CROWD-SOURCED CADASTRAL GEOSPATIAL INFORMATION:

Defining a workflow from Unmanned Aerial System (UAS) data to 3D building volumes using opensource applications

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DECLARATION

The work entailed in this document was done by me in its entirety except for those portions that are clearly cited from other sources. This thesis is the view of the author and not necessarily that of the Institute of Geoinformatics, nor the consortium of Universities that host this Geospatial Technologies master course.

This thesis has not been submitted nor presented elsewhere for award, publicity nor financial gain.

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Chaplin Williams

DEDICATION

To Tamika, Jonathan and Atarah with love.

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ABSTRACT

The surveying field has been impacted over many decades by new inventions and improvements in technology. This has ensured that the profession remains one of high precision with the employment of sophisticated technologies by Cadastral Experts. The use of Unmanned Aerial Systems (UAS) within surveying is not new. However, the standards, technologies, tools and licenses developed by the open source community of developers, have opened new possibilities of utilising UAS within surveying. UASs are being constantly improved to obtain high quality imagery, so efforts were made to find novel ways to add value to the data.

This thesis defines a workflow aimed at deriving Cadastral Geospatial Information (Cadastral GI), as three-dimensional (3D) building volumes from the original inputted UAS imagery. To achieve this, an investigation was done to see how crowd-sourced UAS data can be uploaded to open online repositories, downloaded by Cadastral Experts, and then manipulated using open source applications. The Cadastral Experts had to utilise multiple applications and manipulate the data through many data formats, to obtain the (3D) building volumes as final results. Such a product can potentially improve the management of cadastral data by Cadastral Experts, City Managers and National Mapping Agencies. Additionally, an ideal suite of tools is presented, that can be used store, manipulate and share the 3D building volume data while facilitating the contribution of attribute data from the crowd.

KEYWORDS

Cadastral Geospatial Information

Unmanned Aerial Systems

3D Building volumes

Crowd-sourced data

Opensource applications

ACRONYMS

2D – Two Dimensional

2.5D – Two-and-a-half Dimensional

3D – Three Dimensional

CRS – Coordinate Reference System

CSF – Cloth Simulation Filter

DGPS - Differential Global Positioning System

EPSG – European Petroleum Survey Group

FIG – International Federation of Surveyors

GCP – Ground Control Point

Geo-ICT – Geospatial Information and Communication Technologies

GI – Geospatial (Geographic) Information

GML – Geography Markup Language

GPS – Global Positioning System

ISO – International Standards Organization

JSON – Javascript Object Notation

LOD – Level of Detail

NMA(s) – National Mapping Agency (Agencies)

OAM – Open Aerial Map

OpenGIS or OGC – Open Geospatial Consortium

OIN – Open Imagery Network

OSM – Open Street Map

ROI – Region of Interest

UAS – Unmanned Aerial System

UTM – Universal Transverse Mercator

WGS84 – World Geodetic System 1984

INDEX OF THE TEXT

INDEX OF TABLES

INDEX OF FIGURES

1 CHAPTER 1 - Introduction

1.1 Motivation and Rationale

In recent decades, developing countries such as Jamaica have employed various strategies to acquire imagery for use in updating topographic maps and to build the national cadastral map for registering property ownership. Despite the efforts made, the acquisition of affordable, up to date, high quality imagery for Jamaica remains a futile task. The lack of up-to-date imagery is mainly a resource challenge that stems from governance, institutional and financial constraints. This results in imagery acquisition being prolonged over many years with overarching cost overruns. The challenge is further exacerbated because the imagery that is eventually procured, is usually not freely available for all interested parties to use.

Coupled with this imagery challenge, is the issue of the two-dimensional (2D) cadastre, that is currently unable to fully account for the newer realities of the built environment, which is increasingly complex, Paasch et al. (2016). It has become difficult to manage the three-dimensional (3D) world we live in, using planar 2D resources such as the 2D cadastre. This issue currently affects many National Mapping Agencies (NMAs) and City Managers who find it challenging to manage the complex built environment using the limitations of the 2D cadastre.

The issues highlighted above demonstrates the need for: additional conduits of imagery supply and managing the cadastre in 3D. Another resource problem is that the 3D cadastre is costlier to implement and maintain than its 2D counterpart, and any such implementation by organizations managing cities (City Managers) or countries (NMAs) must be justified, Paasch et al. (2016).

This thesis seeks to point the conversation towards a possible solution for both problems shared above, and by so doing, the following questions have arisen. Can the Cadastral Experts (City Managers and NMAs) capitalize on open access imagery as data inputs to building the Cadastral Geospatial Information (GI) store? How can the current forms of

Cadastral GI be manipulated to better meet the needs of the complex 3D reality we live in? Can these necessary implementations be in a form that is cost effective for all? These questions have led to the search for new capabilities, technologies, and methodologies of acquiring the required imagery and associated data products in a form that will help to increase the Cadastral GI store.

There is a gap in scientific research regarding open UAS imagery and the hosting of derived imagery products on web-based platforms. The research however, seems to trend towards using crowd-sourced resources to aid in interpreting features captured by UAS imagery, hence fast-tracking, and strengthening the participatory process. Crowd participation can be highly beneficial to many jurisdictions such as Jamaica. This thesis will contribute to the scientific community by highlighting a workflow that yields a supply of cost-effective UAS imagery. The workflow also leads to the derivation of 3D building products from the UAS imagery, which will be made openly accessible on a web platform that allows for citizens of a local area to benefit, and to contribute to the growth of this geospatial resource.

1.2 Research Questions

The appropriate research questions to contextualise this thesis are:

1. How can crowd-sourced UAS imagery be used to improve the cadastral data available for base mapping?
    a. In what ways can the crowd participate in this process?
    b. What processes are necessary to facilitate this participation by the crowd?
    c. What data formats will the crowd be required to submit?
    d. Where does the contribution of the crowd end and where does that of the Cadastral Expert begin?
    e. What costs will be incurred by the crowd and the expert throughout this process?
    f. Can the quality of data submitted by the crowd be trusted?

2. What tools and techniques exist, or can be implemented to aid in making Cadastral Geospatial Information more open?
    a. Are the necessary tools freely available?
    b. Are the necessary standards and data formats already implemented?
    c. What final data formats will be created by the Cadastral Experts and will they be shared openly also?

The chosen approach to answer these questions are outlined below.

1.3 Aim and Approach

The proposed workflow requires inputs of free and open UAS imagery from the crowd - which includes Cadastral Experts and UAS enthusiasts. The crowd will capture and perform basic pre-processing on the imagery by using freely available applications such as Precision Mapper. They will then upload the outputted 2D orthomosaic and the 3D point cloud to open online repositories such as Open Aerial Map (OAM) and 3DCity Web Map (hosted by the Cadastral Expert) respectively. This will be the initial contribution of the crowd towards this workflow, but the process does not end there. The Cadastral Experts will then download that 2D imagery and 3D point cloud data, conduct geoprocessing techniques that will be further described within this thesis, and produce building data as 3D volumes that can be further managed as 3D Cadastral GI. The crowd will be allowed to participate again at the end of the process chain by volunteering attribute information to the final 3D building volumes on the 3D web map interface that the Cadastral Experts will provide.

This workflow requires a deep investigation of open geospatial data standards, Hawerk (2001), licenses and tools, with focus on their capabilities for deriving cadastral 2D and 3D data. The workflow also necessitates an investigation of: input data formats, the interchange and interoperability of data formats during the geoprocessing phase, and the final output data formats that must allow for the editing of the 3D building volume attributes.

The thesis objectives and deliverables are seen in Table 1.

GENERAL OBJECTIVES	SPECIFIC OBJECTIVES	DELIVERABLES
Review Literature and State of the Art	• Review literature and State of the Art	
Prepare and conduct flight survey using GCPs for accuracy	• Prepare Flight plan	
	• Conduct UAS survey	✔
	• Collect GCPs on project site using DGPS	✔
Process UAS imagery using Open source applications	• Process UAS imagery using Opensource applications	✔
Produce imagery bi-products in 2D and 3D for cadastral base maps.	• Create 2D imagery products in vector format	✔
	• Create 3D imagery products in point and volume format	✔
Make imagery products openly accessible on OAM or other Open web repositories	• Make 2D imagery openly accessible in OAM	✔
	• Provide users with existing web-based application to visualize and process 3D data	✔
Provide geoprocessing tool for users to classify building types in 3D	• Provide tool for experts to access buildings as individual 3D volumes on a web interface and edit building classes for cadastral purposes.	✔

Table 1: General and specific objectives of thesis.

These represent core tasks that should be accomplished in this project to establish the validity of the workflow strategy. Deliverables highlighted represents the success criteria, they must be fulfilled by thesis completion date.

