International Journal of Engineering and Geosciences

https://dergipark.org.tr/en/pub/ijeg

e-ISSN 2548-0960

Methodology of real-time 3D point cloud mapping with UAV lidar

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Keywords
UAV LiDAR System
3D Point Cloud
Remote Sensing
X3D
3D Modeling Real-Time Mapping

Research Article
DOI: 10.26833/ijeg.1178260

Received:21.09.2022
Revised: 23.01.2023
Accepted:13.02.2023
Published:08.05.2023

Abstract

Accurate and timely availability of LiDAR data is vital in some cases. To facilitate monitoring of any environmental changes, LiDAR systems can be designed, and carried by UAV platforms that can take off without major preparation. In this study, the methodology of the real-time LiDAR mapping system was developed in the laboratory. The designed system shortens the target-based flight planning and post-flight data processing. In this system, the data is taken instantly and thus the change in the mapping area can be detected quickly. The simulation system, produce 3D point cloud, and data was stored in a database for later analysis. The 3D visualization of the data obtained from our developed UAV-LiDAR system was carried out with a platform-independent interface designed as web-based. The X3D file format used in the study to produce 3D point data provide an infrastructure for AI and ML-based systems in identifying urban objects in systems containing big data such as LiDAR.

1. Introduction

Remote sensing systems allow for obtaining a repeatable and consistent image at spatial, spectral, radiometric, and temporal resolutions to monitor the impact of short/long-term environmental changes and human activities on the earth [1–5]. Environmental assessment/monitoring, detection/monitoring of global change, agriculture, meteorology, mapping and military surveillance/reconnaissance are some of the important applications of remote sensing technology [5,6]. Many remote sensing systems have been developed that offer a wide variety of spatial, spectral and temporal parameters to meet the needs of data users working in different application areas [4,5]. Technological developments in these systems increase the number of studies on forest ecology management and water use on a global scale [7, 8]. In recent years, the use of LiDAR data obtained by aircraft or satellites has been preferred to examine urban areas (buildings, roads, vegetation, etc.) where the fastest changes can be observed on earth [9–11].

Platforms used to acquire LiDAR data (3D point cloud) over large and continuous areas are airplanes, satellites, and helicopters [1]. The spatial and temporal resolutions of high-cost inflexible manned aerial LiDAR systems are limited, especially when collecting high-resolution data in small areas [12,13]. When higher data density is required for smaller areas, UAV systems that provide high temporal and spatial resolution data; it has become a widely used remote sensing platform in various applications due to their features such as low cost and flexible data collection [11,14–17].

Accurate and timely acquisition of LiDAR data is vital for monitoring environmental change and post-disaster emergency response [18]. LiDAR data obtained over a certain region (street, city) in different periods is an important resource that can be used in these processes [19]. However, examining and making available LiDAR data at the ground station after each flight takes place through a series of processes/steps and temporal processes [20]. When evaluating the suitability of the UAV LiDAR system for the 3D point cloud at a precise scale, it is encountered that the repeatability and comparability are limited due to the unsystematic flights and the potential effects of flight parameters [21]. To improve this situation, studies are carried out on long-term flight planning, autopilot systems, regular

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Cite this article

Candan, L., & Kaçar, E. (2023). Methodology of real-time 3D point cloud mapping with UAV lidar. International Journal of Engineering and Geosciences, 8(3), 301-309

trajectory determination, and post-flight data processing processes [16,22].

In addition to the accurate and timely acquisition of LiDAR data, it is also important that the relevant LiDAR data can be easily accessed by experts and the public via remote access for various applications and can take action accordingly [23]. The limitations of many of the online tools owned by individual researchers may not allow 3D visualization. The disadvantage of the existing tools is that they are not flexible enough for them to create 3D scenes of a mixture of point-based and triangle-based models when the density of the 3D point cloud is also taken into account [24]. Given the wide availability of the internet world, transmitting remote sensing data via browsers is a good choice [23]. In addition, developments in HTML5 technology and cloud systems have enabled Web-based 3D visualization. In various applications (forestry, environment, etc.) where LiDAR data is used, it is necessary to develop simulations using accurate geospatial information. Developed high-resolution simulations need a real-time 3D simulation infrastructure that can provide a base platform for these various fields and can be shared. The use of this data in 3D environments is possible with the provision of a platform-independent web-based infrastructure. This can be achieved using the extensible 3D (eXtensible 3D: X3D) standard [25]. 3D data can be visualized with X3DOM (X3D+DOM: DOM that describes the concepts of interaction and hierarchical representations associated with the content of HTML documents.), which allows X3D elements to be included as part of any HTML5 DOM (Document Object Model) tree. X3DOM is a WebGL-based library built on the extensible 3D (X3D) standard, allowing users to create 3D scenes with little knowledge of computer graphics [23,24].

