzzaman and Yigitcanlar 2017). The research community has identified the need for application of advanced technological tools and applications that improve visualization, realization and management if city model (Shahat, Hyun and Yeom 2021). Precise and current mapping and modelling of urban areas are crucial for various purposes, including city planning, emergency response, traffic management, and environmental monitoring. Conventional mapping techniques, such as ground surveys and aerial photography, often struggle in providing the necessary detail and precision, particularly in densely populated and quickly evolving urban environments. urban mapping such as 3D city modelling, building and infrastructure assessment, 3D city modelling, Vegetation and environmental monitoring and Disaster management and response. Figure 1 shows an example of UAV-based LIDAR System in Urban Mapping application.

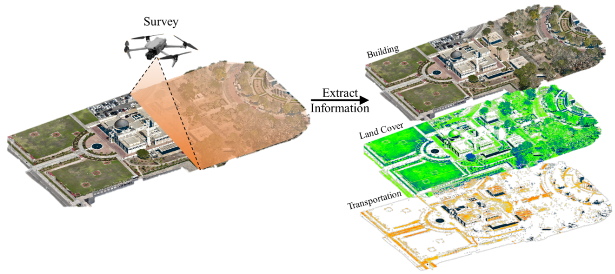

Figure 1. Application of UAV-based LiDAR system in urban mapping

Urban areas are rapidly evolving and expanding, presenting complex challenges for urban planners, infrastructure managers, and environmental scientists. Accurate and up-to-date mapping and modelling of urban environments are essential for various applications, including urban planning, disaster response, transportation management, and environmental monitoring. Traditional mapping methods, such as ground surveys and aerial photogrammetry, often struggle to provide the level of detail and accuracy required for these tasks, especially in densely populated and rapidly changing urban settings. In recent years, advancements in Unmanned Aerial Vehicle (UAV) technology and Light Detection and Ranging (LiDAR) sensors have opened up new possibilities for urban mapping and modelling. UAVs offer the flexibility to navigate through urban environments at low altitudes, capturing data from multiple perspectives with high spatial resolution. LiDAR sensors, on the other hand, provide precise distance measurements and detailed 3D point cloud data, allowing for the creation of accurate and detailed representations of urban landscapes.

The integration of UAVs and LiDAR technology presents a promising solution for overcoming the limitations of traditional mapping methods in urban environments. UAV-mounted LiDAR systems can capture highly detailed and accurate 3D data over urban areas, enabling the generation of comprehensive models with precise geometric information. The use of mobile LiDAR was investigated for urban mapping, highlighting its effectiveness in capturing detailed urban features such as buildings and streets (Wang et al., 2019). However, mobile LiDAR systems are limited in their coverage area and are often hindered by occlusions caused by urban clutter. In contrast, Aerial-based LiDAR systems offer greater flexibility and mobility, allowing for the capture of data from multiple perspectives and overcoming occlusion challenges. Therefore, the aerial-based LiDAR system for building modelling was investigated (Li et al., 2019; Khanal et al., 2020).

Several researchers have explored the use of UAV-mounted LiDAR systems for urban mapping applications. The UAV-based LiDAR for urban modelling, demonstrating the system's ability to generate accurate 3D models of buildings and terrain were investigated where the results showed that UAV-based LiDAR can achieve centimeter-level accuracy in urban mapping tasks, surpassing the capabilities of traditional photogrammetric methods. In addition to accuracy, the efficiency of data collection is a crucial factor in urban mapping projects (Noor et al., 2018). Furthermore, advancements in LiDAR sensor technology have led to the development of lightweight and compact sensors suitable for UAV integration. UAVs have facilitated low-cost non-destructive method for urban modelling, testing infrastructure inspections and monitoring (Pinto, et al. 2020). The performance evaluation of different LiDAR sensors for UAV-based mapping applications, comparing factors such as point density, range, and accuracy was investigated where the findings of this research provided valuable insights into selecting the most suitable LiDAR sensor for specific urban mapping tasks (Ge and Hu, 2020). UAVs based LiDAR systems were employed for topographic mapping and monitoring applications with high performance (Lin et al., 2021; Hu and Minner, 2023). Also, artificial intelligence tool was applied for UAV mapping systems in urban and regional planning, where the integrated drone system is equipped with for real-time 3D reconstruction (Liu (2023; Zhang and Zhu, 2023).