The general and specific objectives in Table 1 refers to the core tasks that were undertaken to successfully prove that the proposed workflow yielded the desired 3D building volumes. The theoretical foundation was first established by conducting literature review, then UAS flight survey was planned and conducted over the Leonardo Campus in Münster, Germany. The resultant imagery was pre-processed using Precision Mapper which produced 2D orthomosaic imagery and 3D dense point cloud. The 2D imagery and

3D point cloud were used to create 3D building volume data as a final product. More details will be shared in chapters 3 and 4.

1.4 Conceptual Architecture

The approach used to achieve the research goals can be seen in Figure 1. The crowd's initial role was to utilise their UAS to capture imagery, to pre-process that imagery using opensource tools, and to share that data on open repositories for others to access. The Cadastral Experts' role is to access the available data from the open repositories and geoprocess this data. Afterwards, the Cadastral Experts uses openly accessible geoprocessing tools to build the cadastral base mapping infrastructure.

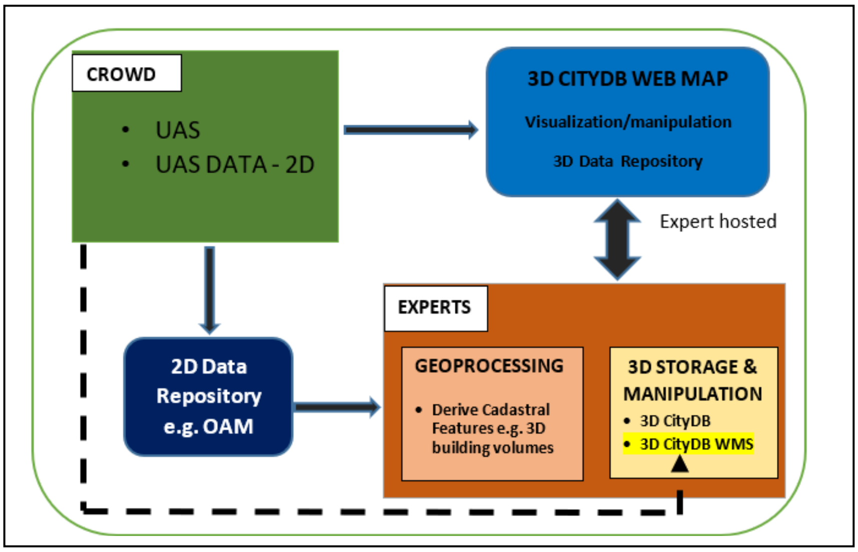


Figure 1: Thesis conceptual architecture.

The crowd consists of experts and enthusiasts who collect UAS data. They will pre-process their data and upload the 2D data to OAM and the 3D data to the 3DCity Web Map implemented by the City Manager or NMA that hosts an instance of the 3DCityDB. The Cadastral Experts will in turn download this data and use them to generate new 3D building volumes using the CityGML tool. The data will be stored on the 3DCityDB and transferred to the 3DCity Web Map which can facilitate attribute edits from the crowd.

The crowd comprises everyone including Cadastral Experts, organizations and UAS enthusiasts who use UAS to collect imagery data which they make available in its pre-processed state i.e., as Red-Green-Blue (RGB) orthomosaic in 2D and RGB sparse or dense point cloud - which represents the same data but in 3D. The 2D products are then uploaded by the crowd unto an open web repository such as OAM which allows this imagery to be accessed by the experts via the OAM interface as a downloadable raster layer. To upload the data to OAM, the crowd must first save the data to a cloud-based service such as Dropbox or Google Drive. The imagery must be shared with the public and without restrictions. This allows the OAM uploader to read the file from the storage repository unto the OAM online repository. This data will then be openly accessible to the Cadastral Experts to conduct further geoprocessing techniques.

The 3D point clouds can similarly be saved to Dropbox or Google Drive by the crowd; who will then use an uploader tool within the 3DCityDB Web map interface to import the 3D point cloud. The 3D point cloud data will be stored unto the 3DCityDB database or any other database hosted by the City Manager or NMA and can then be used to conduct further geoprocessing techniques. Beyond this point, the process necessitates the Cadastral Expert to extract further Cadastral GI by combining the planar 2D features with the 3D point cloud to produce volume data in 3D. This renders cadastral data in 3D which allows for new possibilities of maintaining and upgrading cadastral datasets.

1.5 Contribution

This thesis provides a new outlook within the surveying and geospatial technology fields. It defines a workflow strategy that employs open source applications, standards, methodologies, and data formats in the process of creating and maintaining Cadastral GI, that are of comparable quality to their proprietary counterparts. The project highlights the acquisition of Cadastral GI using inexpensive technology, yielding standard 2D and new 3D products that are beneficial to increasing the Cadastral GI store.

1.6 Outline

The remaining chapters of this document are as follows: Chapter 2 describes the theoretical background regarding UAS in cadastral mapping. Chapter 3 speaks to the methodology and results, while the evaluation and discussion of the process chain and the tools used are in chapter 4. The conclusion, limitations and suggestions for future work comes thereafter.

2 Chapter 2 - Theoretical Background

2.1 Towards a definition of Cadastral GI

Work done by scholars of the Geographic community such as that of the Varenius project defines *Geographic Information* broadly as "information about the features and phenomena located near the surface of the Earth" Goodchild et al., (1999). More specifically, GI was later defined by the same team of scholars as a "tuple < x, y, z, t, U> where U represents something present at some location (x, y, z, t) in space-time" Goodchild et al., (1999). With this context in mind, the scholars then drew the conclusion that the terms *geospatial information* and *geographic information* can be used synonymously, Goodchild, Fu & Rich (2007). The terms *geospatial information* and *geographic information* will therefore be used in this paper to represent the same type of information and in short will be termed *GI.*

Cadastral geospatial information (Cadastral GI) is a subset of GI. It refers to the types of information termed GI objects by other scholars, who give the definition for GI objects as, "one or more tuples or aggregates defined for some practical purpose - in other words a geographic data set or database", Goodchild, Fu & Rich (2007). Cadastral GI therefore refers to those datasets that are created both by established surveying methods and photogrammetry using aerial photographs and/or satellite imagery. These datasets are the initial building blocks of mapping data and are widely used by numerous other fields as base maps or input data. Cadastral GI goes beyond the core classes of data related to surveying such as the parcel and its associated ownership and rights, Oosterom & Lemmen (2003), but includes all possible classes of topographic data that is associated with cadastral data. Below is a non-exhaustive list of Cadastral GI objects:

- Parcel/plot of land;
- Boundary (wall, fence etc);
- Building in 2D and 3D;
- Ground Control points and boundary location points;
- Access (Roads and footpaths) along with street centre-lines;
- Drainage features (concrete or earth drains, gullies, rivers, ponds, lakes etc);

- Vegetation features (forests, grasslands, farmlands etc);
- Imagery (satellite imagery and/or aerial photographs);
- Elevation (Digital Elevation Model or DEM);
- Elevation (Contours and spot heights);
- Slope;
- Aspect; and
- Land use.

2.2 Definition of Crowd-Sourced (as it regards Cadastral GI)

'Crowd-sourced' refers to the way in which the Cadastral GI objects mentioned above are collected, pre-processed, and supplied. This is in-keeping with the definition given by scholars regarding the 'providers' of GI objects. A provider of GI is defined as "an individual, agency, web site, or archive possessing or controlling one or more GI objects" Goodchild, Fu & Rich (2007). In the case of this thesis, the providers of Cadastral GI are viewed as the public or the 'crowd'. These are anyone, anywhere who wishes to contribute this type of data or GI objects, regardless of their skill, qualification, or motive for sharing this data. More on this issue will be discussed in section 2.3.

Another important definition is that of the 'user' of Cadastral GI. The Cadastral GI user is "an individual or agency in receipt of one or more GI objects from a provider", Goodchild, Fu & Rich (2007). This definition is adopted throughout this thesis and therefore the users of Cadastral GI are held to be anyone, or any entity that use or can make use of the Cadastral GI objects provided by the crowd. This does not exclude the crowd itself from being users of that data, however the focus of this thesis is on the Cadastral Experts as users of Cadastral GI such as NMAs, private surveyors, and other GI professionals.

2.3 The case for crowd-sourced Cadastral GI

Cadastral information has historically been provided by Cadastral Experts as they are the authoritative bodies who are specifically qualified to collect, process and disseminate this type of information. In more recent decades however, the trend has been to broaden the scope of standard formulation for cadastral mapping, surveying and information gathering. A major move in this direction was the inclusion of the Open GIS Consortium (OpenGIS) into standardization initiatives of the International Federation of Surveyors (FIG) and the International Standards Organization (ISO), Oosterom & Lemmen (2003). Oosterom and Lemmen mentioned some of the more recent advancements in cadastral systems in 2003, which they termed '*Geo-ICT'*. They proceeded to highlight the improvements in '*quality, cost effectiveness, performance and maintainability'* that are accrued within cadastral systems. It is the view of this thesis that more collaboration between the established authorities in Cadastral Mapping and OpenGIS will unveil additional ways in which improvements and cost savings can be garnered; thereby making the collection and sharing of Cadastral GI more open. To further substantiate this viewpoint, the work of other scholars was explored, and is seen below.