The main motivation of this study is to contribute to the solution of the problems arising from pre-flight (long-term flight planning, autopilot systems, regular trajectory determination etc.) and post-flight processes (data processing) of the UAV-LiDAR systems. One of the results of this motivation is to produce a real-time 3D point cloud that can be used effectively in rapid decision-making processes in disaster situations.

In this study, a methodology that allows instant visualization of LiDAR data is presented. Within the scope of this methodology; the real-time processing processes of the data obtained from the UAV LiDAR system are described. This system provides instant visualization with a web-based interface that can be constantly renewed/improved with the development of web technology. With this system, besides the production of an instant 3D point cloud that can be used in areas where fast access to data is needed, this data is also instantly stored in a database (PostgreSQL or MySQL) for later analysis. There are exponential increases in information processing capability and storage capacity with the increase in big data on a global scale. Therefore, artificial intelligence (AI) and machine learning (ML) are becoming important in data processing processes. One of the systems containing big data is LiDAR. AI and ML provide important information and predictions in LiDAR applications which is used natural disasters that require quick decision-making.

2. Method

Accurate and timely availability of LiDAR data is vital in some cases. For this purpose, an effective methodology has been put forward that provides instantaneous 3D point cloud generation that can be used easily in disaster situations as well as eliminating the problems arising from the pre-flight (long-term flight planning, autopilot systems, regular trajectory determination etc.) and post-flight processes (data processing) of UAV-LiDAR systems.

A two-component system was designed to realize the Real-Time 3D Point Cloud Mapping Methodology with UAV LiDAR. The structure of this methodology developed in this context, suitable for the real environment, is shown schematically in Figure 1. The first of these two main components are the Remote Sensing Platform (Unmanned Aerial Vehicle and LiDAR), and the second is the Ground Control & Recording Station. These two components interact with each other simultaneously. The first thing to do for this methodology to work is real-time data acquisition. This data acquisition process is detailed in section 2.1. The second thing to do is to make these LiDAR data obtained in real time available as a 3D point cloud with a platform-independent web interface. The development of this web interface using X3D file format, PHP programming language and MySQL database is explained in detail in section 2.2.

The methodology developed here is platform independent and was first simulated in a laboratory environment to test the data from all sensors used in real systems. This methodology, which is simulated in a laboratory environment, has features that can be adapted to the desired remote sensing platform and its limits can be expanded. Thanks to the telemetry technologies in use and the rapidly developing innovative technologies (5G), it allows to transfer data wirelessly over longer distances. The development of X3D graphics libraries is continued in a fast and stable manner, increasing their use on more platforms [26]. Although some web-based (HTML5) studies have made geographic visualizations in X3D file format, LiDAR data previously obtained by manned/unmanned aerial vehicles have been used in the relevant systems [23, 27]. In addition to these features of the X3D file format, it is very successful in defining objects in accordance with AI and ML.

The components (X3D, MySQL, PHP, Real-time LiDAR data, etc.) brought together to implement this methodology are not yet available in the literature and are open to development.

2.1. Laser scanning process

In this study, a simulation system that can be adapted to real environment components in the laboratory environment has been created for any flight platform (Figure 2), to reveal the methodology of the "Real-Time 3D Point Cloud Mapping with UAV LiDAR". Here, instead of UAV, a platform that is moved at a constant speed on a sled with a constant height was used for real-time scanning processes. In order to develop the methodology, the SF45B (micro-LiDAR, LightWare

Optoelectronics (Pty) Ltd) model laser scanner, which is a suitable micro-LiDAR for small areas such as laboratory environments, was selected. The selected SF45B laser scanner was placed on the carrier platform, viewing the scanning area (Figure 2). The field of view (FOV) of the laser scanner was adjusted to approximately 60º to obtain more detailed data. The distances from successive positions of the platform moving at a constant speed to the ground were measured by making a series of scans.