In this paper, an urban mapping and modelling is investigated using a low-cost DJI UAV-based LiDAR system. Also, this research discusses the challenges and opportunities associated with a low-cost UAV-based LiDAR mapping in urban environments and highlight potential applications of the UAV-based LiDAR modelling approach.

2. Methodology

The methodology includes five main tasks. The research methodology is illustrated in Figure 2. The general workflow of UAV-based LIDAR urban mapping and modelling includes several hallmarks. The first task involves time stamped LIDAR data collection along with position and orientation data acquired through GNSS/INS from different viewpoints and with different orientations missions to avoid occlusion due to complexity of urban environment. In the second task, the LIDAR data is georeferenced by GNSS/INS post-processed position and orientation solution. In the third task, the missions are combined to produce accurate point clouds product. In the fourth task, the produced point clouds data is segmented and further divided into various classes like buildings, roads, vegetation, and terrain automatically using the algorithm depending on the points attributes and geometric properties. In the fifth task, the actual 3D models of features and structures in the urban space are developed from the classified point cloud data through surface reconstruction and mesh generation. Additionally, this task involves the improvement of the models' attributes by applying texture mapping, colorization, and geometric refinements. During the methodology, strict quality assurance and quality check methods are employed for the purpose of producing credible urban models.

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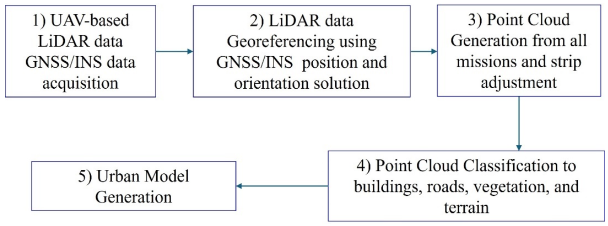

Figure 2. Research methodology.

Georeferencing of LIDAR data is required to accurately locate the point clouds in the desired coordinate system and allow the integration of LIDAR data with other spatial data and extraction of useful information from them. This process involves integrating LIDAR sensor data with positioning and orientation data from navigation systems including GNSS and IMU.

The georeferencing process requires the sensor location and orientation. There is always an advantage of having GNSS to supply the 3D sensor coordinate while the IMU affords roll, pitch, and yaw. The GNSS/IMU integrated system position and orientation solution for corresponding LIDAR point is translated from a local sensor coordinate system to the required mapping coordinate system, for instance the geographic or projected systems. The LIDAR point clouds can reach accuracies of about centimeter level by using the RTK-based or PPK-based GNSS/IMU positioning and orientation system.

UAV-based LIDAR systems enable strip-wise acquisition of dense and accurate height data by distance measurements. The LIDAR strips should have an overlapping area with tie points where these strips is combined to produce the final products of the surveyed area. The tie points is detected using the points slope and intensity values. One-dimensional height strip adjustment is applied using the tie point clouds information obtained through matching height data in overlapping areas and these height difference errors are mathematically modelled using two-dimensional surface. Then the strips points will be corrected using the model. After strip adjustment the tie point clouds in overlapping areas from all strips are matched and smooth terrain model is obtained. Figures 3 and 4 show strips configuration with tie points before and after strip adjustment.

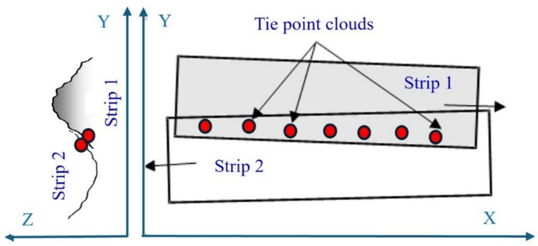

Figure 3. LiDRA data strips configuration before strip adjustment.

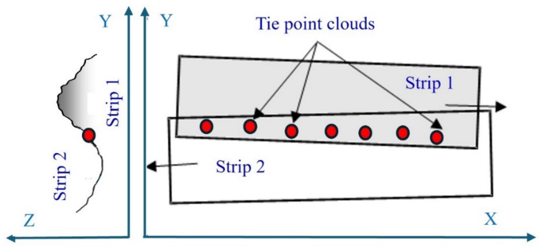

Figure 4. LiDRA data strips configuration after strip adjustment.