Goodchild (2007) expressed his views of the current trends of contributions of GI over the Web by members of the public. He mentioned web applications that facilitated sharing of information by the public such as '*Wikimapia*', '*Flickr*', '*Openstreetmap*' and '*Google Earth*'. He continued by naming the technological developments that have enabled this participatory contribution to GI by the public, such as '*Web 2.0*', '*Georeferencing enabled by GPS and Geocoding', 'Geotags', 'Graphics' and 'Broadband communication'.*

Butler (2006) expands Goodchild's view of the impact that the Web plays in making the public - formerly mere users of GI from the internet - creators and contributors of GI. Butler reviews both open access and proprietary web applications such as '*Google Earth*', ESRI's '*ArcGIS Explorer*', '*TerraExplorer*', '*Skyline Online*' and Nasa's '*World Wind Virtual Globe*'. These applications not only allowed users to view and create imagery products, but also to perform various types of analysis based on how adept those individuals were. It is evident therefore that the users of the major digital web GI repositories or applications not only demanded high quality imagery, but also processing ability. They need to be able to create new products to meet their needs from the resources available online. The Cadastral Experts should grasp the opportunity to advance their field by accepting the contribution from the crowd which will lead to an increase in the Cadastral GI.

2.4 The cadastral situation in Jamaica

NMAs worldwide historically acquired most of the Cadastral GI due to: high cost of data acquisition, the specialised equipment required, and the qualifications necessary to ensure highest quality was achieved. Goodchild related that up to the first half of the twentieth century, GI collection and sharing was the sole role of these NMAs that were usually government funded, Goodchild, Fu & Rich (2007). Changes towards the second half of the twentieth century fuelled by the need for reduction in government expenditures, led to the adoption of new technologies and inventions in GI production such as desktop computers, and sophisticated GI related software that made acquisition and processing of GI data easier, cheaper, and more innovative, Goodchild, Fu & Rich (2007).

Jamaica is one such country with a NMA called the National Land Agency (NLA). NLA has the responsibility to manage the land resource, including, but not limited to, the surveying of government owned lands and creating and maintaining the cadastral map within Jamaica. As a developing country, Jamaica underwent the changes Goodchild mentioned above in managing its Cadastral GI, yet many challenges still exist. One such challenge is an extremely slow growth of its cadastral map as outlined in Figure 2 below, despite improvements in surveying equipment, and computer hardware and software.

The areas seen in red in Figure 2 represents groups of parcels that have been surveyed, compiled, and coordinated to the Jamaican datum (Jamaica datum 2001 or JAD2001). Of the 831,256 parcels of land island-wide, approximately eleven percent (11%) was represented in the cadastral map, NLA (2017).

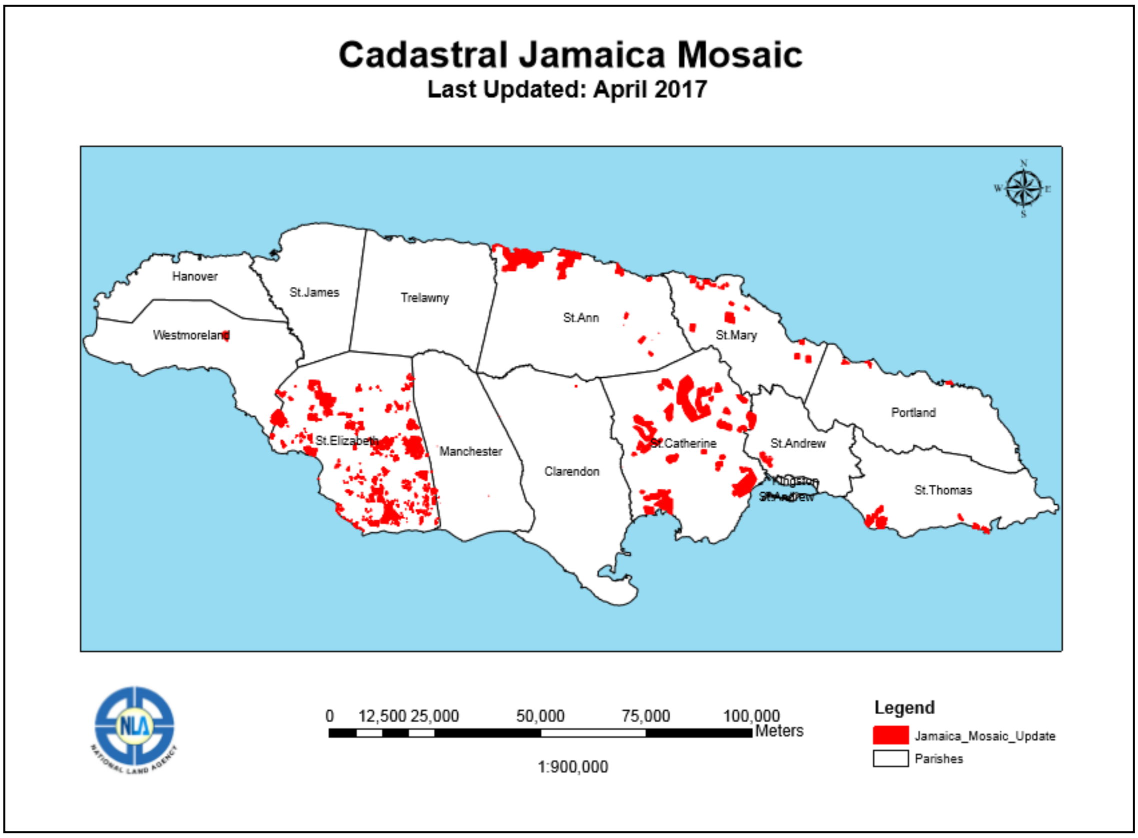
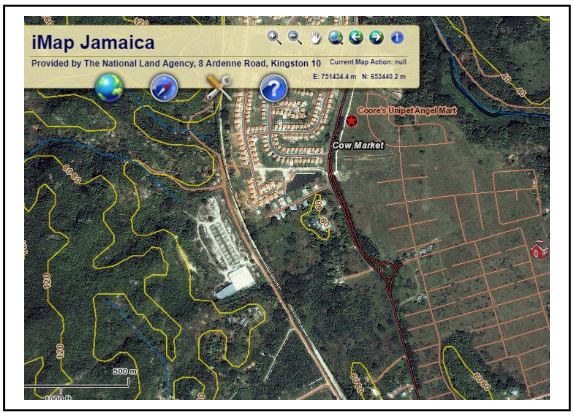


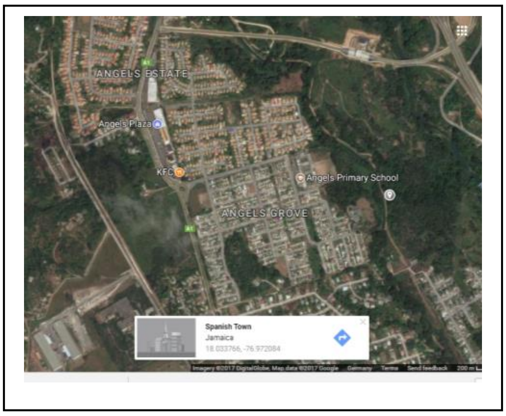
Figure 2: The state of completion of the cadastral map of Jamaica as of April 2017. NLA (2017)

The parcel blocks in red were compiled from individual surveys and subdivision plans over many years. This dataset represents the most accurate cadastral dataset available in Jamaica, however resource challenges have hampered the growth of this dataset.

Among the many challenges for the slow pace of cadastral map completion is the resource challenge, and one such resource is the lack of up-to-date, high quality imagery to assist in the cadastral surveying and mapping process. Despite technological upgrades over the last couple of decades, the NLA still struggles to keep pace with the high cost of inputs such as aerial photographs, satellite imagery, hardware, and equipment. Progress on conducting and compiling these surveys were mainly achieved through special projects that targeted specific parishes, which accounts for the disparity of compiled surveys between the various parishes as seen in Figure 2. Importantly, the image in Figure 2 is not intended to suggest that no surveys were conducted in the parishes without red polygons as this is not the case. It means that those parcels with red polygons were co-ordinated to the national datum and compiled within the cadastral map. This slow pace of Cadastral Map compilation is due in parts to the imagery challenge that exists in Jamaica.



iMapJamaica



Googlemap

Figure 3: The Imagery challenge in Jamaica

Screenshots taken 5/10/2017 of the 2002 IKONOS imagery hosted on the iMapJamaica geospatial information sharing platform (left) and the corresponding Googlemap Digital Globe imagery bearing a 2017 image of the same area (Right).

