University of Nairobi
Faculty of Engineering

Application of UAV-LiDAR System in Forest Inventory; A case of Mombasa Bamburi Cement Forest

By

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Declaration

I, (Felix Wachira Ngure), hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

Felix Ngure

Name of student

22-08-2022

Date

This project has been submitted for examination with my approval as university supervisor.

Dr. Sammy Musyoka

Name of supervisor

22.08.2022

Date

Dedication

I wholeheartedly dedicate this project to my late Dad, Eustace Ngure Wangai

Acknowledgement

This academic undertaking is wholeheartedly acknowledged by my supervisor Dr. Sammy Musyoka whose insights and knowledge of the subject directed me through this research. I would also like to thank the staff at the Department of Geospatial and Space Technology, the Faculty of Engineering at the University of Nairobi for the valued support, critique, and guidance during this research project.

To my family, colleagues, siblings, friends, and classmates who shared their words of advice and encouragement to finish this study. I offer my sincere appreciation for the learning opportunity provided during the entire period of undertaking this work.

And lastly, I dedicate this work to the Almighty God, thank you for the guidance, strength, power of the mind, protection, and skills and for giving me a healthy life. All of these, I offer to you.

Abstract

Forests help regulate the global climatic condition through the absorption of carbon dioxide from the environment and storing it in biomass and soil. In 2016, about 27% of carbon dioxide emitted from fossil fuels and industries was absorbed by the forests(*UN*, 2019). Forests also can absorb and keep about one-tenth of global anthropogenic emissions in their biomass, soil, and products. However, nearly 12 million hectares of forest are ruined annually through deforestation, coupled with farming and other land-use changes such as urban development, which is accountable for 25 per cent of global greenhouse gas emissions (UNEP 2022).

The main objective of this study was to use LiDAR data from the UAV to support forest monitoring and management through forest inventory. This study focused on the Bamburi forest in Mombasa County, Kisauni Sub-county. The forest is located within the coastal region where the effects of climate change include a rise in sea level, high temperatures, etc.

The study used the DJI Matrice 300 RTK drone mounted with a LiDAR camera. The study undertook flight mission preparations, flight mission, and data processing and validation in a GIS environment to generate the point cloud data that were used to generate forest attributes and earth models. The output of the project was the 0.5 m DEM of the study area and forest attributes, including tree count, tree heights, tree crown diameter, and tree crown areas and their spatial distributions.

The study concluded that it is possible to use UAV LiDAR data to generate forest attributes which are important in forestry management. The study then recommended that in the application of UAV LiDAR for forestry monitoring, a multispectral camera should also be used to be able to generate tree species information in the forest to not only support the sustainable management of the forest but also enhance biodiversity conservation measures.

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List of Abbreviation

ASCII	American Standard Code for Information Interchange
COP 26	26th United Nations Conference on Climate Change
CSV	Comma separated value
CHM	Canopy height model
DEM	Digital elevation model
DSM	Digital surface model
DTM	Digital terrain model
FAO	Food and Agriculture Organization
GPS	Global positioning system
GNSS	Global navigation satellite system
GIS	Geographic information system
IMU	Inertial measurement unit
INS	Inertial navigation system
KCAA	Kenya Civil Aviation Authority
KFS	Kenya Forest Service
KWS	Kenya Wildlife Service
KCAA	Kenya civil aviation authority
LiDAR	Light detection and ranging
MP	Megapixel
MSL	Mean sea level
RTK	Real-time kinematic
TIN	Trangulation irregular network

USGS	United States Geological Survey
UN	United Nation
UNEP	United Nations Environment Programme
UAV	Unmanned Aerial Vehicle

CHAPTER 1: INTRODUCTION

1.1 Background

Forests help regulate the global climatic condition through the absorption of carbon dioxide from the environment and storing it in its biomass and the soil. In 2016, about 27 percentage of carbon dioxide emitted from fossil fuels and industries was absorbed by the forests (UN, 2019). Forests also can absorb and keep about one-tenth of global anthropogenic emissions in their biomass, soil, and products. However, nearly 12 million hectares of forest are ruined annually through deforestation, coupled with farming and other land-use changes, which is accountable for 25 percentage of global greenhouse gas emissions (UNEP 2022).

Companies across various sectors, international organizations, and governments are promising to stop deforestation and increase forest restoration processes to reduce the impacts of climate change, reduce biodiversity loss and maintain the benefits of forests to people and nature (FAO 2022). The efforts by these agencies were witnessed in the recent COP26 declaration in 2021 at Glasgow where leaders from more than 138 countries committed to working collectively to stop and restore the forest loss by 2030 while providing sustainable development activities and encouraging inclusive transformations (FAO 2022).

Advances in remote sensing, cloud infrastructure, and machine learning are increasing by the day. These technology breakthroughs, combined with government and private sector commitments, have the potential to drastically transform the way landscapes are monitored. The geospatial data generated through these technologies will drive dependable and organized monitoring and authentication, which is dynamic in averting deforestation and re-establishing tainted lands.

1.2 Problem Statement

According to FAO, the global land surface covered by forest is about 31% (FAO, 2022), and half of this forest area is moderately undamaged. More than a third of it is made of the natural forest while the rest is man-made. There is, however, a problem with the distribution of these forested areas, more than half of them are found in five countries which are Brazil, Canada, China, the United States of America, and Russia. There is therefore a need for the remaining countries to not only protect the areas within their boundaries, but also promote afforestation activities on the degraded areas, mining, and quarry sites which are no longer active among others. These efforts will not only enhance the process of halting the effects of climate change, but also will restore the lost biodiversity since most terrestrial plants and animals are living in the forests.

Currently, the afforestation in the degraded is being done through a community partnership with the government whereby the local people are allocated portions of land and tree seedlings to plant the trees and food crops in a mixed crop farming arrangement. This practice, however, cannot cover the whole area since some of the degraded lands are not fertile enough to sustain agriculture or are inaccessible, especially in the old quarry sites which could be dangerous due to bare soil and rocks. Restoration of such areas would therefore require a remote-controlled system which can be used to plant and monitor the growth of the trees by periodically generating the attributes like the tree heights, tree girth, tree counts among others, which helps in the generation of information for management decisions.

This project, therefore, intends to use UAV to provide forest attributes including, DEM with a high-resolution for the study area, tree heights, the number of trees and the diameter of the canopies of the study area. Bamburi forest is situated near the Bamburi Cement factory in Kisauni Sub county , Mombasa County in the republic of Kenya.

1.3 Study Objective

1.3.1 General Objective

The main objective of this study was to demonstrate that UAV LiDAR data can used to support forest monitoring and management through forest inventory. This study focused on an old quarry site measuring approximately 134 acres of land currently undergoing afforestration and land restoration by the Bamburi Cement Company in Mombasa County in Kenya.

1.3.2 Specific Objectives

The specific objectives of this study were to;

- To generate a high-resolution DEM of the study area.
- To generate an inventory of the trees in the study area.
- To generate tree attributes, including tree location, tree heights, and crown diameters.

1.4 Justification for the Study

The lack of mapping resources has been affecting the forestry departments in developing countries including Kenya. The available earth observation data through satellite sensors are expensive and do not offer real-time data that can be used to monitor and manage forests effectively. Manual labour is also equally expensive, slow, and inaccurate.

The use of UAVs is getting common due to its advantage over the satellite sensors and manual monitoring methods. The inexpensive UAVs are currently being used in various research projects, including vegetation monitoring, car counting, contour mapping, 3D analysis, flood mapping, vegetation cover mapping, baythmetric survey and analysis, landslide analysis, and transmission line checks, among others.

UAVs have made surveying and mapping of small areas to be extremely quick and also provide for multi-temporal acquisitions over the same area at predefined times. This project aimed at using the UAV to generate both the spatial and non spatial data, including tree count and their respective locations, tree heights, canopy area, volume and diameter of the study area. This will help in supporting the forest managers to make decisions on measures to be taken to improve the health of the trees in the forest under their management.

1.5 Scope of work

This study focused on approximately 134 acres of Bamburi Cement forest in Mombasa County, as shown in Figure1.1. The area identified had a higher percentage covered by trees and thus deemed good to determining whether LiDAR sensor is a good source in generating DEM in forested area. The study focussed on generating the forest attributes including tree heights, tree count, tree canopy diameter and canopy areas. The study did however not provide data for the tree species in the forest since the camera used did not have the multispectral capacity which is needed in the identification of tree species in the forest.

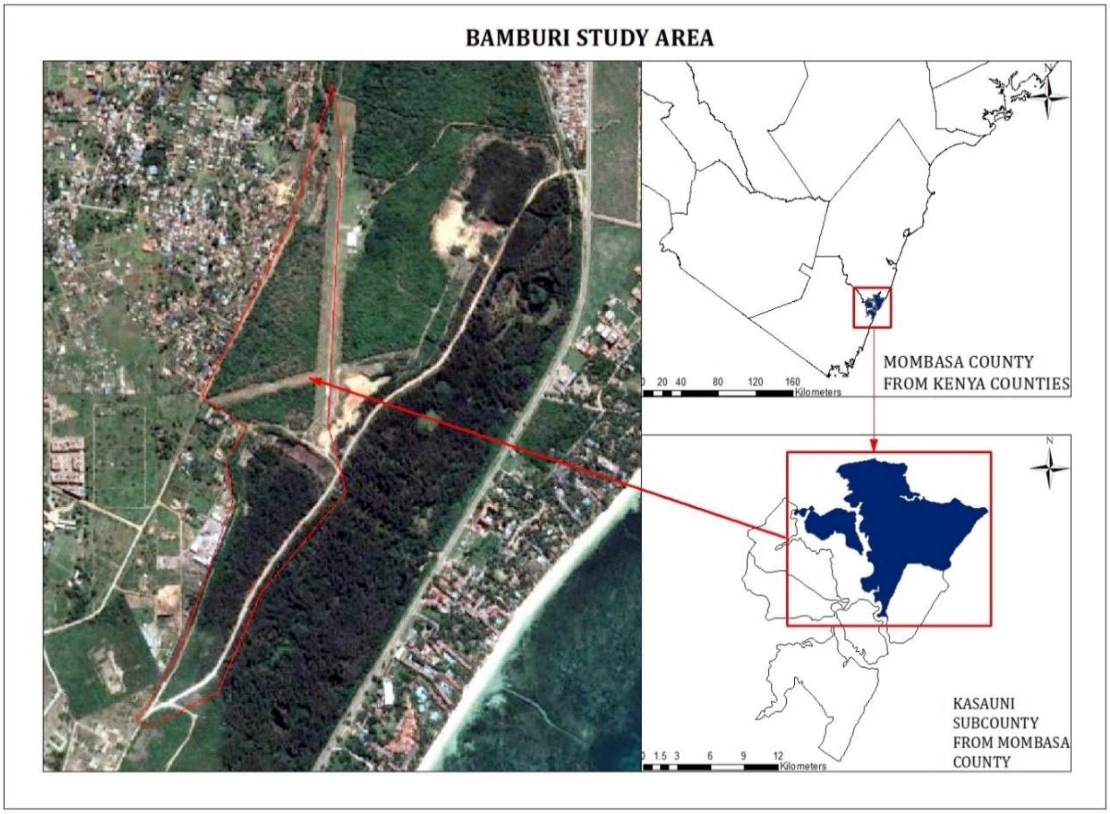


Figure 1.1: Location and Context of study area. Source; Author

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Forests are home to more than half of the world's land-based flora and fauna. Forests also combat the changes in climatic conditions by providing sinks to greenhouse carbon emissions. Forests equally provide a buffer from storms and floods and provide livelihoods to forest-dependent populations(Pagán et al., 2019; UNEP 2022).

The need to sustainably manage the forests for them to support the current benefits without compromising the future needs is therefore very important. (Pagán et al., 2019). opined that a sustainable way of managing forests is through constant forest data collection and analysis of the forest inventory data, including heights, canopies, biomass among others. (Pagán et al., 2019). This is particularly important because it will help in protecting the biodiversity in the forests, maintain the livelihoods and continue to mitigate climatic situations.