SF45B model laser scanner has a 1 cm linear resolution, ±10 cm precision, and angular resolution of less than 0.2º. In addition, the scanner makes 5000 readings per second at a scanning angle of 340º and up to 50 m measuring distance. Generally, GPS systems are used to determine the location of Remote Sensing Platforms (RSPs). In the system created in the laboratory, location information was obtained by using a VL53L0XV2 model laser range finder (LRF), which measures horizontally sensitive distance, instead of GPS due to the short distance (~1 m). Acceleration, roll, pitch, and yaw data are also utilized by using an Inertial Measurement Unit (IMU: usually includes an accelerometer, a gyroscope, and a magnetometer) to determine the position of the UAV platforms. In this system, MPU6050 model IMU was adopted to get information from acceleration, roll, pitch, and yaw sensors (Figure 2).

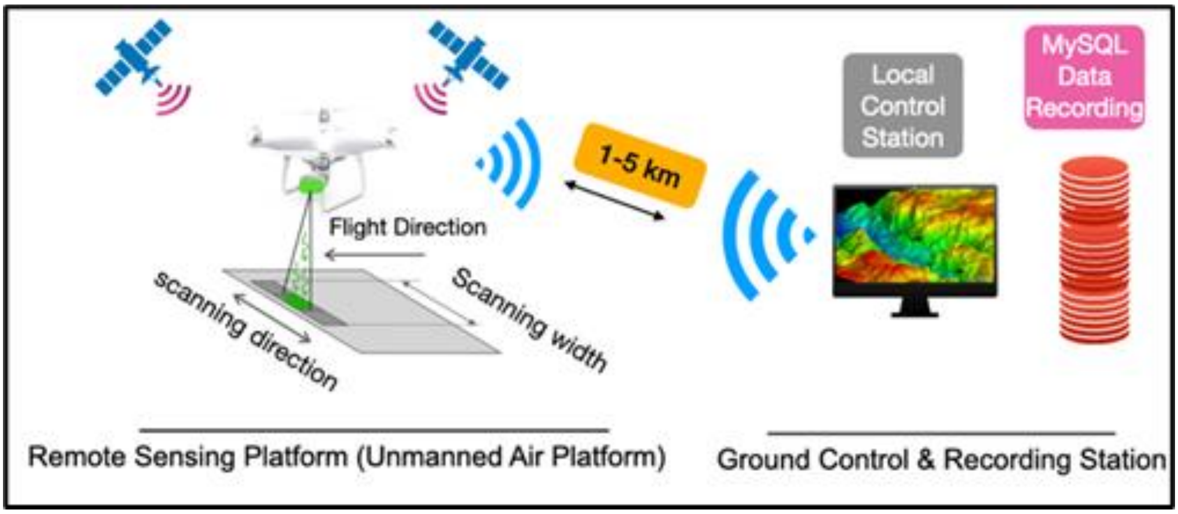

Figure 1. Schematic representation of Real-Time 3D Point Cloud Mapping System with UAV LiDAR providing data transfer for real environment. Remote Sensing Platform (Unmanned Aerial Vehicle) and Ground Control & Recording Station