Figure 3 above illustrates the dated imagery that is available for use on NLA's website, which illustrates the outdated nature of the available imagery. When compared to the current imagery on Googlemap, also seen in Figure 3, one can see the vast development within the same area. Most notable changes are the housing scheme in the centre of the Googlemap imagery along with the highway in the upper right corner. In 2016, the NLA and the Government of Jamaica acquired more recent Digital Globe imagery, however because of resource challenges, that imagery was largely between 2-5 years old, and this was after a lengthy procurement process of approximately two years. Neither is this imagery openly accessible, as there are licensing issues. These factors highlight the resource challenge of acquiring and updating Cadastral GI in Jamaica, and this thesis is an attempt to aid in that process of making high resolution UAS imagery openly accessible for building the Cadastral GI resource pool, and by extension the cadastral map of Jamaica.

2.5 UAS for Surveying Purposes

The use of UAS for surveying purposes was evaluated from the standpoint of: data accuracy, the costs involved, and a comparison between UAS and traditional surveying methods. To begin with, UAS technology has improved in terms of data collection, to levels that are comparable to established Global Positioning Systems (GPS) surveying technology. UAS data has been proven to be within 3-8cm accuracy when compared to data surveyed with regular GPS equipment, Kerr & Dionne (2005). The study by Kerr and Dionne has illustrated that a one-hour UAS survey can capture data for an area that would take 4 days using GPS ground station surveying methods. In their study, the UAS data yielded millions of 3D data points for a given field survey compared to mere thousands of 3D data points with the traditional GPS ground survey methods, for the same area. This highlights the tremendous benefits that can be gained by using UAS technology to collect Cadastral GI.

The need for cost reduction in GI production along with technological advancements have always resulted in older methods giving way to newer innovative realities. The author believes that the field of Cadastral Surveying and Mapping will again be shifted with the now widespread use of UAS technology and equipment. Kakaes relates that UAS have grown very fast to now become an innovation that cannot be ignored based on its ability to acquire imagery that is of a comparatively very high quality, Kakaes et al., (2015). Kakaes supports that UAS can reduce the costs of GI collection even more than regular aerial photography and satellite mapping can, and highlights the various uses of this UAS imagery, namely: '*defining and maintaining property rights', 'defining community boundaries', 'land use planning', 'population censuses',* and *'natural resources inventory and management'*, Kakaes et al., (2015).

Recently, a UAS department was created within the Municipal Surveying and Cadastral Office of the City of Düsseldorf, Germany with the aim of aiding in Cadastral Mapping, Rose (2017). The department used a hexacopter UAS to assist in their surveying tasks, including capturing data about roofs and bridges along with general data to update the city maps and to create 3D models. The department projected the need for acquiring additional UAS devices, which reflects the need for utilizing this technology in the field of surveying to generate high quality imagery products as posited by this thesis.

Kakaes believed that UAS empowers both individuals and communities and adopted a similar term as that given by Goodchild. Kakaes calls the advent of UAS the "*democratization of technology and information"*, Kakaes et al., (2015). This ‘democratization’ of Cadastral GI comes with some challenges, two of which are the surveillance and privacy issue, along with the issue of data quality and accuracy, Haklay (2010). Surveillance and privacy are beyond the scope of this thesis, so they will not be addressed here, sufficing to say that individual jurisdictions or governments must assess and create laws to address this issue. This thesis however, deals with the issues of data quality and accuracy, and both are addressed in the following sub-section.

2.6 Crowd sourced Cadastral GI quality

High data quality is a major requirement for Cadastral Mapping and Surveying. Cadastral GI serves both as base mapping information, and the core dataset for property ownership. Cadastral GI therefore has both a legal and a spatial component and so the creators and maintainers of Cadastral GI are historically professionals or experts who have been trained to collect such. Cadastral GI requires positional accuracy, metadata, completeness, logical consistency, and time-based chronological validity, Bennat et al., (2007) and Haklay (2010). Goodchild relates that the NMAs have historically assured highest quality of GI by employing and training professionals, Goodchild (2007). Qualified surveyors usually create and collect Cadastral GI, while trained cartographers or other GI professionals would use this Cadastral GI to derive other products and create consumer goods such as maps, Haklay & Weber (2008) and Haklay (2010). If the ‘crowd’ now become creators of Cadastral GI such as providing UAS imagery, questions of data quality may arise, as highlighted in Goodchild (2007) and Haklay (2010).

The strength of the crowd contribution may depend on the real or perceived authority or influence of the web application on which the data is stored and shared. Applications such as the ArcGIS Online platform and Google Earth or Open Street Map (OSM) are all very established data repositories, however this does not necessarily vouch for the quality of data stored and shared. Google Earth for example has been found to host rather erroneous data, Goodchild (2007), while OSM is known to have many data gaps, Haklay (2010). However, a part of the development model of OSM is that data users/creators who themselves are aware of errors in the data will correct those errors, so the map is intended to be continually updated by contributors who correct the errors of others, Haklay & Weber (2008) and Haklay (2010). Haklay spoke about the growth rate of the OSM project from 2005 to 2008, highlighting the great interest and support that was given to such a project from the public.

This thesis holds, like Haklay concluded, that the data housed on open repositories such as OAM can be of very high quality, and benefits of having this data available and shared with the public far outweighs the ills of low data quality. The Cadastral Experts should be able to conduct their own assessment of this UAS imagery, and where possible, use their expert knowledge, tools, and methodologies to improve the data quality.

There are ample examples of projects successfully carried out using UAS for surveying purposes. UAS photogrammetry for mapping and 3D modelling have been on the increase, Remondino et al. (2011). This thesis seeks to explore some of these prospects, and to place emphasis on the 3D building products that can be derived from UAS imagery and used for Cadastral GI updates.

2.7 A closer look at OAM

OAM was created in 2015 as a repository to facilitate upload, indexing and availability of imagery for mapping and responding to disasters. The imagery data on OAM is freely available for download by all users. Contributions of imagery to the repository are freely sourced from the crowd.

OAM consists of an open community of developers, contributors, and users. Its source code is openly available, and it operates under an open standard with the Creative Commons Attribution 4.0 License, Smith, Giovando, Emanuele & Schuler (2015). Imagery published on OAM is used for humanitarian purposes such as disaster response, mapping of vulnerable communities, flood prone areas and other disaster risk areas. OAM imagery is saved on the Open Imagery Network (OIN) and therefore also becomes available on OSM.

2.8 Summary of Literature Review

Cadastral GI represents more than just information about property boundaries and ownership, it extends to GI such as imagery, along with all other datasets and resources that contribute to the cadastral base map resource.

Historically, Cadastral GI was collected by experts within the field, however the technological developments in recent decades along with the proliferation of open access GI have caused a change in the way Cadastral GI is collected and shared. Improvements in openly accessible Geo-ICT capabilities have opened new doors for the public to participate in the process of geodata creation. Consequently, members of the public such as UAS enthusiasts can contribute Cadastral GI to open online GI repositories equally with experts, and the experts in turn can use this UAS data and various geoprocessing tools to create additional value.

3 Chapter 3 - Methodology and Results

3.1 Outline of Methodology

Figure 4 illustrates the overall methodology that was performed to complete this master thesis.

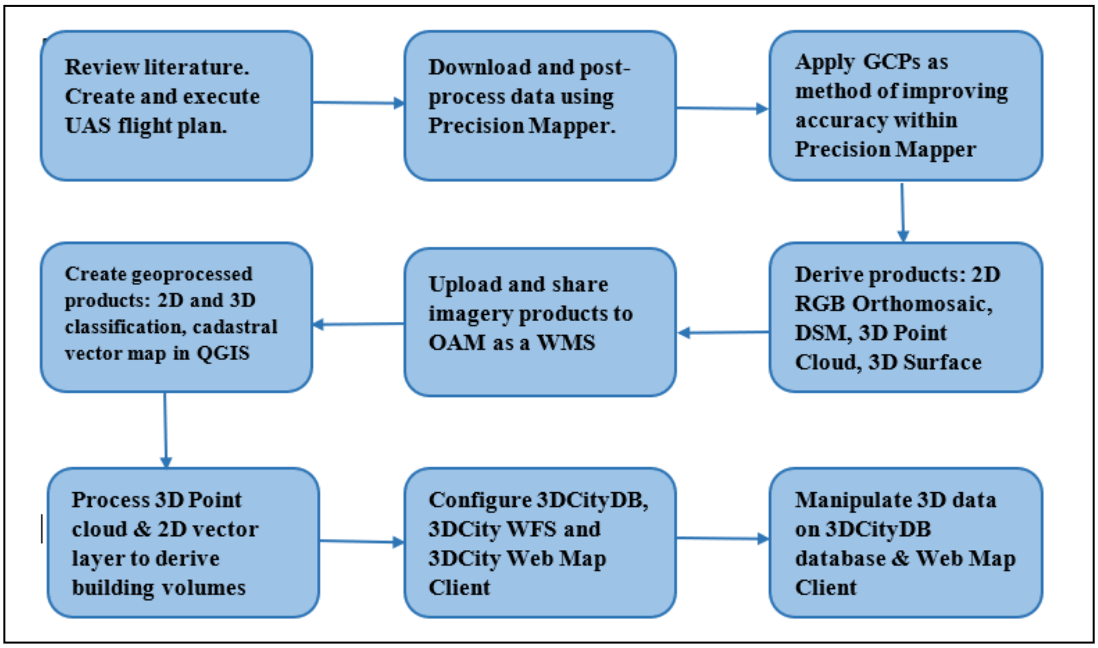


Figure 4: Methodology to complete master thesis

Literature was first reviewed, then the UAS flight survey conducted. The resultant data was pre-processed using the online application Precision Mapper, producing data layers such as 2D RGB Orthomosaic, and 3D Point cloud among other datasets. The 2D orthomosaic was shared on OAM and used for further geoprocessing within QGIS to create classified layers and then, vectors layers. Additionally, the 3D point cloud was used, along with the 2D vector layers, to extrude the buildings as 3D volumes using the 3dfier tool. This produced 3D building volumes with the CityGML standard and gml data format. The 3DCityDB database, Web Feature Service (WFS) and Web Map Client were then used to store, transfer, view and manipulate the data as building volumes.