2.2 Forest Inventory

According to Brad Smith, forest inventory is the collection, compilation, analysis, publication and archiving of forest data including the tree attributes(Smith, n.d.). This inventory should be conducted periodically and assessed to provide the long-term status of the forest, and variations and tendencies in the health of the trees. The approach to be used in conducting this periodic data collection should therefore be more responsive to the information needs about the most important issues and trends that are capable of directly impacting the use and management of the forest.

Recently the use of UAV technology in the field of ecosystem studies has increased over the last decade . The most common data that are obtained from UAV monitoring include the plant species, plant heights, location of the stem, biomass that is located above ground, and canopy orientation as was listed by Kentsch in his 2021 publication on the “Analysis of UAV-acquired wetland orthomosaics using GIS, computer vision, computational topology and deep learning” (Kentsch et al., 2021). UAV can create a higher amount of spatial information on forests as it allows the quick survey of a large forest area.

This study focused on using LiDAR from a UAV to extract the biophysical composition of a forested area in Mombasa County, including the number of trees in the forest, and the elevation information of the study area.

2.3 Methods currently used to monitor the forest.

The use of remote sensing and GIS techniques to monitor and manage the forests has not been adopted fully, especially in small-scale forests. The forest managers mostly rely on the traditional manual method of visiting the forests and taking field observations and measurements. This method is not only time-consuming, but also quite expensive especially when the forest requires frequent data to inform the trends in the forest.

The large forests however have embraced the use of remote sensing techniques to obtain data about the forests and carry out spatial analysis including change detection. One of the common sources of data for such analysis is the Landsat imagery which has a spatial resolution of 30m and one cannot generate the tree attributes from Landsat data. The use of Airborne ortho-imagery remote sensing to manage the forest inventories has also been used and it has become a powerful tool being used by the forest management authorities due to the flexibility it offers to the managers since they can determine the time to fly the aircraft as opposed to the satellite data which are not within their control (Otero et al., 2018). An extensive range of data products from airborne imagery to extract the forest attributes have been adopted by the recent and ongoing research in the processing and analysis of ortho imagery data(Hyyppä et al., 2008). Forest managers have been provided with significant statistics on tree-level attributes and they have managed to gain insightful information about their forests. However, the ortho imagery data are not able to give the heights and other 3D information of the trees and forest which are key indicators in forest health monitoring and management. The cost of carrying out the airborne survey and manpower skills required to analyze the orthoimages through photogrammatrice analysis to obtain the forest data are not possible to achieve especially if the forest coverage is not vast.

2.4 UAV LiDAR

The potentials of UAV LiDAR data in forestry management are not yet fully exploited both in terms of research and actual application in forest management. (Hyyppä et al., 2008; Wallace et al., 2012). The study conducted by Hyyppä et al.,2008, measured the forest aspects such as strength, defoliation, digital elevation modelling (DTM), and frequency of the canopy closer using the UAV LiDAR. However, all these attributes are not achievable from the current LiDAR surveys available for use by the forest managers due to a lack of exposure to such information.

The recent improvement in UAVs has offered a combination of high-resolution 3D data collection. UAV technology has allowed the generation of point cloud data with high density which can be evaluated for forest monitoring as was proven by (Chiabrando et al., 2011). The capability of UAV LiDAR to generate point clouds which can be processed and rendered to give the 3D visual display of the forest has given the UAV LiDAR a strong advantage over the RGB imagery.

2.5 History of UAV Data Collection Technique

According to a study on Unmanned aerial vehicles in forestry by Hartley R. (2017), he noted that UAVs were first used in the early 1950s and the main application was in the military where they were used mainly for surveillance in the enemy territory or defence (Hartley, 2017). However, since 1990, UAVs of different shapes and sizes have been developed rapidly and their application has expanded into civilian usage, especially in the fields of forestry, biodiversity, emergency operations, meteorology, wildlife management, research, land administration, and traffic monitoring among other uses (Rombouts et al., n.d.). Figure 2.1 shows, the relative increase in usage of UAVs over time.

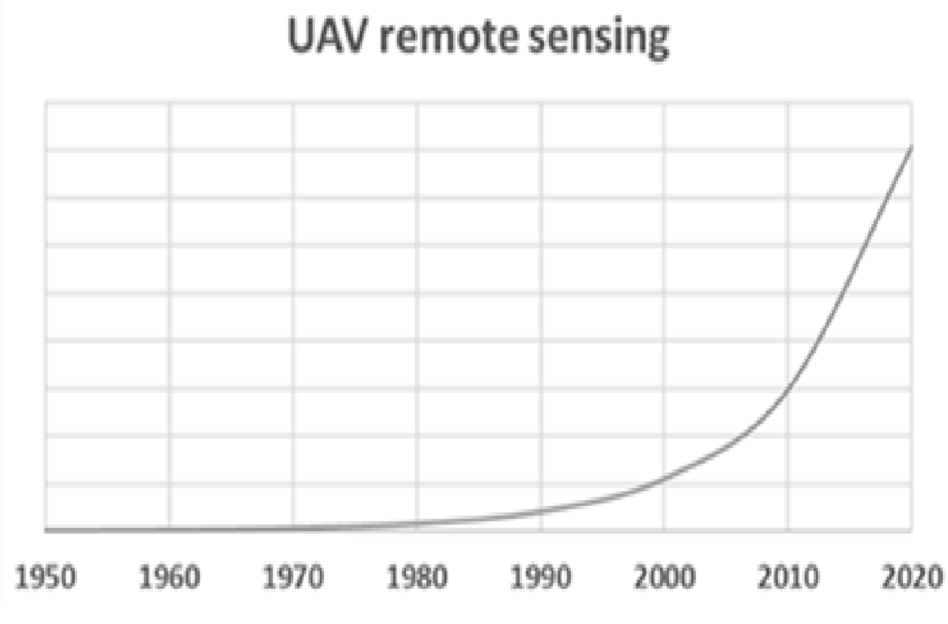


Figure 2.1: Image showing a relative increase in the wide usage of UAVs (Source; Mokroš et al., 2016)

2.6 UAV LiDAR for Forest Mapping

The potential use of UAV LiDAR in forestry research was used by (Jaakkola et al., 2010). He deployed a rotor-wing UAV which was equipped with sensors for navigation, LiDAR sensors, and high spatial resolution data collected offered improved individual tree level mapping as shown in figure 4. (Jaakkola et al., 2010), measured to a finer scale and precision the forest attributes using the UAV LiDAR point cloud compared to earlier LiDAR platforms. This was achieved due to the higher spatial and temporal resolutions together with low operation costs. The targeted approach provided by UAVs in forest monitoring together with the use of multitemporal surveys can help in monitoring other forest attributes(Chiabrando et al., 2011). The combination of the low cost of surveying and high-resolution data capture has proven that UAVs are expected to be the tool of high-quality preference for improving thorough surveys within forests.

This project used UAV LiDAR system mounted with a lightweight and low-cost sensor to demonstrate the ability of UAVs in collecting accurate, dense, and repeatable spatial measurements for forest inventory and management (Hyyppa et al., n.d.). Figure 2.2 shows the UAV system that was used in the project to collect the forest attributes. The project aligned and assessed the accuracy of the UAV LiDAR point cloud. The workflow used accurately geo-referenced LiDAR points, including the orientation of the HD video camera (Nelson et al., 2012). The observation from the camera and GPS receiver was proposed to overcome the presence of orientation errors which normally occur in GPS-only-based platforms. The system evaluated the absolute accuracy as well as the accuracy of the derived forest attributes at the individual tree level.

Figure 2.2: Image showing the UAV system that was used in the project to collect the forest attributes, Source; Author

2.7 UAV LiDAR for topographic mapping

The active sensor in LiDAR technology is not normally influenced by the shadow cast by the sun angle which is a common challenge in photogrammetry technology. This, therefore, reduces the influence the shadow has on the data quality. The UAV LiDAR, therefore, is capable of producing high-precision elevation data. The elevation data produced from LiDAR can be modelled to give the terrain and canopy information that can be utilized in a wide range of research assignments and questions. LiDAR is also highly complementary to other forms of remote sensing, including satellite or aerial imagery to gain more insights that could not have been possible if only one system was relied upon.

2.8 How LiDAR data are collected and represented

A thorough pre-planning is needed at the beginning of the LiDAR data collection process. A deep understanding of the uses of the data to be collected is necessary to help in determining the flight parameters (Raber and Cannistra, 2005).

The following are the steps that can be taken to collect LiDAR data for the forestry inventory and monitoring to support forestry management.

a. Flight Planning

The accuracy and the coverage of the study area are the most important constraints addressed in this stage. The flying heights and the amount of the flight overlap for the strips, the speed of the aircraft as well as the width of the swath area are other parameters that are determined in this stage. Additionally, the flight permits from the flight regulatory authority eg. KCAA are also obtained at this stage.

b. Mobilization

It involves the deployment of the UAV platform together with a sensor, and field operations staff to the project site. Depending on the scope of work, the size of the operations staff may vary. However, this team must include a trained pilot and a trained observer (Raber and Cannistra, 2005).

Mobilization also includes the establishment of a GPS base station, ground control points as well as checkpoints. Putting together all safety equipment is also a vital part of the mobilization step. These include:

- Fire Extinguisher
- First Aid Kit
- Safety Tape

c. Flight Mission

i. Installation and calibration of the Instrument

The LiDAR system is installed in the UAV. The LiDAR system is calibrated since it is mandatory to calibrate the LiDAR system any time it is installed in the UAV.

ii. Flight

The actual flight mission and initialization of LiDAR are then commenced. The UAV is flown in swaths with each swath making the flight mission.

d. Field Verification

Raber and Cannistra recommended that data validation should involve a field survey where the RTK or field observations are taken in the study area on sample points which can be used to validate the data collected from the UAV (Raber and Cannistra, 2005).

2.9 LiDAR Data Processing

When LiDAR data is collected, it consists of timing data which requires to be correlated with navigation information (Easting, Northing, and Elevation, and attitude information) (Raber and Cannistra, 2005)

There are a variety of formats to deliver LiDAR data, including laz, TIN, Grid, ASCII, Shapefile, and contours. The most widely accepted format for storing LiDAR attributes is the laz file. These attributes include GPS coordinates, Inertial Measurement Unit orientation data, and other information such as projection information which enables the latitude, longitude, and elevation to be obtained. An advantage of the .laz file is that all the final classified attributes are stored in one database table, hence enables users to have a single file with many views and analysis possibilities (Raber and Cannistra, 2005).

This data has to be processed to generate usable elevation products such as DSMs, DTMs, and TIN. Further processing is required to generate contours and other earth models.

The processing workflow involves the following:

i. LiDAR point cloud reconstruction, whereby GPS/INS processing correlates the timing information from the laser.
ii. Classification and filtering that involve classification of above ground features
iii. Generation of surface products that includes creating various elevation products such as the bare earth surface model (DEM, DTM, TIN, etc.)

2.10 LiDAR Point Cloud Reconstruction

After mission completion, the data is downloaded and pre-processing commences. Some robust LiDAR pre-processing software includes DJI Terra and LiDAR36 (LiGeoreference).

After GPS processing, INS data and GPS trajectory are combined using advanced filtering methods. The outcome is a complete set of orientation information (x, y, z, and attitude) of the sensor origin and output. A dense point cloud is then computed using a combination of measured ranges, mirror-scan angles, and orientation information.

Additional adjustment computation should be undertaken during processing stage. Adjustment methods vary in sophistication depending on the application and size of the scope (Raber and Cannistra, 2005).

2.11 Point Cloud Filtering and Classification

There are different Software that can be used for post-processing of LiDAR data. Some proprietary software includes LiDAR360, TerraSolid, Surfer 8 and ArcGIS. An example of an open-source LiDAR post-processing software is QGIS. Consideration for price, capabilities, user friendliness and support should be made before acquiring a LiDAR processing software.

Classifying and filtering raw LiDAR data identifies and removes elevation points reflecting off vegetation, bodies of water, and man-made structures. As part of the classification process, noise or low points, as well as ground clutter, are also removed (Raber and Cannistra, 2005)

Using various algorithms, the points are classified into several classes. This depends on the post-processing software being used. Some of the common classes include Bare ground, Water, Urban areas, tall building, Bridge deck, High vegetation, Low vegetation, High noise, Low noise, and Processed, but unclassified (Sandy).