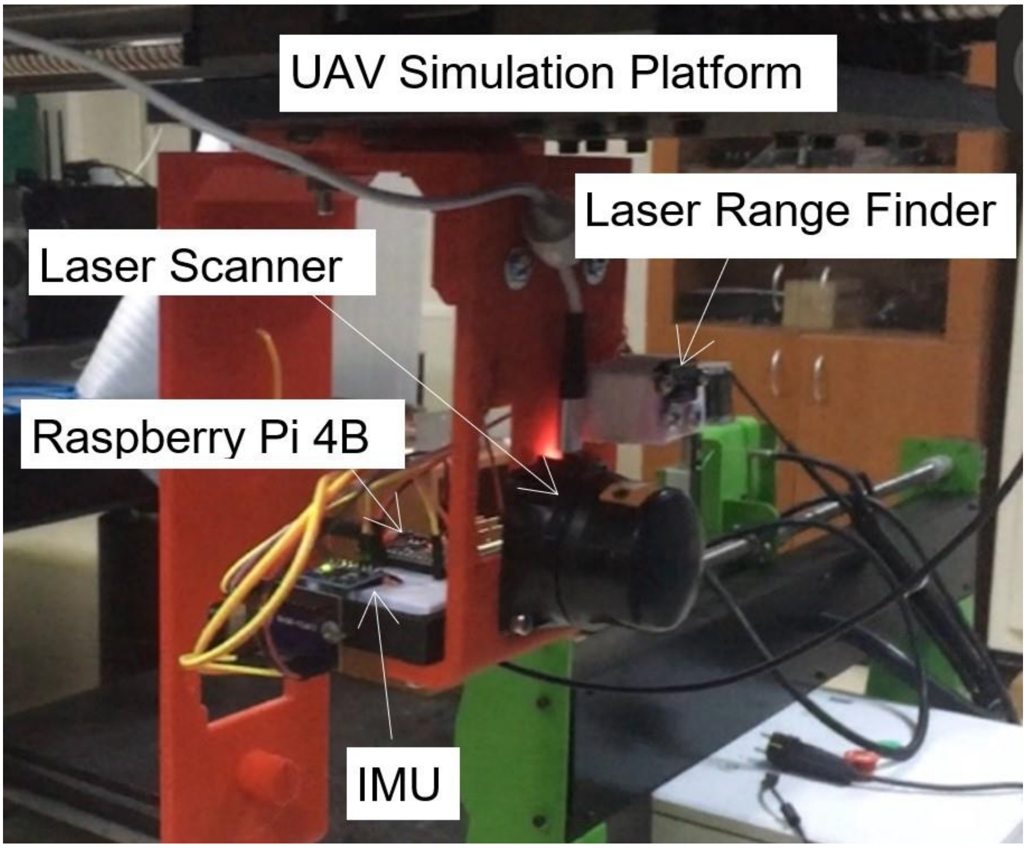

Figure 2. UAV Simulation Platform: Scanning system, LRF, recording system, and IMU

In the environment where the platform is used, objects of various shapes of known sizes (Table 1) were placed on the floor and the external environment was simulated (Figure 3). The LRF used to obtain position information (r_{LRF}) during the scanning process was positioned to move parallel to the ground. While the system was moving, different angle values were obtained for each measurement by making right angles to the laser scanner movement direction. By using the angle values (θ_n) and distance values (hypotenuse = r_n) measured from the laser scanner, the vertical edge distances of the right triangles formed as shown in Figure 3 were calculated with the equations in Table 2.

Table 1. Dimensions of target objects labeled in Figure 3

Target	Size (m)
First (yellow)	x = 0.215, y =0.075, z = 0.180
Second (pink)	x = 0.21, y = 0.190, z = 0.08
Third (blue)	x = 0.20, y = 0.025, z = 0.05
Fourth (white)	h= 0.20, r=0.028

Table 2. Coordinate equations of the transformed point in accordance with the X3D scene

Terms	Defined as
measured distance for point n (cm)	r_n
advance distance for point n (mm)	r_{LRF}
x coordinate of point n (m)	$x_n = (\sin\theta_n . r_n)/100$
y coordinate of point n (m)	$y_n = (\cos\theta_n . r_n)/100$
z coordinate of point n (m)	$z_n = r_{LRF}/1000$

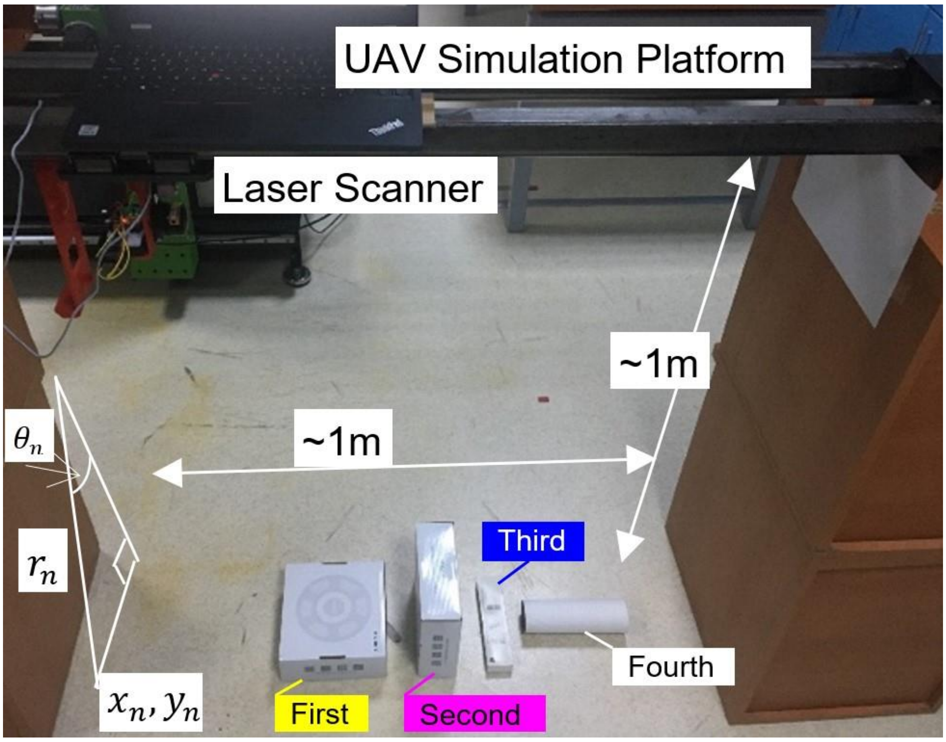

Figure 3. Overview of the experimental workspace for realistic simulation in the laboratory environment