Figure 4 illustrates the processes undertaken during this thesis. During this process, data was transformed into various forms. Raw data from the UAS was obtained as jpeg files. After pre-processing in Precision Mapper, various output formats were obtained. These were: 2D RGB Orthomosaic as a georeferenced TIF file; 3D Point Cloud as a las file representing millions of data points; DSM containing elevation values representing terrain height; kml tiles containing png files for upload to Google Earth and Google Maps; ply (triangle mesh) containing flat polygons; 3D model (triangle model) representing the data vertex positions; DXF layer representing the data in CAD format; Contours in shapefile format representing isolines connecting areas of similar height.

A rich resource of datasets was received as output from Precision Mapper, however emphasis was paid mainly to the georeferenced 2D orthomosaic layer (TIF file) and the dense 3D Point Cloud layer (las file) in realising the workflow proposed by this thesis. After data pre-processing, 2D post processing commenced. This entailed the classification of the 2D RGB orthomosaic layer, then the creation of 2D vector layers. The next step of the workflow was the post processing of the 3D point cloud data into building volumes and the configuration of the 3DCityDB suite of tools for geoprocessing. These processes along with the tools used can be seen in Table 2 below.

PROCESS	TOOLS
Flight Planning	Mission Planner (Open source)
UAS flight – Data Acquisition	DJI Mavic Pro UAS (specifications in Appendix A)
Data Pre-processing	Precision Mapper – limited free access to web platform, storage capacity and web tools
Post Processing 2D – Data Analysis e.g. 2D classification, 2D vector layers	QGIS (Open source)
Post Processing 3D – Data Analysis	Cloud Compare, MeshLab – (Open source)
Deriving of 3D volumes (e.g. Buildings)	3dfier tool – (Open source) MeshLab, Meshmixer – (Open source)
Geo processing tool for 3D building classification	3DCityDB Web Map, WFS and database – (Open source)

Table 2: Processes and tools used within Thesis

Flight planning was done using the opensource tool 'Mission Planner'. A lightweight, inexpensive UAS (DJI Mavic Pro) was used to capture the data in approximately 15 minutes. Data was then pre-processed in Precision Mapper and post-processed in QGIS (2D orthomosaic) and CloudCompare, Meshlab, Meshmixer and 3dfier (3D dense point cloud). Final storage, manipulation and visualization of the 3D building volumes were done using the 3DCityDB suite of tools – i.e. the database itself was used to store the 3D building volumes, the WFS for data manipulation/retrieval from database, and the Web Map Client for visualising and manipulating the data.

3.2 Flight Planning

Flight Planning was a critical first step in the UAS imagery acquisition process. It was done using the open source software called Mission Planner, ArduPilot (2016). This was in keeping with the main idea of this project that only open source tools will be used. The crowd can choose any open source mission planning software; however, care should be taken to ensure that the output file is compatible with the UAS being used.

A **section of the Leonardo Campus Münster, Germany** (a branch of the Westfälische Wilhelms-Universität Münster seen in Figure 5) was selected as the project area because of several reasons. These were: an existing license to fly a UAS over the university buildings within Münster; the buildings and trees in this location were on average below 3-4 storeys high and this was necessary for the UAS to fly below the allowable 100 meters maximum flight height (Government imposed restriction for civilian UAS flights); most of the features that were of importance to cadastral geospatial information could be found in that location.

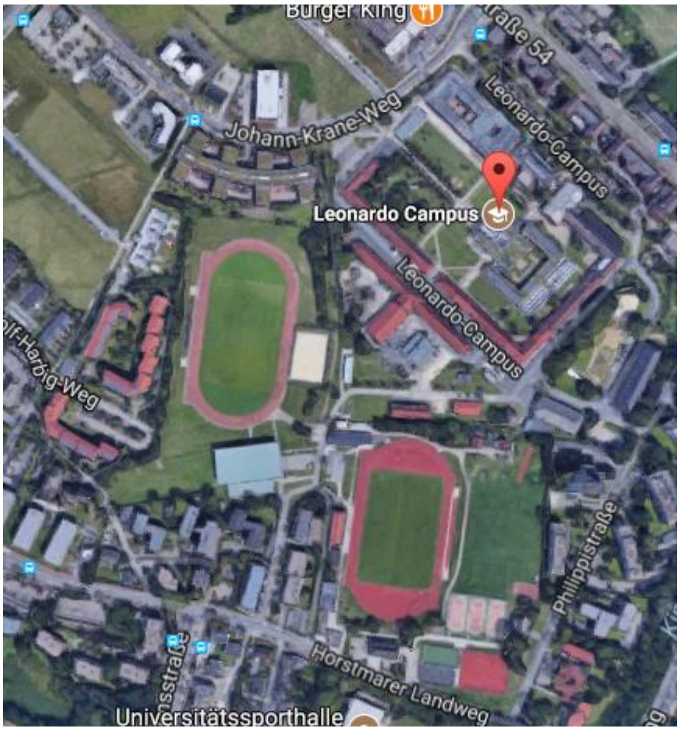


Figure 5: Google image of the Leonardo Campus Münster

Study area is southwest of Steinfurter Strasse, north of the Institute of GeoInformatics Geo-C Building. The study area covers approximately 21 hectares and houses the Sports faculty of the WWU.

The polygon representing the study area was digitized on Google Earth Pro and imported to Mission Planner as a kml file. The mission was designed to follow the transect pattern with regularly placed flight lines and regularly placed exposure points or waypoints as seen in Figure 6 below.

It was necessary to acquire UAS imagery with a high level of accuracy, and for cadastral mapping, below ten-centimetre accuracy was required. An attempt was made during this project to obtain the lowest possible ground sampling distance based on the specifications of the camera built-into the DJI Mavic Pro UAS (Appendix A) while considering the maximum allowable flying height and the height of features in the field for safety of the UAS. The planned and actual flight plan specifications are as follows.

The flight plan seen in Figure 6 had an 80% forward overlap of images and a 70% lateral overlap with flight lines being 30 meters apart. Flight height was 100 meters with a ground resolution of 1.23cm and a total of 540 images. At flight time however, challenges with uploading the flight plan to the UAS resulted in a manual flight being done. The manual flight was kept as close to the planned flight as possible, with a flying height of approximately 98 meters, ground resolution of 3.22cm, a total of 507 photographs taken and a surveyed area of 21.7 hectares.

Figure 6: Flight plan done in Mission Planner for the Leonardo Campus Muenster, ArduPilot (2016)

The UAS flight survey was manually done in the field. Parameters were kept like the original flight plan created in Mission Planner – Altitude was 98m, Ground resolution was 3.22cm, an area of 21.7 Ha was surveyed, and a total of 507 images taken.

3.3 Data Processing

A data processing workflow was adopted to successfully derive Cadastral GI products, this can be seen in Figure 7 below.