These classification systems try to sort out non-bare earth returns (clouds, structures, power cables, tree canopies, cars) from bare earth returns. To distinguish bare earth in forested areas, differences in elevation between the first and last returns, relative changes in elevation, and slope are used (Giglierano, 2007)

In dense forested sites, it is common to find information gaps due to the non-penetration of pulses through the tree canopies, but these regions are ocassionally less than ten meters across and are easily filled in by interpolation. Leaf-on conditions and tall crops, such as corn, should be avoided since they block laser beam penetration (Giglierano, 2007).

However, (Raber) notes that the large volume of data points generated by a LiDAR system poses a huge challenge in terms of data management and raw processing power (Raber and Cannistra, 2005). With these huge data sets, simply visualizing or analysing LiDAR data sets can be challenging.

2.12 Processing LiDAR points to TINs and DEMs

Once the point cloud is classified and filtered, the next step is to generate earth elevation models. Surface products may include the following:

- Gridded DEMs (regularly spaced, gridded DEM)
- Mass-point files of bare earth
- Point files of elevated features (buildings, vegetation, etc.)
- Intensity images
- LiDAR-generated contours

The products can be provided in a variety of GIS formats, in addition to the first and last return information.

The exact methodology is a function of the accuracy required and the product to be produced. However, the ground points are used for generation of TINs and DEMs to obtain bare earth terrain models (Raber and Cannistra, 2005).

Once the raw LiDAR point tiles are processed into high-resolution DEMs, other useful mapping products can be derived(Giglierano, 2007).

2.13 Quality Control of LiDAR data

LiDAR data can be influenced and rendered less accurate in many ways. Each stage of a mission from planning to delivery has potential error opportunities, which are able to adversely affect the overall accuracy of the LiDAR data (Raber and Cannistra, 2005).

Some potential source of error include:

I. Planning: Incorrect project boundary, Conversion and translations, Ground sample distance inadequate to meet accuracy expectations, Wrong horizontal or vertical datum, Flight line breaks because of extreme elevation change.

II. Airborne LiDAR Acquisition: Wrong navigation input (incorrect coordinate system), Laser malfunction, IMU malfunction, Pre-mission and/or post-mission calibration not performed, Aircraft electrical problem, Operator error.

III. Ground Support: Erroneous reference station (horizontal or vertical), GPS baseline distance too long, No redundant GPS receivers in case a receiver malfunctions, GPS base station problems (not enough satellites, incorrect antenna-height measurement, battery failure, vandalism, etc.), Postprocessing error (poor constraint network, lack of local control knowledge, datum transformation, etc.), Operator error.

IV. LiDAR Postprocessing: Application of wrong horizontal and vertical survey adjustments, Incorrect office boresiting, Incorrect Calibration of each flight line to adjacent lines, Breaklines not referencing the LiDAR data during compilation.

2.14 Validation Methods

a. Individual Checkpoints.

These are single locations with valid horizontal and vertical locations. This procedure is useful to check horizontal accuracy.

b. Area Surveys.

Area surveys allow verification over a larger area. Two examples of area surveys are engineering as-built drawings and construction design surveys. The advantage of this approach is that engineering surveys are typically performed to a high level of horizontal and vertical accuracy.

c. Cross-Sections or Survey Breaklines.

Cross-sections, which are created using vertical survey level technology, are strings of elevation points. This method is typically used in heavily vegetated areas to test the behavior of the LiDAR under vegetation.

d. Ground-Truth Surveying.

Ground-truth surveying is usually performed during or following the LiDAR mission. The primary purpose of this type of validation surveying is to assist the user in determining how accurate the contour and elevation data are in obscured areas. The technique for a ground-truth accuracy assessment includes surveying individual points and cross-sections in a wide range of land-use and land-cover classifications (under trees, marsh, low ground cover, urban areas, etc.).

2.15 Merits and Demerits of using LiDAR for Topographic Mapping

2.15.1 Merits

LiDAR technology has an active laser pulse sensor, which is not influenced by the shadow angle of the sun, reduce their influence on data acquisition. Compared with photogrammetry technology, it avoids information loss (from 3D to 2D) and has high elevation accuracy. A significant reduction in ground control survey, air flight routes can automatically adjust, increase the level of automation, it can produce digital elevation model (DEM), digital surface model (DSM) and digital orthophoto map (DOM) of mass productions quickly (Meng et al., 2017).

Most accurate 3D information. LiDAR provides the most accurate data on 3D structure of any remote sensing technique, particularly when it comes to dense vegetation, with low-pulse density LiDAR typically exhibiting sub-meter accuracy (Melin, Shapiro and Glover-Kapfer, 2017).

Versatile data. LiDAR data can be used to produce digital models of terrain and canopy and customized for myriad needs to suit the research questions at hand.

High complementarity with remotely sensed imagery. LiDAR provides highly complementary data that can be used in conjunction with satellite and aerial imagery to gain insights that neither imagery nor LiDAR can reach alone(Melin, Shapiro and Glover-Kapfer, 2017).

2.15.2 Demerits

Lasers in the LiDAR systems that map earth features generally operate in the near-infrared portion of the spectrum. Certain earth features such as water (depending on the angle and turbidity), new asphalt, tar roofs and some roof shingles often absorb laser pulses in this wavelength.

Moisture, including rain, clouds, fog, also absorb the laser signal and appear as holes in the data set

LiDAR data sets, especially when coupled with imagery, are quite large. Users need to augment computing resources to store and process the information

Frequently, as with other digital spatial data, users need enhancements to the basic LiDAR data. This could include data formats, data models, data segmentation and/or compression, and other value-added products and/or software.

High cost of collection of LiDAR data. LiDAR costs decrease per unit area as the total area surveyed increases, but can be substantial, and depend on the cost of fuel, pilots, airplane rental, all of which depend on geography and weather (Melin, Shapiro and Glover-Kapfer, 2017).

Technically complex processing, analyzing and interpretations. LiDAR data processing is time-consuming and technically challenging, particularly for the unexperienced, and depending on the task may require expertise in GIS and remote sensing to use and interpret properly (Melin, Shapiro and Glover-Kapfer, 2017)

Lack of multispectral information. That LiDAR currently largely lacks multispectral data limits its utility to non-spectral analyses (Melin, Shapiro and Glover-Kapfer, 2017).

LiDAR cannot penetrate thick canopies. For instance, dense tropical forests are problematic due to lack of ground hits (Melin, Shapiro and Glover-Kapfer, 2017).

2.16 GIS in Mapping

The interoperability of the GIS and UAV technologies has been used to analyze the images from the UAV(Shrestha & Wynne, 2012). GIS has helped in reducing the complexities within the images and the findings are normally presented in an elaborate visualization in the GIS platform(Mokroš et al., 2016). This study will use the imagery analysis tools available in ArcGIS pro 2.9.2, a GIS software to clean, process, and analyse the UAV images. The incorporation of remote sensing and GIS technologies will allow the study to investigate the attributes of the forest in the study area. The figure 2.3 shows how the data from the UAV will be visualized on GIS software.

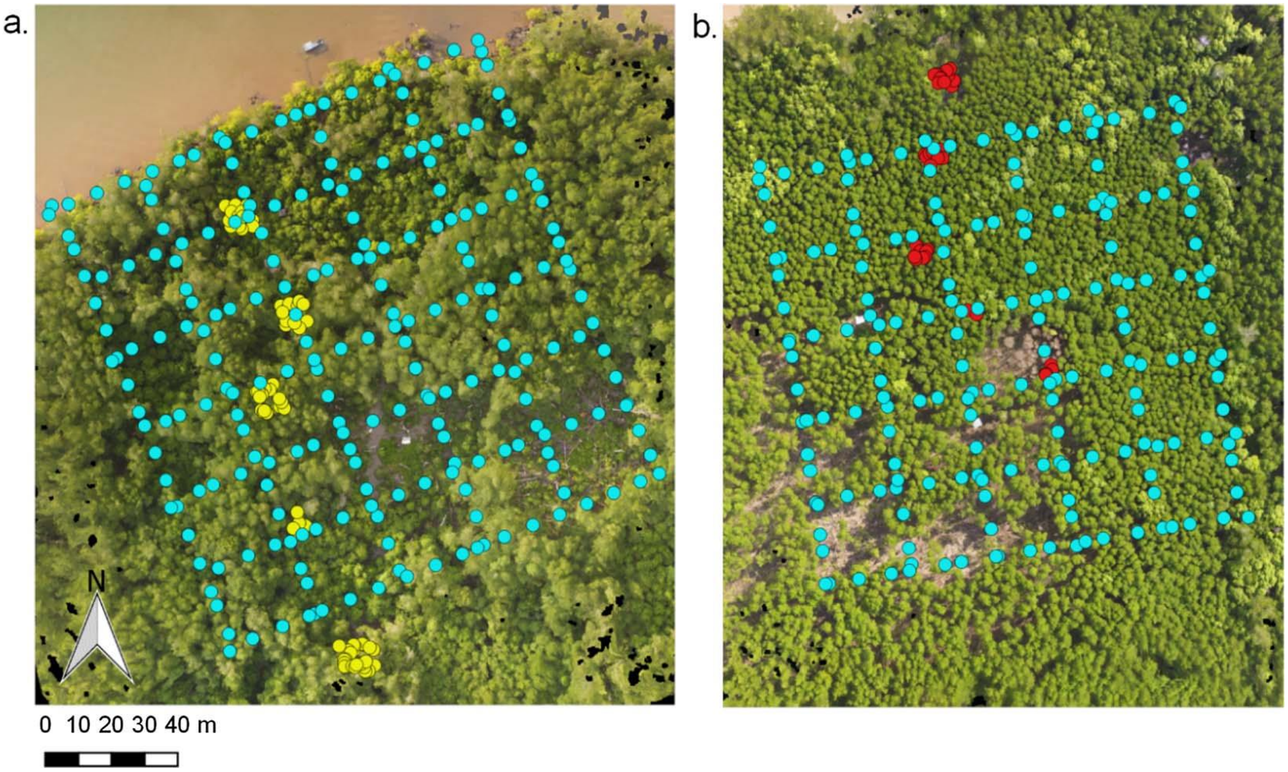


Figure 2.3 Image showing the visualized data from the UAV on a GIS software (source Shrestha & Wynne, 2012)

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

This chapter is about the study area, datasets and their respective sources, data cleaning process and data analysis methods and techniques used to attain the goals of this study.

3.2 Study Area

The site is located in Mombasa County as shown in figure 3.1. It is geographically located between latitudes: 3°58'10.32''S and 3°59'41.97''S and longitudes: 39°43'41.10''E and 39°44'18.27''E. The altitude of the study area is extending from 1 meter to 13 meters above sea level. It is located 9 kilometres from Mombasa Central Business District. Mombasa is the second largest city in Kenya. Mombasa is also the largest city in the coastal region of Kenya. Its economy is majorly dependent on hospitality and tourism due to its hot and humid weather conditions throughout the year. Mombasa city also has Mombasa port, the major seaport in Kenya thus making trade, transport and logistics part of the major economic drivers in the region.