2.2. Data processing

Data from all sensors were recorded on Raspberry Pi 4B (Raspi4B), a computer with a single board structure. The Raspi4B (Raspberry Pi Foundation) used in this study has 8 GB LPDDR4-3200 SDRAM, Broadcom BCM2711-Quad core Cortex-A72 (ARM v8) processor with 64-bit architecture, and 64 GB data storage. In this microcomputer, on which C codes were compiled, all data from the sensors were instantly recorded in the MySQL database on it. In about 1 minute, 114.438 3D point coordinates (x, y, z) were obtained. Raspi4B can connect to a common internet network (modem) in a laboratory environment with its built-in 2.4/5.0 GHz WiFi module. By using this feature, connection with another computer defined as Ground Control & Recording Station can be established by using the SSH (Security SHell) protocol, which is a secure remote login method. With this connection method, the real-time 3D point cloud was obtained by providing online wireless remote access to the instant data obtained from the MySQL database running on Rasp4B via the web interface developed on the Ground Control & Recording Station. The web interface was developed using the PHP programming language and the X3D file format. In approximately 1 minute, x, y, z coordinate information was obtained for each point measured with the data taken from the laser scanner and other sensors. During this period, 3D visualization was made for 114.438 x, y, z point coordinates.

3. Results

In the Ground Control & Recording Station of the "Real-Time 3D Point Cloud Mapping with UAV LiDAR" System, whose methodology was given in the previous section, instant data were received with the web interface created using PHP programming language. By selecting the relevant data table in the web interface and clicking the "Show 3D Point Cloud" button, it was directed to the web page where the 3D point cloud obtained by scanning was displayed (Figure 4).

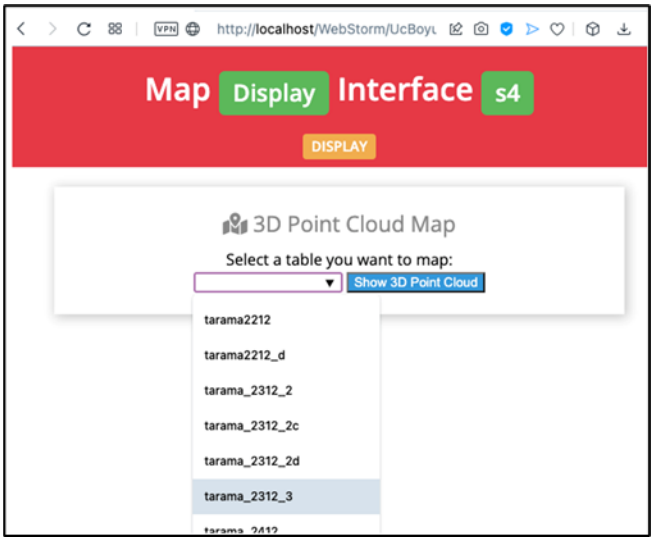

Figure 4. 3D Point Cloud visualization web interface.

These data were obtained by instant, wireless and remote access. The obtained data was visualized as a 3D point cloud using the XML-based X3D (Extensible 3D) file format, which is the Web3D standard that can run on a platform-independent web browser. Figure 5 shows the point cloud map that is extracted simultaneously with the real-time data. Figure 6 shows 3D point cloud overlapping with objects in X3D scene.

As seen in Figure 5 and Figure 6, coordinate transformations were made between IMU and X3D file format during the scanning process. According to these transformations, the +y axis of the IMU is the +z axis in X3D file format and is outward from the page plane (Figure 5). The +z-axis of the IMU is the +y-axis (green colored axis) in X3D file format, pointing upwards (Figure 5). The +x axis of the IMU is the same as the +x axis (red color axis) in X3D file format and is to the right (Figure 5).