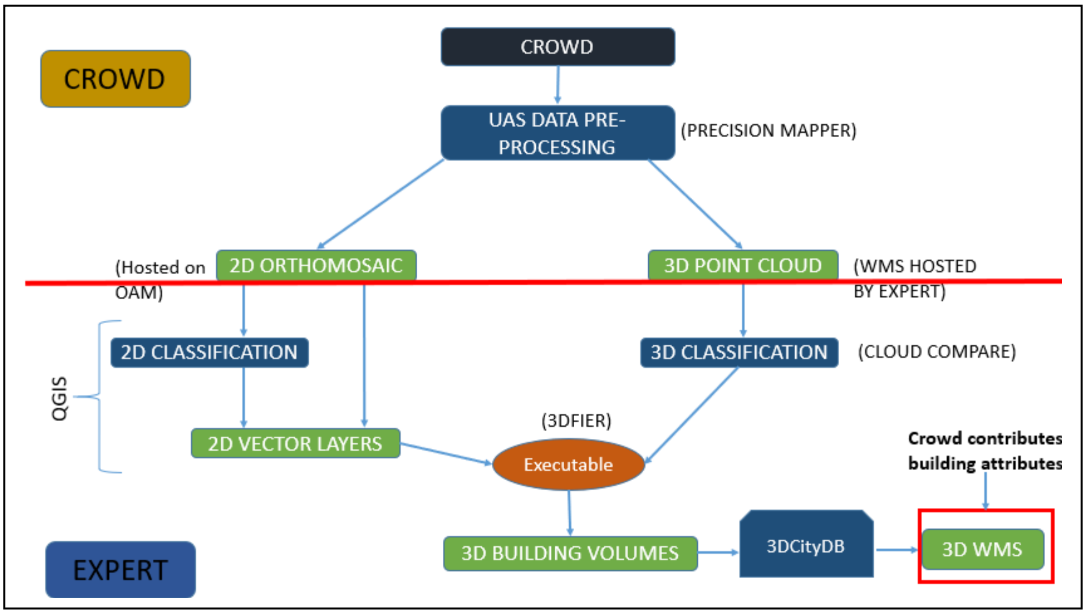


Figure 7: Data Processing workflow

As seen in Figure 7, the workflow began when the crowd collected UAS data. The tool Precision Mapper was used to pre-process the raw data. The 2D RGB orthomosaic was published on OAM and the 3D dense point cloud was shared on the Web Map Service hosted by the Cadastral Expert. The Expert then downloaded both datasets and began post-processing. The 2D orthomosaic was classified, then 2D vector layers were created using QGIS. Similarly, the 3D point cloud was classified within CloudCompare. The 2D vector layers and the 3D classified point cloud were used to extrude the 3D building volumes with the gml file format (CityGML Standard) using the 3dfier tool. These building volumes were then stored on the 3DCityDB and hosted on the 3D City WMS. The crowd will then be at liberty to volunteer attribute data for the 3D building volumes in the 3DCity WMS.

3.3.1 Data Pre-Processing

The data obtained from the UAS was pre-processed using the free online application (Precision Mapper) and free desktop version (Precision Viewer), Precision Hawk (2018). Figure 8 illustrates the Ground Control Points (GCPs) being processed.

Post-processing results can be seen in Figures 9 and 10. Figure 9 is the 2D RGB orthomosaic and Figure 10 is the 3D dense point cloud containing over 22 million points representing the features of the study area. As it regards this thesis, the 2D RGB orthomosaic and the 3D Point cloud layers both represent the **1st order Cadastral GI final output** generated from the UAS imagery and are good for cadastral mapping.

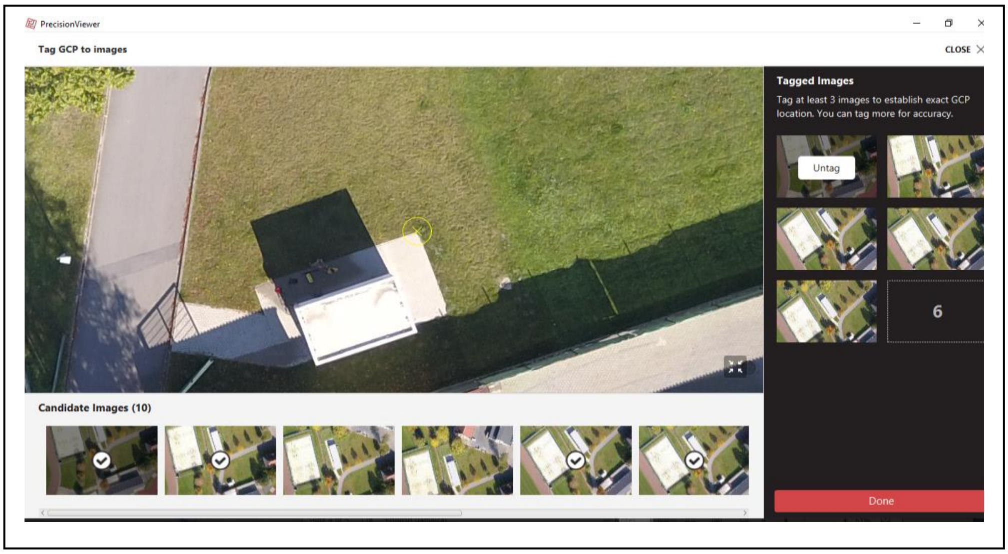


Figure 8: Processing of GCPs in Precision Viewer

Thirty-one (31) GCPs were processed for the study area. A table showing details of the GCP data points can be seen in Appendix B. Precision Viewer has a simple tool for uploading GCPs as csv, then tagging the photographs on which each GCP can be found. This process helped to increase the accuracy of the final output datasets and was a critical step to ensure that the data was fit for cadastral purposes.

The GCPs in appendix B were applied to improve the absolute accuracy of the imagery. GPS Accuracy of the DJI Mavic Pro based on its specifications lies between 1-5 meters of the actual feature position. These GCPs were collected using Differential Global Positioning System (DGPS) and improved the absolute accuracy to within 0.1 meter. This was important for cadastral mapping as it meant that features on the image were accurate to the sub-meter level.

Figure 9: 2D RGB Orthomosaic of UAS imagery taken over the Leonardo campus. (Precision Mapper output)

The 2D orthomosaic was outputted from the pre-processing in Precision Mapper in geoTIFF format. This is a standard product at this stage of the process chain and represents the 1st order final product of the Cadastral Mapping process. This high resolution (3cm) imagery is critical to the process of creating Cadastral GI as it allows for digitizing features such as building footprints, roads, vegetation, and the general terrain which are necessary base mapping information.

Figure 9 was the output from the pre-processing in Precision Mapper and was obtained in geoTIFF format. This 2D orthomosaic represented the dataset that the crowd will receive as output from the pre-processing steps and subsequently upload to the OAM online repository to be publicly shared using the creative commons license. This license allows users of OAM to download the imagery with no limitations of use. The Cadastral Expert will then satisfy themselves whether the imagery is fit-for-use to continue the chain of processes by applying verification methods such as GCPs.

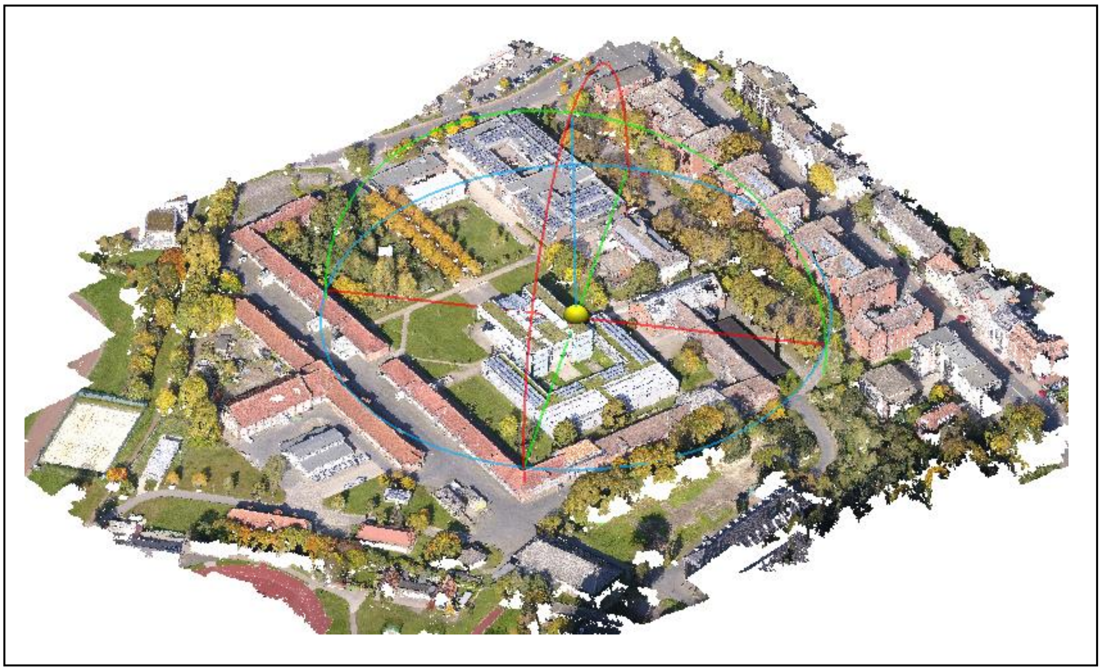


Figure 10: 3D Point Cloud of UAS imagery taken over the Leonardo campus. (Precision Mapper output)

This 3D point cloud was generated by photogrammetric means using 'Structure from motion' algorithm within Precision Mapper. While images were being stitched together it constructed a 3D model of the data using data from overlapping imagery pairs until the entire study area was reconstructed. This resulted in the dense network of over 22 million (22,770,854) points all bearing the RGB information for the point they represent in the original imagery.