After georeferencing, filtering and adjustment, LIDAR data is converted to cleaned and accurate 3D point clouds, where each point contains X, Y, and Z coordinates. This data can be postprocessed for gaining insight regarding various urban planning characteristics. Postprocessing includes LIDAR point clouds gridding for urban model generation. Based on the specific application requirements, the obtained LIDAR point cloud is further processed to isolate and classify such objects as buildings, vegetation, roads and utility infrastructures.

3. Study Area and Data Collection

The projected outcomes of the research, which strategically integrates LiDAR technology and point clouds processing techniques for urban mapping and modelling was investigated in case study area inside Sultan Qaboos University (SQU) campus. The DJI Zenmuse L2 laser scanner system was utilized to collect the laser scanning and navigation data as shown in Figure 5 (DJI, 2024). The DJI L2 system includes L2 laser scanner sensor, RGB camera and precise Global Navigation Satellite System (GNSS)/Inertial Measurement Unit (IMU) positioning and orientation sensors. The laser scanning survey mission was designed to cover the case study area inside SQU campus.

(a) (b) (c)

Figure 5. Site documentation process (a) Setting up GSD points, (b) Defining flight path, (c) Flying on defined flight path.

4. Results and Discussions

The DJI Zenmuse L2 laser scanner system was utilized to collect the laser scanning and navigation data. The collected LiDAR data was georeferenced using the post-processed smoothed GNSS/INS integrated system solution. The georeferenced LiDAR data was then processed to generate the colorized point cloud deliverable. Figures 6, 7 and 8 show the point clouds in RGB, height and intensity (reflectivity) views generated from DJI terra, respectively.

Figure 6 Point clouds in RGB view.

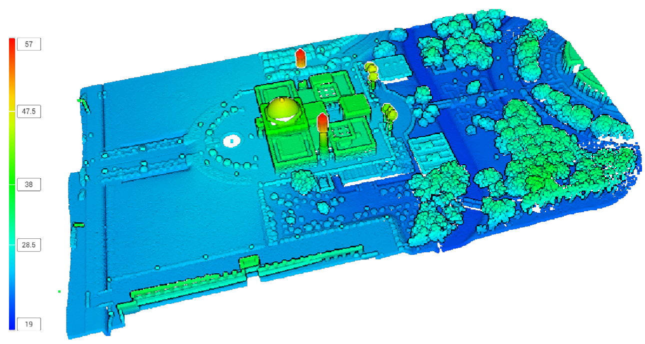

Figure 7. Point clouds in height view.

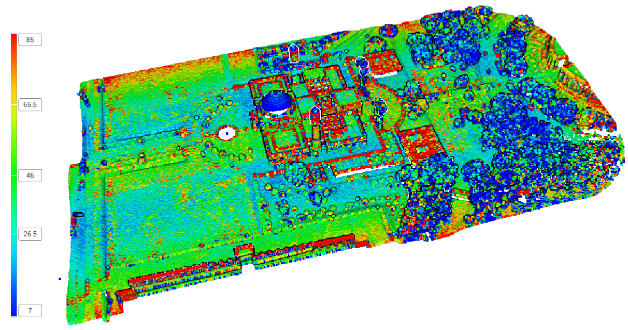

Figure 8. Point clouds in intensity (reflectivity) view

Then the analysis was conducted using CloudCompare software. In the process of data analysis, it is important to understand a pivotal endeavour within the context of point clouds. Sematic segmentation and classification are considered essential tools in this endeavour. LiDAR data classification involves categorizing individual LiDAR points into distinct classes based on their characteristics. These classes could represent any urban component, such as buildings, roads, vegetation, and terrain. To classify the points into different categories as shown in Figure 9, first the 3D elements were extracted using height parameter and elements such as buildings shade, trees can be categorized at this stage. Then, the elements that are on the same plane were extracted based on RGB difference, utilizing it to identify grass, pavement and road regions. These classes represent important urban components, such as buildings, roads, vegetation, and terrain. The classification was conducted in phases as shown in Figure 10, in the first phase urban elements with height were extracted and classified under one category. Elements with height included buildings, shades and trees are extracted. In the second extraction phase, grass surface was extracted based on selected RGB range, after which pavement and road surfaced are extracted and categorized. The identified green space cloud points and pathway cloud points are then split from the overall cloud points and defined as separate components. Table 1 shows the percentage of the classification for all urban elements in the case study under consideration.