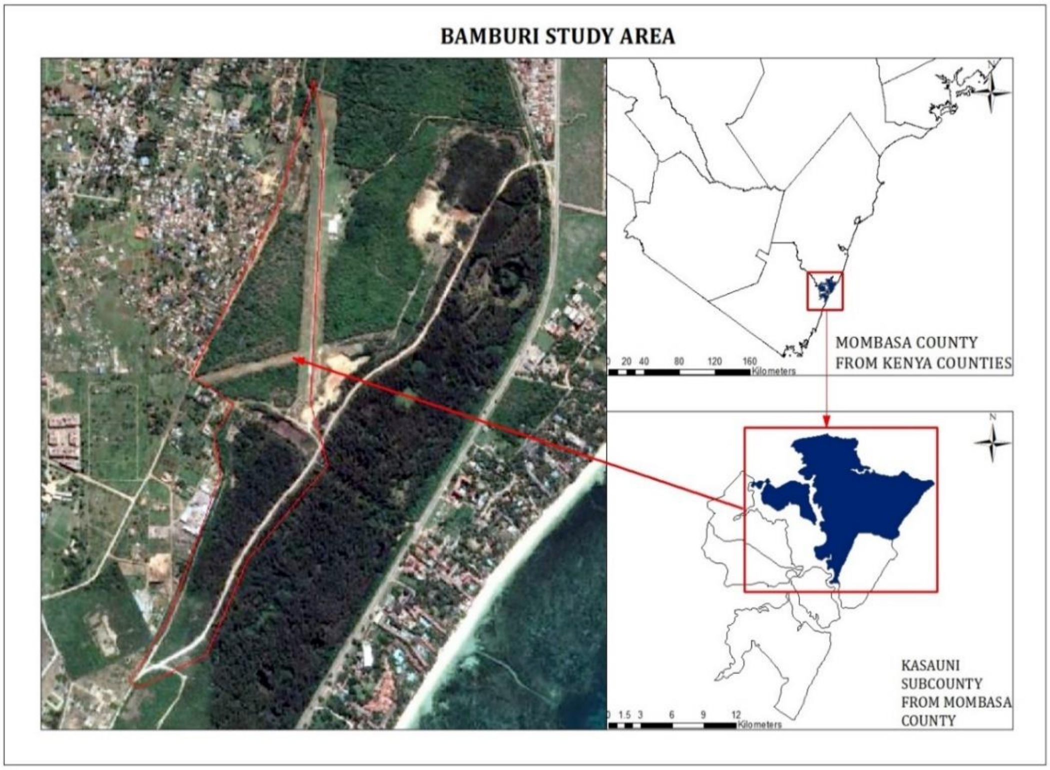


Figure 3.1: Bamburi forest Study Area Map: Source Author 2022

3.3 Research methodology flow chart.

The flow diagram guided the research process as indicated in figure 3.2. The process started with first carrying out a reconnaissance survey of the site, data acquisition, analysis and examination of the results then publication of the results which answered the project objectives.

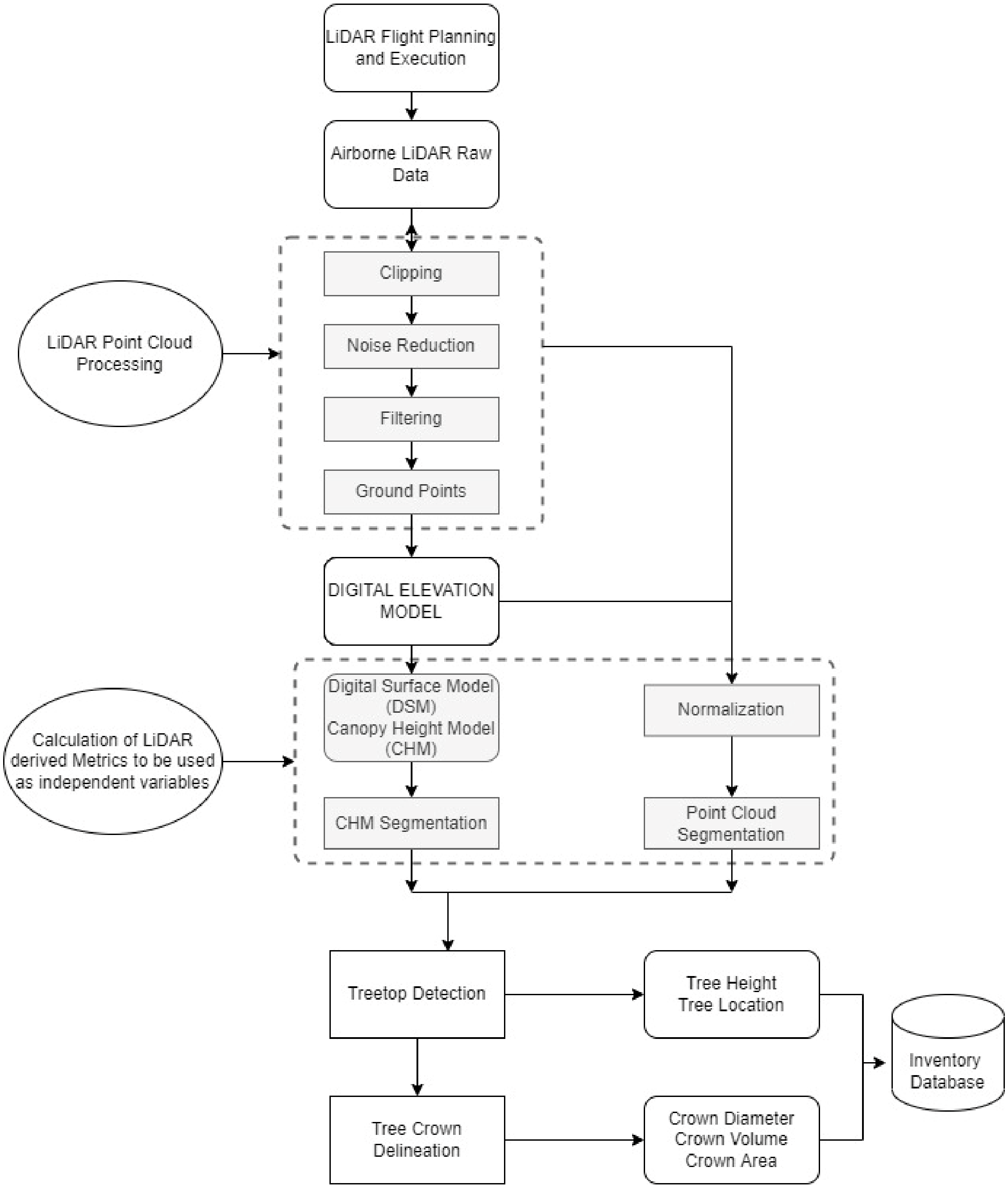


Figure 3.2: A conceptual diagram of the workflow process; Source Author 2022

3.4 Research tools

3.4.1 Software

- DJI Terra Pro Version. This Software was used for pre-processing of the raw LiDAR data.
- LiDAR360. This software was utilized for post-processing of LiDAR data to generate surface models and contours, as well as for the verification of the LiDAR's vertical accuracy.
- ArcMap 10.8. This software was used for verification of the LiDAR's horizontal accuracy.
- Microsoft Office Suite, used for compilation and presentation of this report.

3.4.2 Used Tools

- Processing
    - A personal computer
- Terrestrial Measurements
    - GNSS RTK Receiver KOLIDA K20
- Aerial Survey
    - UAV DJI Matrice 300 RTK

The UAV DJI Matrice 300 RTK, which was used as the platform for mounting the tested laser scanner DJI Zenmuse L1 sensor, is a professional survey-grade quadcopter equipped with a GNSS RTK receiver as shown in figure 3.3. The table 3.1 highlights specefications for a DJI matrice 300 RTK.

Table 3.1 The specifications for a DJI Matrice 300 RTK

Weight	**Approx. 6.3kg (With One Gimbal)**
Max. Transmitting distance	8km
Max. Flight time	55 min
Dimensions	810 * 670 * 430 mm
Max. Payload	2.7 kg
Max. Speed	82 km/h

- Laser Scanner DJI Zenmuse L1

The tested laser scanner DJI Zenmuse L1 combines data from an RGB sensor and the IMU unit in a stabilized 3-axis gimbal, thus providing a true colour point cloud from the RGB sensor; the point cloud must be processed in the manufacturer-supplied software DJI Terra. Basic manufacturer-declared characteristics are shown in figure 3.3 and table 3.2.

Table 3.2: The DJI Zenmuse L1 specifications

Dimensions	**152 * 110 * 169 mm**
Weight	930 + 10 g
Maximum Measurement Distance	450 m at 80% reflectivity, 190 m at 10% reflectivity
Recording Speed	Single return: max. 240,000 points/s; Multiple return: max. 480,000 points/s
System Accuracy	Horizontal: 10 cm per 50 m; Vertical: 5 cm per 50 m
Distance Measurement Accuracy	3 cm per 100 m
Beam Divergence	0.28◦ (Vertical) × 0.03◦ (Horizontal)
Maximum Registered Reflections	3
RGB camera sensor size	1 in
RGB camera effective pixels	20 MP (5472 × 3078)

Figure 3.3: DJI Zenmuse L1

3.5 Data Acquisition

3.5.1 Reconnaissance

A reconnaissance was done to help in determining the best flight factors to incorporate as well as locate the optimum areas for marking the ground control points. The flight permit was also obtained from Kenya Civil Aviation Authority (KCAA) at this stage.

3.5.2 Establishment and marking of Control Points

The survey conducted here was isolated in nature hence, it was not tied to the National coordinate grid system. The controls used for this work were established and monumented. A GNSS RTK base receiver was mounted on one of the concreted control points and its coordinates value was obtained through the use of averaging measurement technique. The rover receiver was then used to obtain the values of the other five concreted beacons.

Ground Control Points (GCPs) were identified and marked using mats shaded in white and black. Five GCPs were enough, as more GCPs do not contribute significantly to increasing accuracy. They were essential in establishing High Global/ Absolute Accuracy. Three checkpoints were required to verify the accuracy.

3.5.3 Setting up the Drone RTK on one of the control points

The DRTK was set up on one of the controls and left to average its position. The averaged coordinates were then compared to the earlier observed position of control. The observed coordinates of control were converted to geographic coordinates using Global Mapper, and input on the Drone’s Remote Controller in the format indicated in table 3.3.

Table 3.3: The projection used for the data.

	UTM ZONE 37 FORMATS	**WGS-84 format** (0°0’00.00” E/W 0°0’00.00” S/N)
Site Coordinates	Easting/X: 580,876	X: 39° 43’ 42.75” E
	Northing/Y: 9,559,484	Y: 3° 59’ 06.36” S

3.5.4 Aerial Mapping

As soon as all the Ground Control Points were marked, the UAV was deployed for aerial mapping. After designating the study area, the flight planning software DJI Pilot was used to determine the optimal path and automatically perform the flight as shown in table 3.4 below.

Table 3.4: The camera and flight parameter setting

Altitude	*70m*
Measurement type	Normal
Vertical gimble pitch	-90°
Calibration Flight	Yes
Flight Speed	5 m/s
Side Overlap	50%
Echo Mode	Triple
LiDAR Sample rate	160khz
Scan Mode	Repeat
RGB Coloring	Yes

3.6 Data preparation and Pre-processing

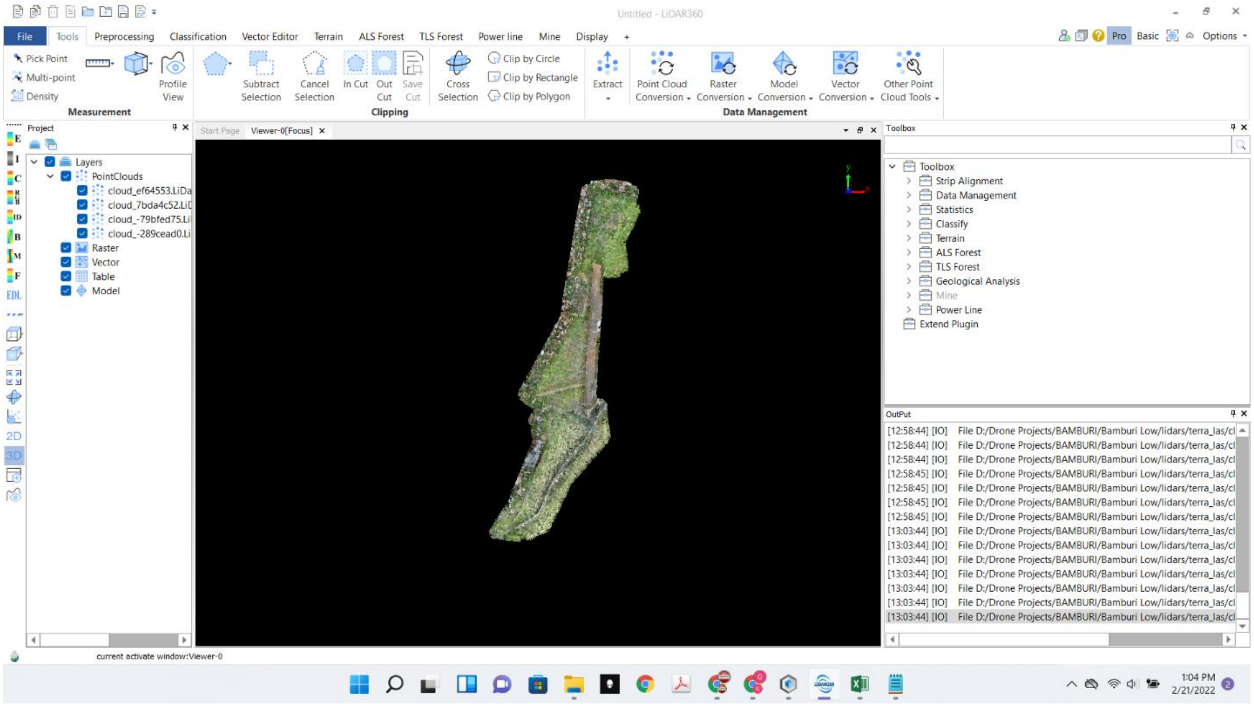
A proprietary software DJI Terra was used to process the UAV data. The following were the steps involved: The command New Mission LiDAR Point Cloud Processing with preset parameters Point cloud density ***High***; Optimize Point Cloud Accuracy ***Yes***; Output Coordinate System ***WGS84***; Reconstruction output ***PNTS, LAS*** triggered a calculation and exported the point cloud in the chosen format. The used LAS format also recorded additional attributes of each point, namely the RGB colour, signal intensity, measurement time, order of reflection, and other data.