The 3D point cloud from Precision Mapper seen in Figure 10 was output in las format. This format was designed to store lidar data but works well with other 3D point data holding x, y, and z coordinates. These points were arrayed in a dense structure with over 2 million points all bearing the respective RGB information for the points they represent. This dataset is important because it allows for cadastral features to be observed and managed in a 3D format. Like the 2D orthomosaic, this 3D point cloud is a **1st order final product** of the process chain. Nevertheless, this is not the final output of the thesis because the cadastral features are desired in volume format and not point format.

3.3.2 2D Data sharing on the OAM Repository

The 2D RGB orthomosaic imagery was uploaded to OAM and was later made available on OSM. Upon upload, the imagery was assigned a creative commons license, Smith, Giovando, Emanuele & Schuler (2015). This license facilitated, among other things, the use of the uploaded imagery for digitizing features unto the available layers of the OSM, and for download of the imagery at will.

In order for the crowd to contribute imagery to OAM, a login had to be created either directly to the OAM website or using a Google or Facebook account. The OAM platform also allows for metadata about the imagery to be created by the contributor, which provides valuable information about the imagery to users. The 2D RGB orthomosaic of the study area that was uploaded to OAM can be seen in Figure 11. The imagery is also available on the OSM repository as seen in Figure 12.

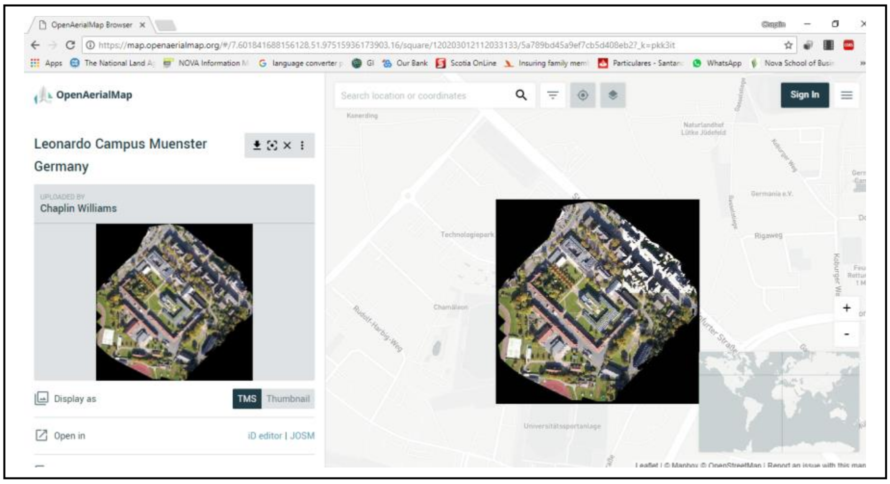


Figure 11: 2D RGB Orthomosaic uploaded to OAM in geoTIFF format

The 'Leocamp' geoTIFF obtained from the pre-processing stage in Precision Mapper was published on OAM as a Web Map Service (WMS). This is now publicly available for download by any interested party, including Cadastral Experts who require the data for further post-processing.

The 'Leocamp' geoTIFF was also made available on OSM. It is now one of the layers available for base mapping within OSM and allows individuals from the public to digitize the features on the imagery such as buildings, roads, vegetation etc. Figure 12 shows the data on OSM.

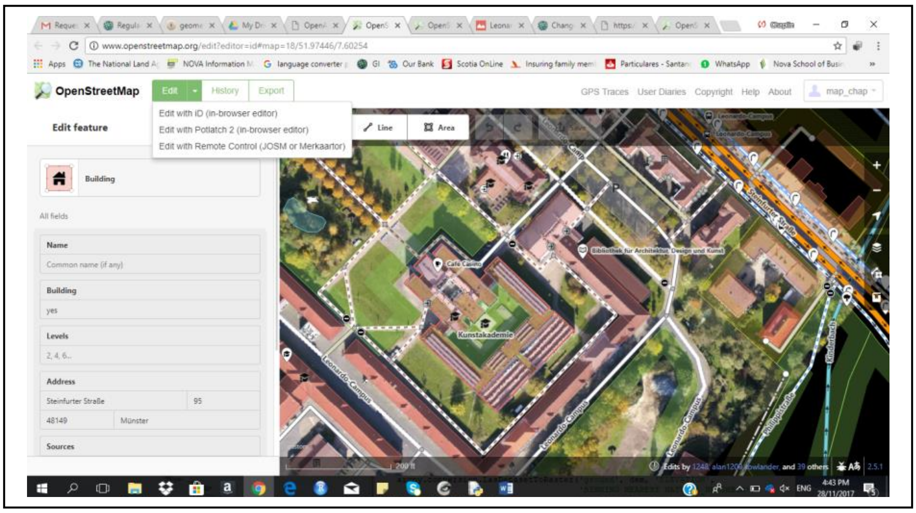


Figure 12: 2D RGB Orthomosaic available on OSM in geoTIFF format

The imagery uploaded to OAM is stored as a part of the Open Imagery Network (OIN), so it is automatically made available on OSM for building of the humanitarian base mapping features. Members of the public are free to edit vector features from the imagery or download the imagery for their own use.

The upload of the imagery to the OAM repository and its subsequent availability on the OSM repository are both critically important to the central theme of this thesis, which is that the imagery obtained from UAS whether taken by experts or enthusiasts should be ideally made available to the public.

3.3.3 Post Processing: 2D Data Analysis

After pre-processing and uploading the 2D RGB orthomosaic to OAM/OSM, the data was imported to the opensource application QGIS and was used to create classification layers. Classifying the imagery was the most appropriate way of distinguishing the features to determine the classes that existed within the study area.

First, an unsupervised classification was done using seven (7) classes as seen in Figure 13. Seven classes were selected as a way of judging how the algorithm would separate and distinguish the features on the imagery. The results illustrated that the unsupervised classification could not effectively distinguish the features. A reason for this is that some features such as buildings had varied RGB digital numbers, and so spectrally they were distinguished as separate features. Also, some buildings had the same spectral signature as roads and concrete, while some buildings had grass planted on top. This necessitated the creation of a supervised classification to aid in distinguishing features from the imagery.

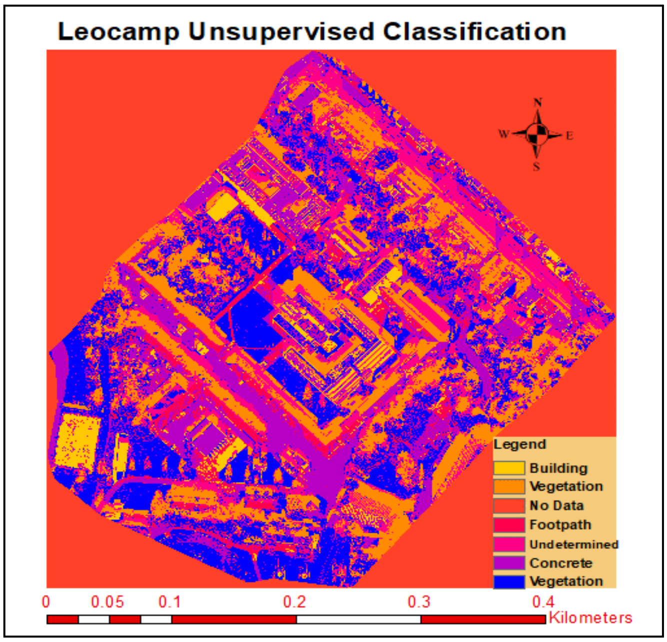


Figure 13: Unsupervised classification with 7 classes

The 7 classes produced by the unsupervised classification were Building/Play area, Vegetation (Grass), Vegetation (Trees/Forest), Footpath (Bare soil) and Building/Concrete, No Data and Undetermined.

There were overlaps regarding the digital signatures of the features within the imagery. There were inconsistencies in the building roof material within the study area, such as rooftops with grass. There were also similarities between different features, such as some roof material having the same reflectance as roads and concrete. The inconsistencies and similarities confused the classifier.

The unsupervised classification seen in figure 13 was created at the pixel level with a 3cm minimum mapping unit. The classification captured the distinct features of the landscape but had some mixing of classes based on various factors, such as building rooftops reflecting similar digital numbers as concrete areas in some cases, and as grass in other cases. These inconsistencies confused the classifier and caused some features to be improperly classified.

To gain control over the interpretation of the features of the imagery, a supervised classification was created using 6 classes. These were Building, Road/Concrete, Grass, Tree, Play area and Bare soil. Figure 14 illustrates the supervised classification. The supervised classification was done to introduce training samples to the classifier in order to distinguish the features. Eighty-three (83) training samples were used to identify the category to which the features belonged. The results are seen in Figure 14.