Figure 5. 3D point clouds of objects in X3D scene

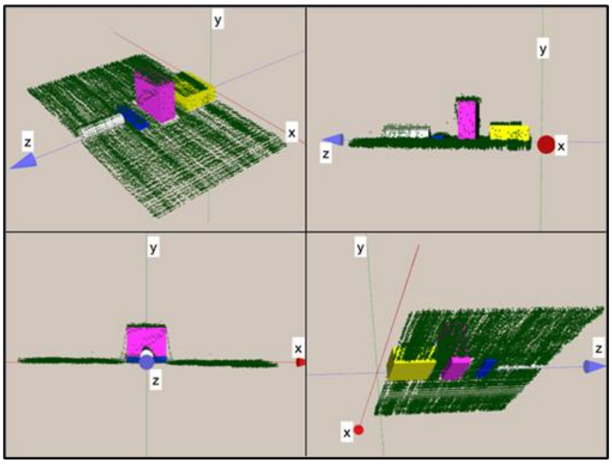

Figure 6. 3D point cloud overlapping with objects in X3D scene

The altitude value initially measured by the laser scanner moved at a constant height was accepted as a reference (0.985 m). The distances from all measured successive positions to the ground were obtained by subtracting (for y-axis) from this reference value. Then, the accuracy of the 3D point cloud of the data obtained simultaneously and wirelessly with the developed simulation was evaluated. For this, the real dimensions of the relevant objects in the X3D scene were created in the Ground Control & Recording Station. Figure 6 shows the overlap of the 3D point cloud obtained with the objects in the X3D scene. Although this system is a remote sensing platform at a constant height and constant speed, the information obtained from the IMU is also considered to process the data realistically. The data obtained from the IMU consists of acceleration values in m/s^2 unit for x, y, z axis separately and gyroscope angle values in rad/s unit separately for x axis roll, y axis pitch, z axis yaw.

The appearance of real objects on the scanned surface at various time intervals in the X3D scene is given in Figure 7.

The accuracy comparison was made between the height of the objects measured by laser scanning and the actual height of the objects as in Figure 8. Root Mean Square Error (RMSE) was calculated as 0.020158 m in the comparison. In other words, a 2% variation was observed between the actual object heights and the measured heights. It was observed that the measurements were within the accuracy values of the laser scanner used.

The acceleration changes and gyroscope changes obtained for all three axes during the scanning process are shown respectively in Figure 9 and Figure 10. In addition, the gravitational acceleration was measured as ~9.80 m/s^2 according to the sensitivity of the IMU in the z-axis of the IMU (Figure 9). Although these data did not change in the laboratory environment, they were used in the calculations. Thus, adaptive simulations of this methodology to systems containing a relatively high-altitude UAV LiDAR system (for real environments) have been obtained.

4. Discussion

Real-time 3D Point Cloud Mapping with UAV LiDAR system, whose methodology was given in the previous sections, was simulated in a laboratory environment in a realistic way. The structure of this methodology developed in this context, suitable for the real environment, is shown schematically in Figure 1. The first thing to do for the methodology to be successful is the real-time data acquisition process. For this, a LiDAR system that receives real-time data was designed. Accurate and timely acquisition of LiDAR data is vital for monitoring environmental change and post-disaster emergency response [18]. LiDAR data obtained over a certain region (street, city) in different periods is an important resource that can be used in these processes [19].

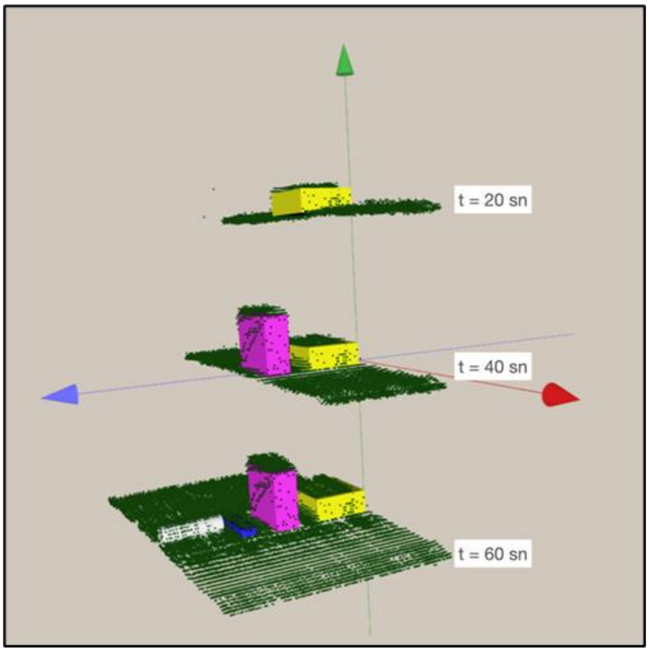

Figure 7. The appearance of real objects on the scanned surface in the X3D scene at various time intervals