3.7 Data Processing

The LiDAR data were pre-processed using a software called DJI Terra and post-processed using a software kwown as LiDAR 360.

3.7.1 Import LAS/LAZ File

The LAS file which contained LiDAR point data records, and combined GPS, IMU, and laser pulse range data formats were imported to produce X, Y, and Z point data as shown in figure 3.4.



```
[12:58:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[12:58:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[12:58:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[12:58:45] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
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[12:58:45] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[13:03:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[13:03:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[13:03:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[13:03:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
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[13:03:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
[13:03:44] [IO]   File D:/Drone Projects/BAMBURI/Bamburi Low/lidars/terra_las/cl
```

Figure 3.4: Imported Point Clouds

3.7.2 Merging Point Clouds and Clipping the area of interest.

Processed point clouds from DJI Terra come as a set of files. The first step involved was merging point clouds and this was followed by clipping the merged point clouds, thus obtaining the area of interest for further analysis.

3.7.3 Automatic classification of ground points

Once low- and high-level outliers were removed from the point cloud, the control points were classified automatically in the system to generate the digital surface and elevation models as one of the attributes of the forest.

3.7.4 Tree Segmentation

Two methods were used to segment the point cloud into individual trees to extract individual tree attributes such as locations, heights, canopy diameters, and so on.

These two methods were:

- The canopy height model (CHM)
- Point Cloud Segmentation

3.7.5 CHM Segmentation

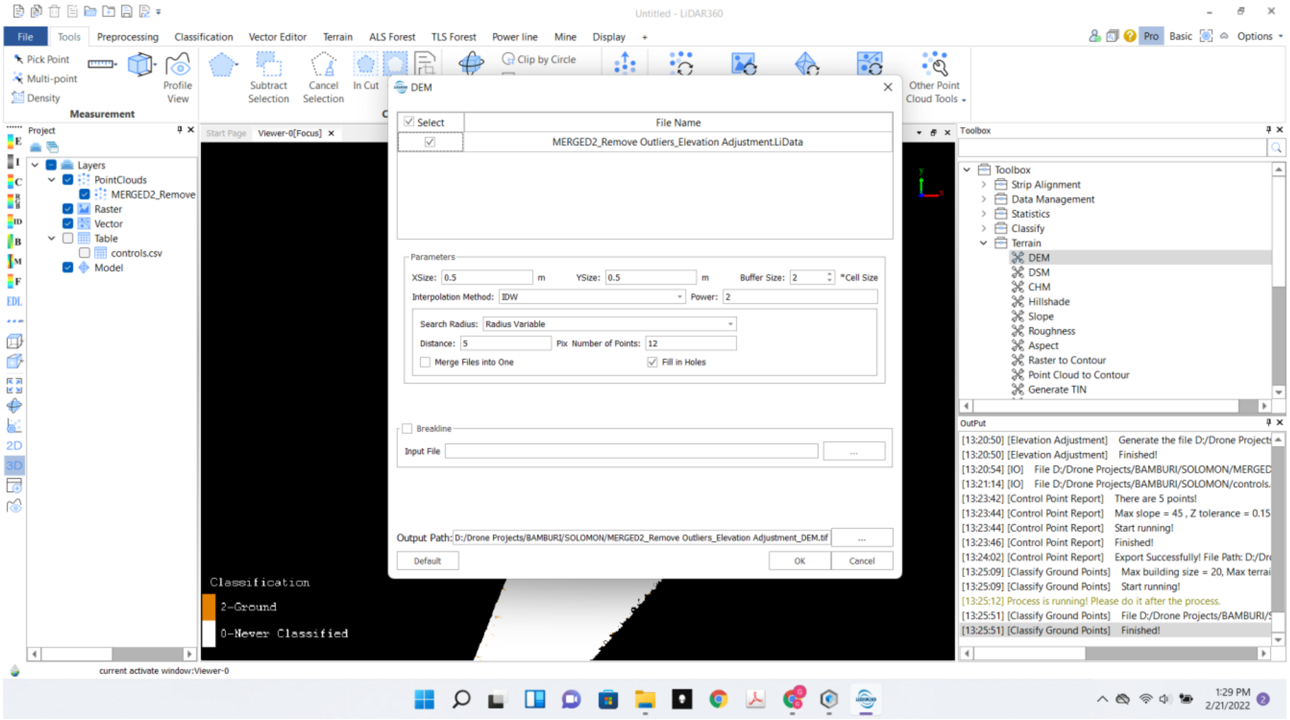
Canopy height model segmentation uses the watershed segmentation method to target and delineate individual trees, and therefore obtain individual tree attributes, such as tree position, tree height, crown diameter and crown volume among others. After the CHM segmentation is completed, each input CHM data were generated and a corresponding CSV file and SHP file, and the CHM were superimposed and displayed with the CSV file and the .shp file

3.7.6 Point Cloud Segmentation

Point Cloud Segmentation was directly segmented. The LiDAR point cloud reduced the influence of under-canopy data loss in the CHM segmentation method. Individual tree attributes features were obtained from the segmentation output. *This method assumed that there are always gaps between trees.* By finding the local maximum as seed points, each tree was segmented based on the geometric correlations between each point and the seed points.

3.7.7 DEM Production

A Digital Elevation Model (DEM) is a representation of the bare ground elevation. DEM was created from the LiDAR point cloud which had ground points classified. The process involved going through the terrain menu of software and then the DEM generation tool which then took in the point cloud that had ground points classified as input list as indicated in figure 3.5.



DEM

☑ Select	File Name
☑	MERGED2_Remove Outliers_Elevation Adjustment.LiData

Parameters

XSize: 0.5 m
YSize: 0.5 m
Buffer Size: 2 *Cell Size
Interpolation Method: IDW
Power: 2
Search Radius: Radius Variable
Distance: 5 Pix
Number of Points: 12
☐ Merge Files into One
☑ Fill in Holes

☐ Breakline
Input File

Output Path: D:/Drone Projects/BAMBURI/SOLOMON/MERGED2_Remove Outliers_Elevation Adjustment_DEM.tif

```
[13:20:50] [Elevation Adjustment]    Generate the file D:/Drone Projects
[13:20:50] [Elevation Adjustment]    Finished!
[13:20:54] [IO]    File D:/Drone Projects/BAMBURI/SOLOMON/MERGED
[13:21:14] [IO]    File D:/Drone Projects/BAMBURI/SOLOMON/controls.
[13:23:42] [Control Point Report]    There are 5 points!
[13:23:44] [Control Point Report]    Max slope = 45 , Z tolerance = 0.15
[13:23:44] [Control Point Report]    Start running!
[13:23:46] [Control Point Report]    Finished!
[13:24:02] [Control Point Report]    Export Successfully! File Path: D:/Dr
[13:25:09] [Classify Ground Points]    Max building size = 20, Max terrai
[13:25:09] [Classify Ground Points]    Start running!
[13:25:12] Process is running! Please do it after the process.
[13:25:51] [Classify Ground Points]    File D:/Drone Projects/BAMBURI/S
[13:25:51] [Classify Ground Points]    Finished!
```

Figure 3.5: DEM Generation

3.8 Validation Methods

A ground-truthing Survey was carried out on a sample area of the forest as shown in figure 3.6. An area measuring 50 m by 50 m was marked for ground truthing and manual tree counting exercise was conducted after the flight mission. The primary goal of this type of validation surveying was to assist the researcher in finding out how the tree count data from the UAV-LiDAR was accurate. The manual tree count within the sampled area was found to be 190 trees, while the automatic tree count gave a total of 182 trees. This, therefore, meant that the accuracy of using UAV technology to determine the number of trees in a forest can give a 94% confidence level. This was established to be good enough to work with considering the cost-benefit of using UAVs over the manual methods.

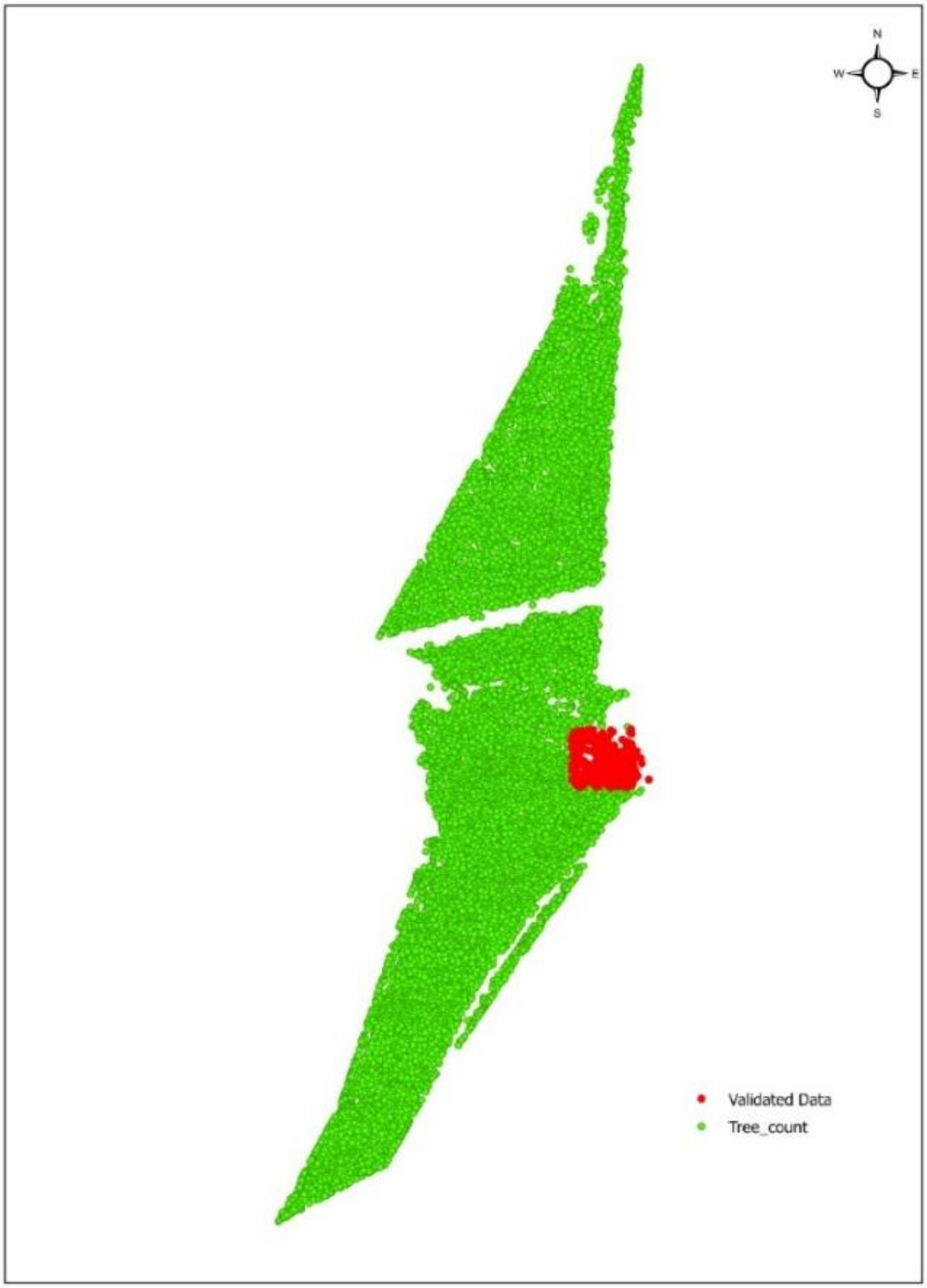


Figure 3.6: Validation sample size

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter entails the results obtained and how they contributed to achieving the main objective.