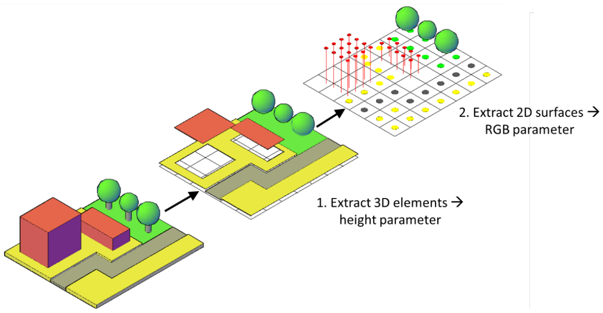

Figure 9: Stepwise extraction of urban elements.

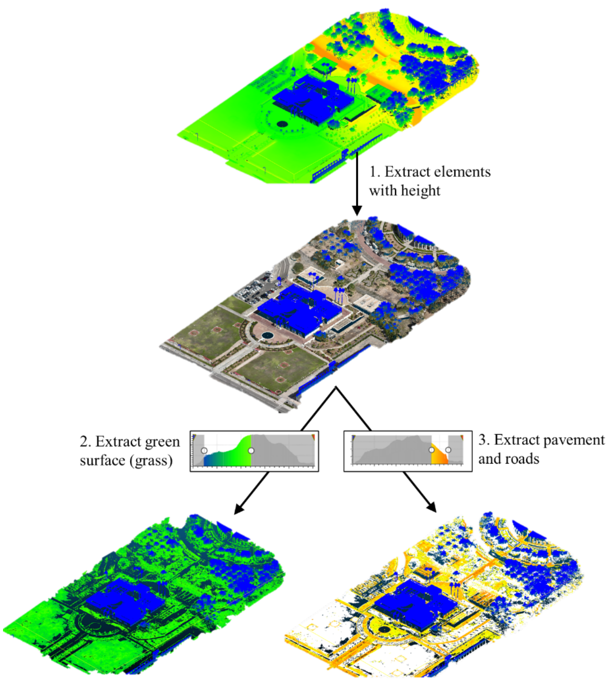

Figure 10: Extracting and classifying elements in the urban model.

Class	Percentage
Building	10 %
Pathways	18%
High vegetation	16%
Medium vegetation	3%
Grass surface	40%
Ground surface	13%

Table 1: Classification for all urban elements in the case study

Segmenting the different urban elements into categories helps in transferring the generated classified model can be used for different application, either modelling or urban simulation as each category can be lined to specific characteristics. The 3D digital model can be used in the planning stage to understand the site and its surrounding environment including man-made structures and natural features. This detailed information helps in planning out any intervention in the site accurately and eliminates potential errors. The generated model can also be used for documenting the existing state of a site.

5. Conclusion

This research has demonstrated the effectiveness of UAV-based LiDAR systems for urban mapping and modelling, as evidenced by the case study conducted at Sultan Qaboos University (SQU). Through the integration of state-of-the-art UAV platforms and advanced LiDAR sensors, the highly detailed and accurate 3D digital model elements of the SQU campus were successfully captured that significantly contribute to the creation of comprehensive urban models with precise geometric information. The results obtained from the case study highlight the potential of UAV-based LiDAR systems to revolutionize urban mapping practices, offering unparalleled capabilities for capturing fine-scale urban features and structures. From detailed building reconstructions to vegetation mapping and terrain modelling, the methodology has showed the versatility and utility of LiDAR technology in urban environments. Furthermore, the research contributes to the advancement of remote sensing technologies for urban applications, addressing key challenges such as data acquisition, processing, and integration. By optimizing flight planning strategies, developing robust data.

Acknowledgements

The authors acknowledge the financial support of deanship research fund, Deanship of Research, Sultan Qaboos University, Oman, grant number IG/ENG/CAED/23/03.

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