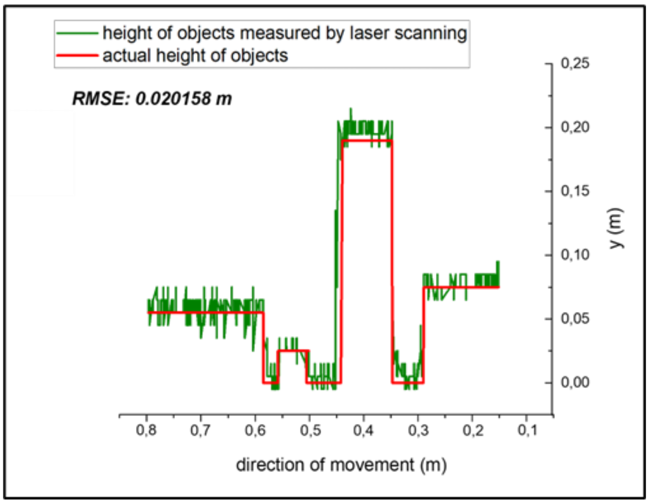

Figure 8. Accuracy comparison between the height of objects measured by laser scanning and the actual height of objects

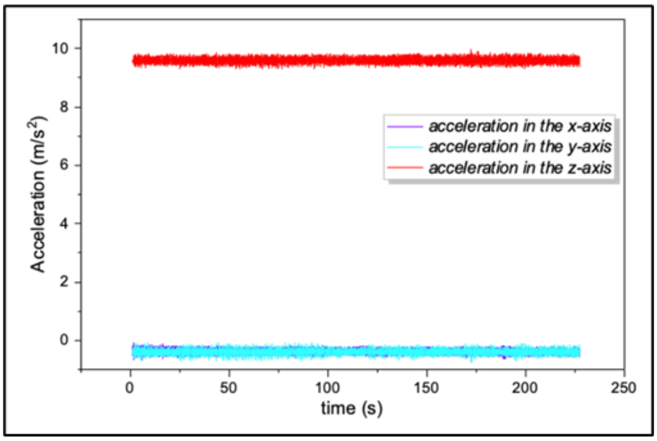

Figure 9. Changes in acceleration in all three axes

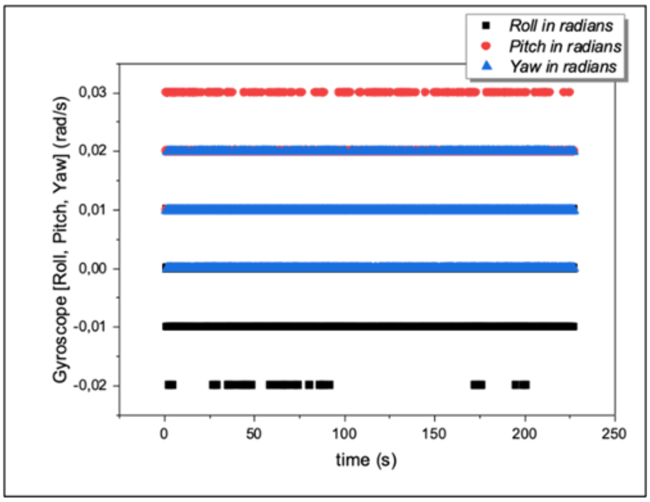

Figure 10. Changes in roll, pitch, and yaw

The UAV-LiDAR platform, which constitutes the first part of the methodology, has the feature of acquiring and recording real-time data on itself. The reason for recording on the platform is to avoid data loss in case of any disconnection with the Ground Control & Recording Station, which is the second part of the methodology. Georeferencing points are obtained from the GPS data of the relevant area in the systems used in the real environment. Although GPS is not used in this system designed for the laboratory environment, it is possible to record these data in a related way.