4.1 Accuracy Verification using Control Points

The control points that were established were instrumental in accuracy adjustments. Ground Control Points have always been critical to mapping projects, as they meaningfully improve accuracy. However, if one is using an RTK drone like in this instance, the control points are used as check points to verify the accuracy, scale and orientation of the reconstructed 2D orthomosaic.

The major Controls used were highlighted in Table 4.1 and figure 4.1. The elevation were found to comprise of both the positive and negative values due to the location of the study area that is close to the mean sea level. The heights were found to be negative since the site was mostly below the mean sea level (MSL).

Table 4.1: The ground Control Coordinates used in the project

ID	**Eastings (m)**	**Northings (m)**	**Elevation (m)**	**DESCRIPTION**
1	579709.683	9557767.455	-13.807	BM01
2	580508.64	9558871.715	-20.062	BM02
3	581028.517	9559725.574	-24.405	BM03
4	581060.181	9560769.896	-16.34	BM04
5	581024.532	9560811.919	-18.964	BM05

Figure 4.1: Showing BM02 and BM05 checking with GCP marker

During post processing, the orthomosaic map was checked against the known points in Arcmap. They were found to superimpose correctly as shown in Figure 4.1.

4.2 LiDAR Point Cloud

DJI Terra software, an open source version was used to reconstruct the raw LiDAR data to generate dense point clouds. During the reconstruction UAV position was determined through the combination of velocity, heading and track angle data from the Inertial Navigation Systems (INS). The dense cloud was imported into the ArcGIS Pro software for analysis. The sensor used had a LiDAR sensor and an RGB camera, which allowed colorization of the point cloud as shown in figure 4.2 below.

Figure 4.2: LiDAR point cloud data processing and visualization on RGB

4.3 Tree count

The CHM segmentation was exported to CSV format with the attributes of the tree heights, canopy diameter, and canopy area and the unique identifier is automatically allocated to the segmented trees as records. Figure 4.3 shows the results obtained from the segregation of the tree canopy areas from the UAV LiDAR data.

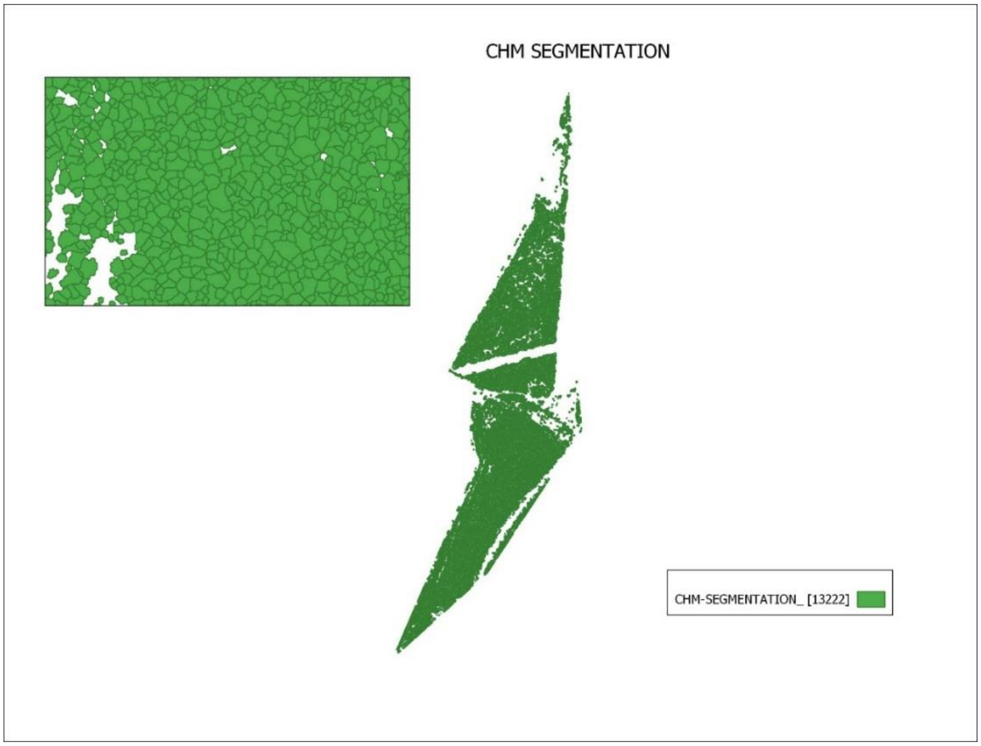


Figure 4.3: Tree crown segmentation

Table 4.2 illustrates the part of the CSV data that was used to generate the statistics on the forest inventory and attributes.

Table 4.2: Part of the Spreadsheet data of CHM segmented information

TreeID	TreeLocationX	TreeLocationY	TreeHeight(m)	CrownDiameter(m)	CrownArea(m^2)	CrownVolume(m^3)
1	580993.219	9560884.981	16.45	7.992	50.17	367.237
2	580998.394	9560888.853	9.761	6.16	29.806	143.583
3	581022.973	9560864.523	7.42	4.619	16.755	66.482
4	580996.763	9560890.304	9.521	2.49	4.868	19.068
5	581006.346	9560880.562	8.02	4.191	13.793	55.359
6	580990.084	9560891.347	12.497	7.208	40.811	256.229
7	580986.44	9560871.835	4.871	4.136	13.434	23.534
8	581012.224	9560882.714	9.271	8.327	54.462	324.951
9	581026.947	9560871.847	22.479	9.922	77.326	750.345
10	580990.581	9560889.451	11.683	5.267	21.791	129.211
11	581001.332	9560884.885	7.708	5.562	24.297	95.31

12	581002.058	9560879.064	8.87	8.634	58.544	281.676
13	580991.727	9560860.672	11.674	6.103	29.251	134.227
14	580995.803	9560871.072	8.431	5.228	21.467	106.973
15	581018.502	9560877.464	10.846	8.776	60.491	383.909
16	580991.337	9560878.233	10.259	12.46	121.928	626.415
17	580984.072	9560853.571	8.511	4.17	13.655	49.034
18	580997.076	9560882.097	10.596	7.03	38.814	211.34
19	580989.735	9560864.672	11.807	9.037	64.142	393.413
20	581008.078	9560879.171	8.466	5.534	24.057	111.154
21	580982.812	9560863.427	9.497	6.918	37.59	171.318
22	581014.832	9560877.973	10.304	4.392	15.148	74.498
23	581013.198	9560841.161	14.122	6.52	33.383	123.988
24	581032.802	9560864.866	17.88	4.925	19.047	106.53

As shown in figure 4.4, the study established that the forest had a total of 10,695 trees in the study area. The coordinates in the spreadsheets were plotted on ArcGIS Pro and the distribution of the trees was established to be random. There are areas which were established to be clear due to the existence of an airstrip in the forest. There was also another clear area on the south-east part of the forest which was established to be a footpath leading to the quarry site which is located close to the forest.

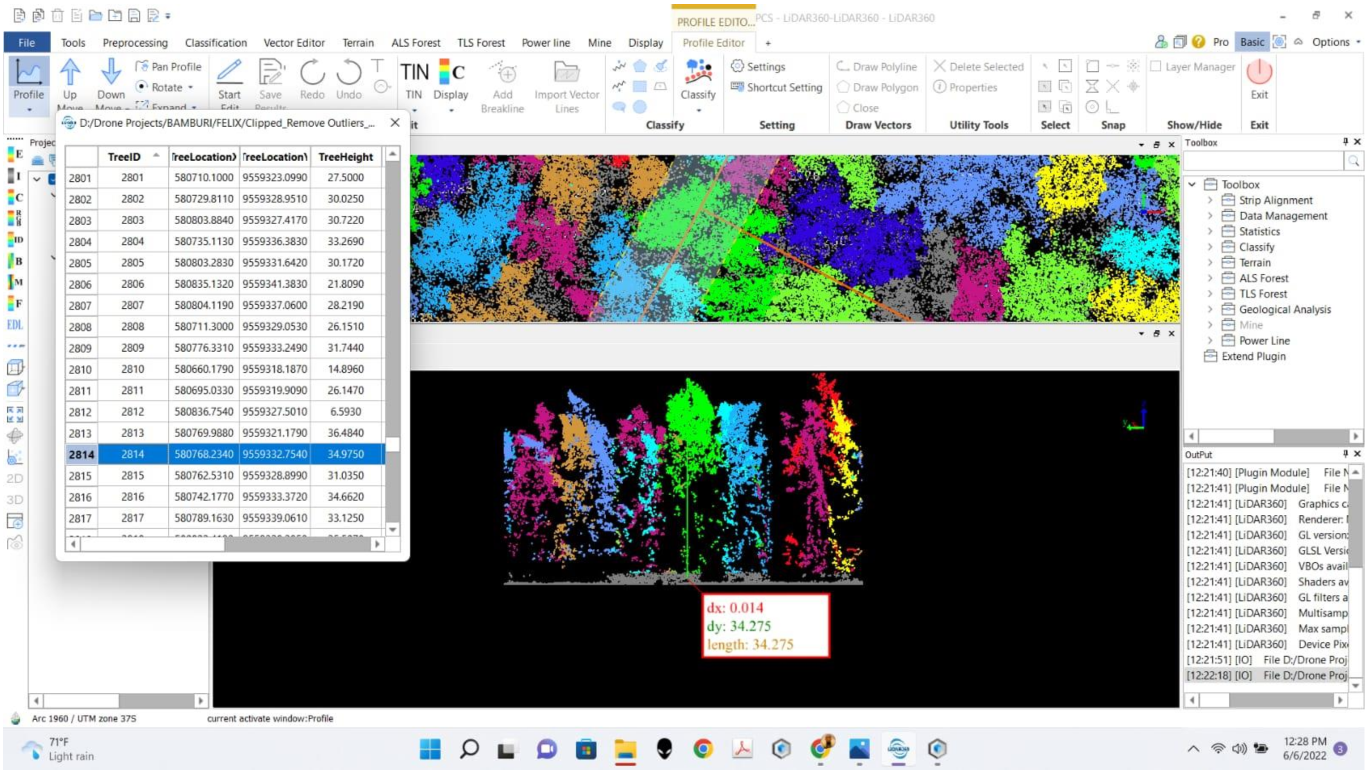
Figure 4.4: Point location of the tree count

4.4 Tree Heights

The ground points were generated through the multiple laser pulses (point clouds) which found the openings between leaves and branches, in much the same way that sunlight filters through the forest canopy, continuing down to the ground emitted from the loaded UAV during the flight.

A filtering process was used to separate the point clouds for earth surface objects and point clouds for ground. Based on several considerations, the point clouds were classified into the ground and non-ground points.

In total, there were 91,218,772 point clouds collected in this study. For ground class, there are 1,951,339 points or about 2.14% from the point clouds. The rest were classified as non-ground. The separation gave the data which could be computed to get the statistical summary of the tree heights for each identified tree in the tree count section as shown in figure 4.5.



D:/Drone Projects/BAMBURI/FELIX/Clipped_Remove Outliers_...

	TreeID	TreeLocation	TreeLocation	TreeHeight
2801	2801	580710.1000	9559323.0990	27.5000
2802	2802	580729.8110	9559328.9510	30.0250
2803	2803	580803.8840	9559327.4170	30.7220
2804	2804	580735.1130	9559336.3830	33.2690
2805	2805	580803.2830	9559331.6420	30.1720
2806	2806	580835.1320	9559341.3830	21.8090
2807	2807	580804.1190	9559337.0600	28.2190
2808	2808	580711.3000	9559329.0530	26.1510
2809	2809	580776.3310	9559333.2490	31.7440
2810	2810	580660.1790	9559318.1870	14.8960
2811	2811	580695.0330	9559319.9090	26.1470
2812	2812	580836.7540	9559327.5010	6.5930
2813	2813	580769.9880	9559321.1790	36.4840
2814	2814	580768.2340	9559332.7540	34.9750
2815	2815	580762.5310	9559328.8990	31.0350
2816	2816	580742.1770	9559333.3720	34.6620
2817	2817	580789.1630	9559339.0610	33.1250

dx: 0.014
dy: 34.275
length: 34.275

Figure 4.5: Tree height generation

From the study, it was established that the trees in the study area had a mean height of 14.77m with the distribution giving a skewed curve where the tallest trees with 40m and above were few in number and the majority of the tree count had a low height of less than 11m as shown in figure 4.6.

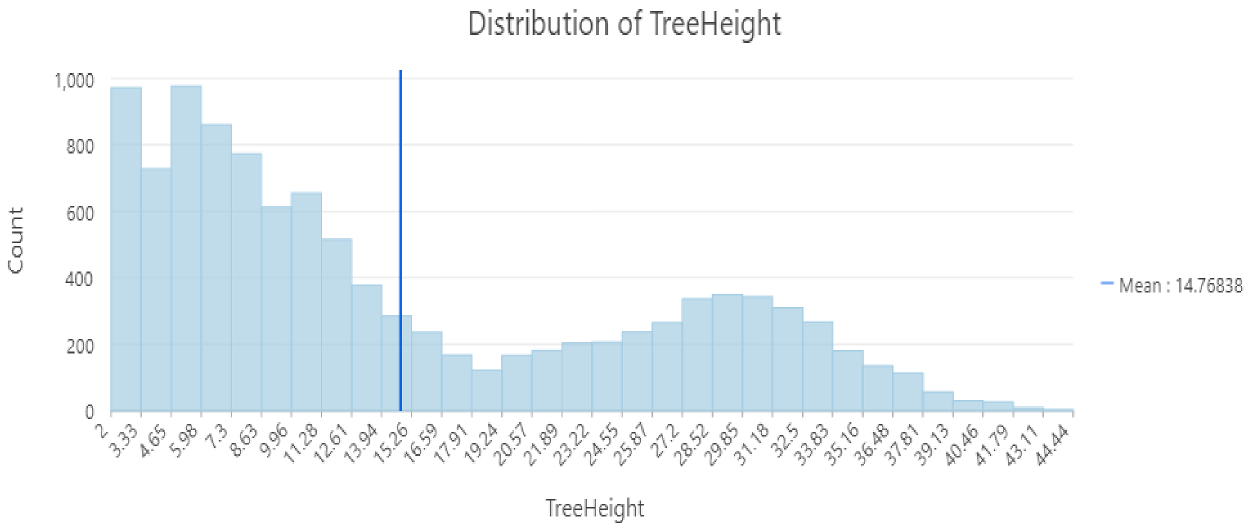


Figure 4.6: Tree height distribution

4.5 DEM generation

After ground and non-ground objects were successfully segregated, a topographical dataset in the form of DEM was generated. The quality of the DEM is highly dependent on the robustness of classification and filtering procedure. The DEM was solely based on the ground class. This was done in LiDAR 360. After the generation of DEM, it was imported into ArcMap and visualized as shown in Figure 4.7.

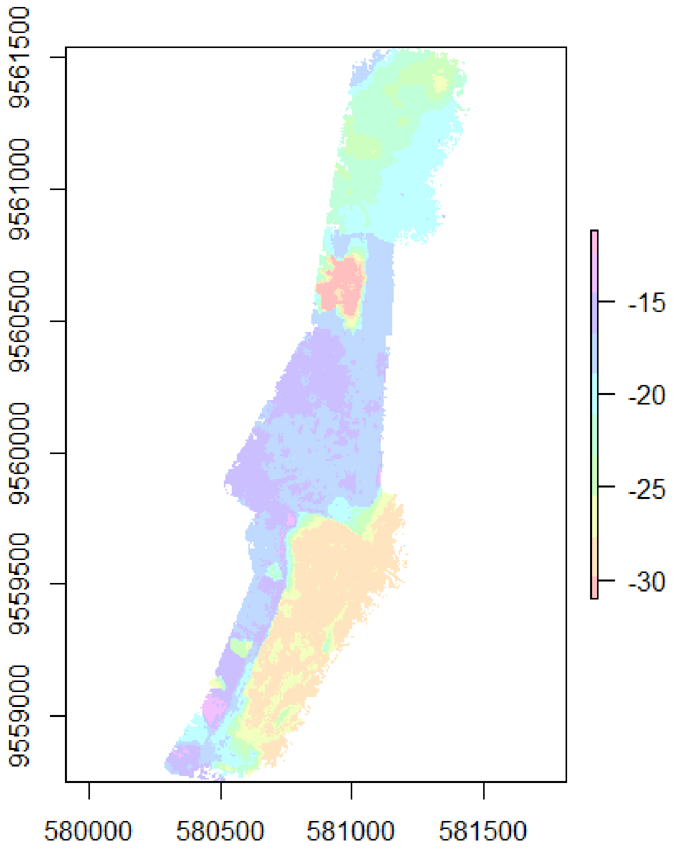


Figure 4.7: Digital Elevation Model

The spatial resolution of a DEM refers to the area of land being represented by a single grid cell. So, a spatial resolution of 10 meters means one grid cell is representing a 10*10-meter area of physical land.

For this study, a resolution of 0.5m was achieved, to mean that one grid cell was representing a 0.5 * 0.5m area of physical land. DEMs downloaded online from sites such as USGS mostly have accuracies of 90m, 30m, and 12.5m. UAV-borne LiDAR generated DEM is therefore of a superior resolution, which implies comparatively greater preservation of land features. The DEM for the study area was shown in the figure 4.8.

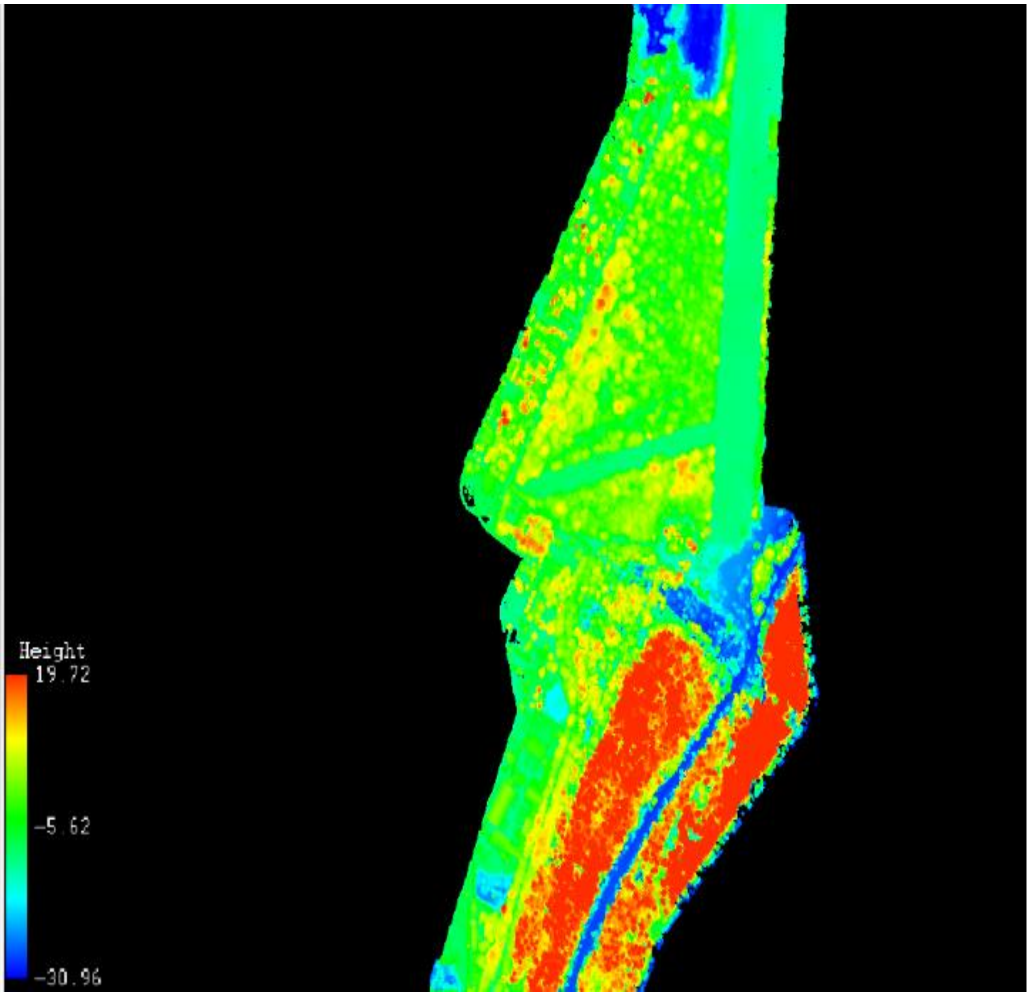


Figure 4.8: Digital elevation model for the study area

4.6 Tree Canopy Diameter and area

The distribution of the tree crown diameter had a skewed left distribution curve. Most trees have near-average canopy diameters on the left of the graph while a few fell to the right, especially for larger diameters. Figures 4.9 , 4.10 and 4.11 show an inset and graph of the diameter and areas of the tree canopy.