Another aim of this study is that LiDAR data can be easily accessed by experts and individual researchers in various fields via remote access. With this system, besides the production of an instant 3D point cloud that can be used in areas where fast access to data is needed, this data is also instantly stored in the MySQL database for later analysis. In addition to the accurate and timely acquisition of LiDAR data, it is also important that the relevant LiDAR data can be easily accessed by experts and individual researchers via remote access for various applications and can take action accordingly [23]. This designed system is very useful in making retrospective research or comparisons by recording the data with date stamps. Developed in accordance with the methodology, this design ensures that data can be accessed by more than one user at the same time. With this access, users have the opportunity to easily search, filter, and quickly visualize the desired data range on the data.

In various applications (forestry, environment, etc.) where LiDAR data is used, it is necessary to develop simulations using accurate geospatial information. Developed high-resolution simulations need a real-time 3D simulation infrastructure that can provide a base platform for these various fields and can be shared. The use of this data in 3D environments is possible with the provision of a platform-independent web-based infrastructure [25]. Also, many of the online tools owned by individual researchers are limited in rendering 3D scenes, given the density of the 3D point cloud [24]. Given the wide availability of the Internet world, transmitting remote sensing data via web browsers is a good choice [23]. In addition, developments in HTML5 technology and cloud systems have enabled Web-based 3D visualization. The 3D visualization of the data obtained from our developed UAV-LiDAR system was carried out with a platform-independent interface designed as web-based. This infrastructure, available to multiple users, is visualized with X3DOM, which allows X3D elements to be included as part of any HTML5 DOM tree. X3DOM is a WebGL-based library built on the extensible 3D (X3D) standard, allowing users to create 3D scenes with little knowledge of computer graphics [23,24]. X3D is a standard maintained by the Web3D Consortium and approved by the International Organization for Standardization (ISO). This developed design provides a compliant complement to existing GIS standards produced by the Open Geospatial Consortium (OGC) and Web Architecture supported by the World Wide Web Consortium (W3C 2004).

In our study, a LiDAR mapping system was designed that shortens target-based flight planning, regular trajectory determination and post-flight data processing. As it is understood from the literature research, examining and making available LiDAR data at the ground station after each flight takes place through a series of processes/steps and temporal processes [20]. When evaluating the suitability of the UAV LiDAR system for the 3D point cloud at a precise scale, it is encountered that the repeatability and comparability are limited due to the unsystematic flights and the potential effects of flight parameters [21]. To improve this situation, studies are carried out on long-term flight planning, autopilot systems, regular trajectory determination, and post-flight data processing processes [16,22].

The Real-time 3D Point Cloud Mapping with UAV LiDAR System, whose methodology is presented, has the advantage of enabling rapid rescanning of the area when missing data is detected. Identifying urban objects, producing accurate and timely information about the location of these objects, is important in urban planning and disaster management.

Another aim of this study to provide an infrastructure for AI and ML-based systems. The X3D file format we used in our study forms the basis of artificial intelligence (AI) and machine learning (ML) based applications. This file format is very successful in identifying relevant urban objects in accordance with AI and ML. AI and ML can be used to create 3D maps using LiDAR data or to identify and classify surrounding objects. AI and ML can improve the accuracy and speed of LiDAR applications when used to process, filter and extract meaningful information from LiDAR data. In addition, AI and ML allow modeling and forecasting about the environment using large volumes of LiDAR data. This valuable information and estimates can assist institutions and organizations in making decisions in natural disasters.

This study can be easily extended for real environments with more advanced and currently in use telemetry and GPS technologies. In addition, thanks to rapidly developing innovative technologies such as 5G, allow faster wireless data transfer over longer distances. The results of this simulation study in the laboratory environment, whose methodology is presented, can be easily integrated into the relatively high-altitude UAV LiDAR system with all its components in the real environment. We also believe that the presented methodology is in line with OGC's mission, which connects people, communities, and technology to solve global challenges and meet daily needs.

5. Conclusion

In this study, a real-time LiDAR measurement system was established. The designed system shortens the processes of target-based flight planning and post-flight data processing. With this developed real-time LiDAR mapping system in laboratory, data is obtained instantly, so that the change in the area in question can be detected and fast solutions can be produced to the problems. The simulation system, produce 3D point cloud, and data was stored in a database for later analysis. The X3D scene used in the study to produce 3D point data provide an infrastructure for AI and ML-based systems in identifying urban objects in systems containing big data such as LiDAR.

Acknowledgement

This work has been supported by Kocaeli University Scientific Research Projects Coordination Unit under grant number #2561.

Author contributions

Levent Candan: Conceptualization, Methodology, Software, Field study, Writing-Original draft preparation, Data curation, Validation. **Elif Kaçar:** Investigation, Writing-Reviewing, and Editing. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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