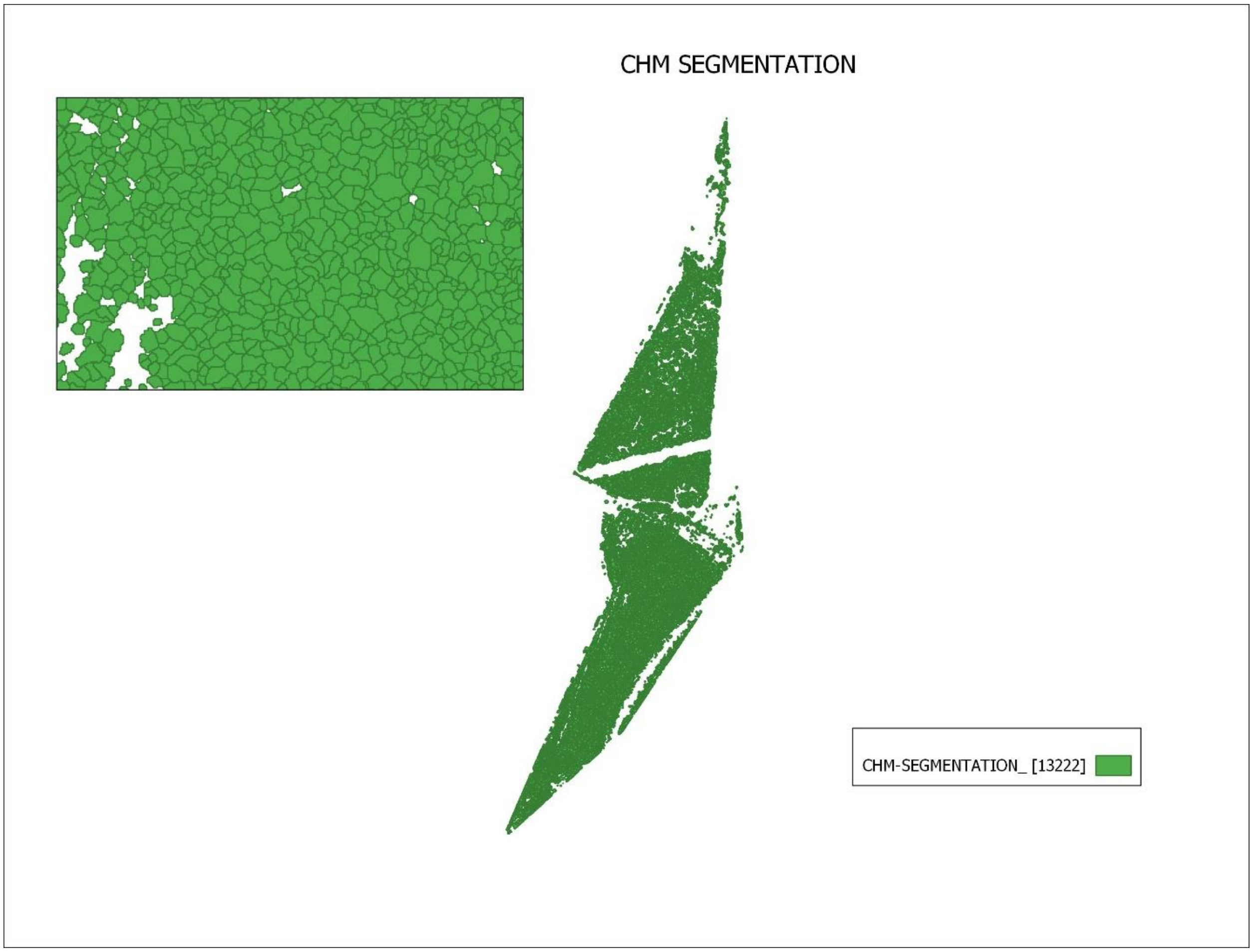


Figure 4.9: CHM segmentation of the tree diameter

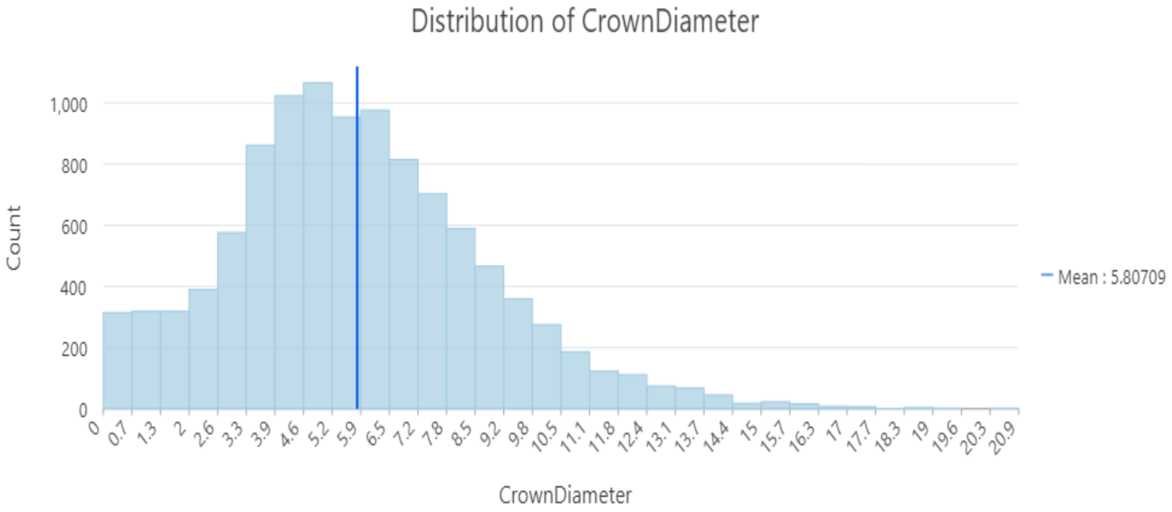


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Figure 4.10: Distribution of tree crown diameters

The crown area also had a skewed left curve. This is because the larger the diameter of the crown, the larger the area of the tree canopy. Figure 4.11 shows the skewed left distribution of the areas of the tree canopies. The largest tree had a crown area of 344 m^2 and the smallest tree had a canopy area of 10.7 m^2

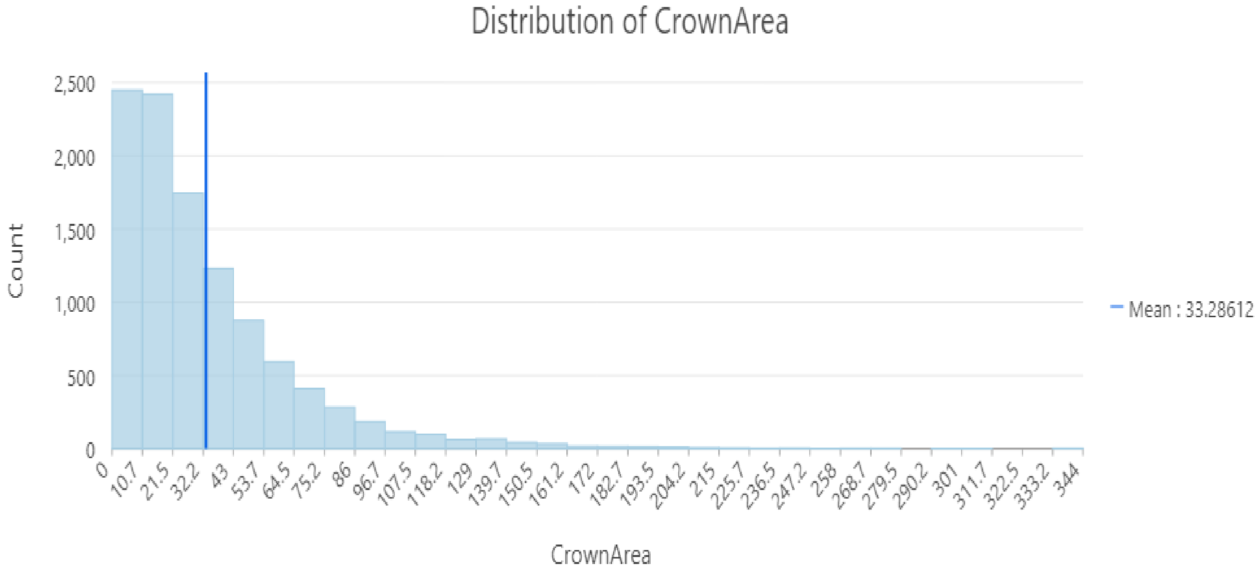

Figure 4.11: Tree crown area distribution

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study has shown that LiDAR data collected from the UAV can be used successfully to generate the attributes of the forest including the DEM which had 0.5m horizontal accuracy. It has also been used in this study to generate forest attributes, including the tree heights, canopy diameter, tree counts and tree canopy diameters in the study area.

The forest attributes were generated from the LiDAR data collected from the UAV flight mission. A combination of specialized data processing software (DJI Terra and LiDAR 360) and ArcGIS pro software was used to analyse and provide the required forest attributes including the count of the forest trees, tree heights and tree diameter among other key attributes. The geostatistical information from these datasets is very important in forestry management since the authorities can make informed decisions including which part of the forest requires special attention increasing surveillance to stop deforestation activities, planting more trees in the bare land areas etc.

The DEM of 0.5m horizontal resolution was also generated from the project thus providing a more accurate surface model compared to the SRTM which has a 30m resolution which might not be useful in large-scale areas including this particular study area which is not only small in size but also is found in the coastal region characterized by moderately flat surface, thus making it hard to determine the small variations in the surface model. The generated DEM can therefore be processed further to generate surface features, including the aspect, slope and hillshade which have an impact on the type of trees to be planted in a particular place, thus making the forest restoration process to be much faster and less costly.

5.2 Recommendations

The study has proven that forest attributes are possible to be obtained from UAV data collection and processing methods. However, the sensor used during the flight did not support a multispectral and hyperspectral imaging technology. It is therefore recommended that further studies can consider using the multispectral sensor camera that is capable of generating the tree species in the forests. This will help in determining the location and the number of trees and species that are under threat of extinction.

5.3 Limitations of the results

Since LiDAR sees through vegetation holes in the foliage, it cannot be used in dense canopies. If the canopies are so thick that sun rays cannot penetrate through to the ground, it also means that laser signals from a LiDAR sensor cannot penetrate through to the ground, and in this way, the canopy acts as a roof. In such scenarios, therefore, this method of carrying out the topographic survey is rendered impossible.

REFERENCES

Chiabrando, F., Nex, F., Piatti, D., & Rinaudo, F. (2011). UAV and RPV systems for photogrammetric surveys in archaelogical areas: Two tests in the Piedmont region (Italy). *Journal of Archaeological Science*, *38*(3), 697–710. https://doi.org/10.1016/j.jas.2010.10.022

Fao 2022. (n.d.). Retrieved April 18, 2022, from https://www.fao.org/connect-private-sector/stories/detail/en/c/1454981/

Hartley, R. (2017). Unmanned aerial vehicles in forestry-reaching for a new perspective. In *NZ Journal of Forestry* (Vol. 62, Issue 1).

Hyyppa, J., Hallikainen, M., & Hyyppa, H. (n.d.). *FOREST INVENTORY USING FOREST CANOPY PROFILES zyxw*.

Hyyppä, J., Hyyppä, H., Leckie, D., Gougeon, F., Yu, X., & Maltamo, M. (2008). Review of methods of small-footprint airborne laser scanning for extracting forest inventory data in boreal forests. *International Journal of Remote Sensing*, *29*(5), 1339–1366. https://doi.org/10.1080/01431160701736489

Jaakkola, A., Hyyppä, J., Kukko, A., Yu, X., Kaartinen, H., Lehtomäki, M., & Lin, Y. (2010). A low-cost multi-sensoral mobile mapping system and its feasibility for tree measurements. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(6), 514–522. https://doi.org/10.1016/j.isprsjprs.2010.08.002

Kentsch, S., Cabezas, M., Tomhave, L., Groß, J., Burkhard, B., Caceres, M. L. L., Waki, K., & Diez, Y. (2021). Analysis of UAV-acquired wetland orthomosaics using GIS, computer vision, computational topology and deep learning. *Sensors (Switzerland)*, *21*(2), 1–24. https://doi.org/10.3390/s21020471

Koch, B. (2010). Status and future of laser scanning, synthetic aperture radar and hyperspectral remote sensing data for forest biomass assessment. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(6), 581–590. https://doi.org/10.1016/j.isprsjprs.2010.09.001

Mokroš, M., Tabačák, M., Lieskovský, M., & Fabrika, M. (2016). Unmanned aerial vehicle use for wood chips pile volume estimation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *2016-January*, 953–956. https://doi.org/10.5194/isprsarchives-XLI-B1-953-2016

Nelson, R., Krabill, W., & Maclean, G. (1984). Determining Forest Canopy Characteristics Using Airborne Laser Data. In *REMOTE SENSING OF ENVIRONMENT* (Vol. 15).

Otero, V., van de Kerchove, R., Satyanarayana, B., Martínez-Espinosa, C., Fisol, M. A. bin, Ibrahim, M. R. bin, Sulong, I., Mohd-Lokman, H., Lucas, R., & Dahdouh-Guebas, F. (2018). Managing mangrove forests from the sky: Forest inventory using field data and Unmanned Aerial Vehicle (UAV) imagery in the Matang Mangrove Forest Reserve, peninsular Malaysia. *Forest Ecology and Management*, *411*, 35–45. https://doi.org/10.1016/j.foreco.2017.12.049

Pagán, J. I., Bañón, L., López, I., Bañón, C., & Aragonés, L. (2019). Monitoring the dune-beach system of Guardamar del Segura (Spain) using UAV, SfM and GIS techniques. *Science of the Total Environment*, *687*, 1034–1045. https://doi.org/10.1016/j.scitotenv.2019.06.186

Rombouts, J., Melville, G. J., & Stone, C. (n.d.). *Operational deployment of LiDAR derived information into softwood resource systems DATASET · FEBRUARY 2015*. https://www.researchgate.net/publication/274375876

Shrestha, R., & Wynne, R. H. (2012). Estimating Biophysical Parameters of Individual Trees in an Urban Environment Using Small Footprint Discrete-Return Imaging LiDAR. *Remote Sensing 2012, Vol. 4, Pages 484-508*, *4*(2), 484–508. https://doi.org/10.3390/RS4020484

Smith, W. B. (n.d.). *Forest inventory and analysis: a national inventory and monitoring program*. www.elsevier.com/locate/envpol

UN. (2019).

UNEP 2022. (n.d.). Retrieved April 14, 2022, from https://www.unep.org/explore-topics/forests/why-do-forests-matter

Wallace, L., Lucieer, A., Watson, C., & Turner, D. (2012). Development of a UAV-LiDAR system with application to forest inventory. *Remote Sensing*, *4*(6), 1519–1543. https://doi.org/10.3390/rs4061519