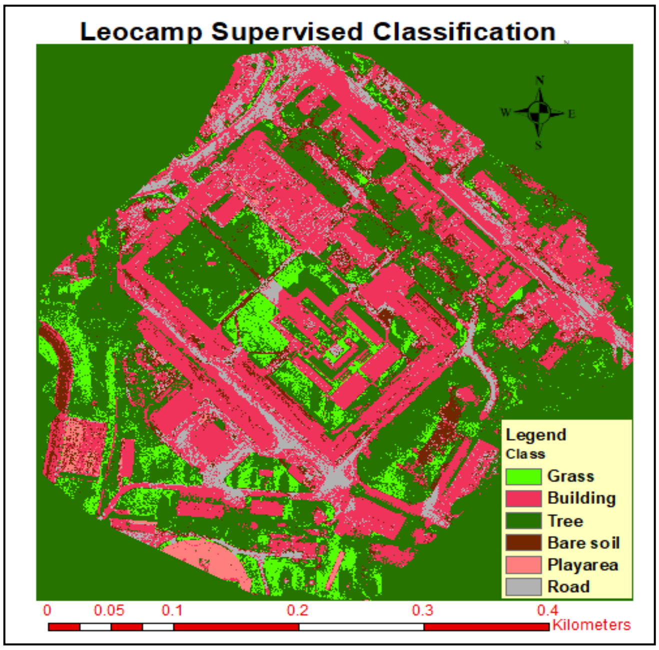


Figure 14: Supervised Classification showing 6 classes

A training sample was created with 83 polygon samples taken from the 2D RGB orthomosaic. The samples were of 6 classes, namely; Grass, Building, Tree, Bare soil, Play area and Road/Concrete.

This was processed with a Maximum Likelihood algorithm to determine the classes for the output imagery.

Both unsupervised and supervised classifications were created using the Orfeo Toolbox, a geoprocessing tool available in QGIS. The K-means algorithm was used for the unsupervised classification, while a Maximum Likelihood algorithm was used for the supervised classification. Both were classified on a pixel basis using the digital numbers of each pixel of the 2D RGB orthomosaic imagery.

The two classification layers were converted from raster to vector, then edited manually with the aid of the 2D orthomosaic imagery through visual interpretation, to create the final 2D vector layers seen in Figure 15. Adjustments were made where necessary to produce vector layers for all features of the original 2D RGB orthomosaic layer. The adjustment included separating Bare ground into two classes (Bare soil and Footpath) to give a final classification of 8 classes.

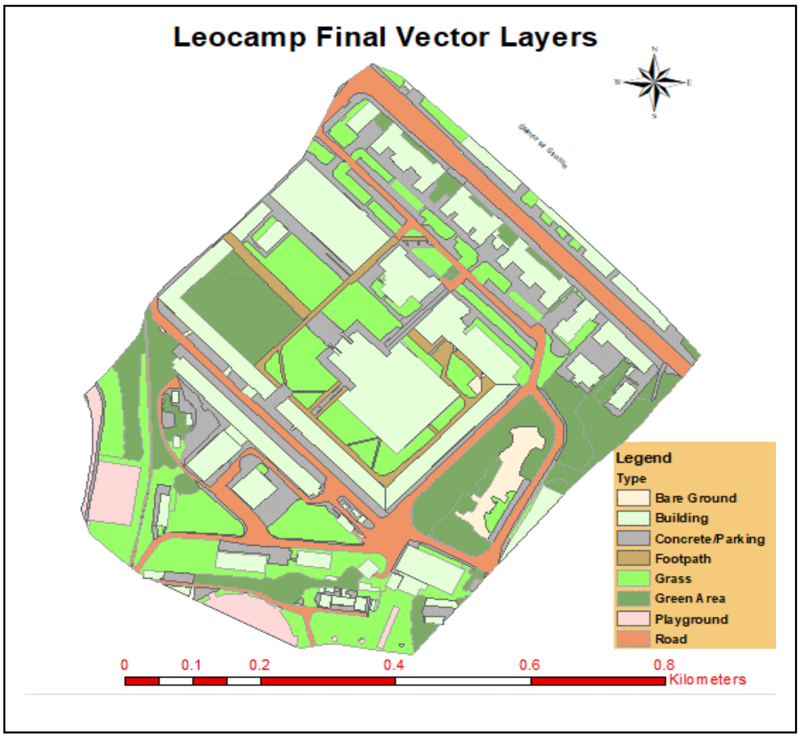


Figure 15: Final Vector layer created by refining the classification layers

The final vector layer was created with eight (8) classes. These were Bare Ground, Building, Concrete/Parking, Footpath, Grass, Green Area (Trees or Forest), Playground and Road. These features are very important for cadastral mapping and it was critical that they are distinguished and separated for the remainder of the analysis.

The vector layers created and illustrated in Figure 15 are the standard cadastral features that would normally be generated from the UAS imagery, apart from the 2D RGB orthomosaic itself which is also a critical resource for cadastral mapping. These 2D planar cadastral features are the traditional features derived from the photogrammetric process or satellite imagery for base mapping.

Other products would now be derived from these vector layers such as:

- Street centerlines
- Street Polygons
- Building footprints
- Vegetation
- Fences/Walls
- Parking areas and
- Recreational areas

These would be stored within a 2D cadastral database and would most likely be sold to clients especially in the case of NMAs.

As it concerns this thesis, these 2D vector layers are **2nd order Cadastral GI final output** generated from the UAS imagery.

3.3.4 Post Processing: 3D Data Analysis

The point cloud provided the most challenges within this project in terms of data processing. It was first processed by open source applications such as Cloud Compare, CloudCompare 2.9.1 (2017), Meshlab, Meshlab (2016) and Meshmixer, Meshmixer (2017). It was necessary to classify the point cloud to distinguish those points that represented buildings before we could generate building volumes.

3.3.4.1 CloudCompare

Analysis within CloudCompare included a few processes, namely:

- Point cloud segmentation;
- Calculation of normals;
- Classification; along with
- Shape detection and Mesh application.

These processes were of critical importance to determine where the faces of buildings and other features within the point cloud were, so that building walls could be determined.

The point cloud was segmented to obtain smaller subsets of the data to facilitate smooth data processing. Then the normals of the data was determined using the calculate normals tool. [select '*Leocampus*' file in DB Tree>*edit*>*normals*>*compute*]. The command line code below could also be used:

> Command line Code -> *CloudCompare COMPUTE_NORMALS -O Leocampus (where 'Leocampus' is name of point cloud)*

The classification was done using the 'qcanupo' Point Cloud Classification plugin, Brodu & Lague (2012). This plugin was a default plugin within CloudCompare, it enabled the user to create a training classifier by duplicating the point cloud. The plugin required that a point cloud be created per class. Regions of Interest (ROI) were drawn which were used to create a classifier. This classifier was then used to perform the classification. The result of the qcanupo classified point cloud segment with normals applied can be seen in Figure 16.

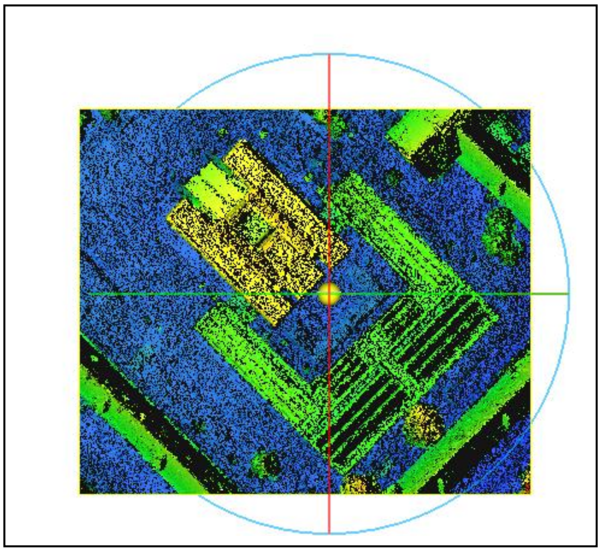


Figure 16: Result of qCanupo classification of a segment of the 3D point cloud with normals applied

This figure illustrates the resultant 3D point cloud created after classification using the qCanupo plugin. The original point cloud was segmented to allow for faster processing time. Then the Point cloud normals were calculated. This was done to determine how the faces of the surfaces within the point cloud were oriented. Finally, the scalar field was activated. This scalar field had information about the attributes of the classified features. It was used to differentiate the spectral signature of the features.

Automatic classification was also done using the Cloth Simulation Filter (CSF), Zhang et al., (2016). This plugin allowed for separating steep slopes, relief, flat areas, and other slopes within the point cloud dataset. The buildings were later extracted from the point cloud dataset by filtering the vegetation out of the classified layer according to the scalar field. Figure 17 shows the outputs of this process redisplayed using its RGB properties.

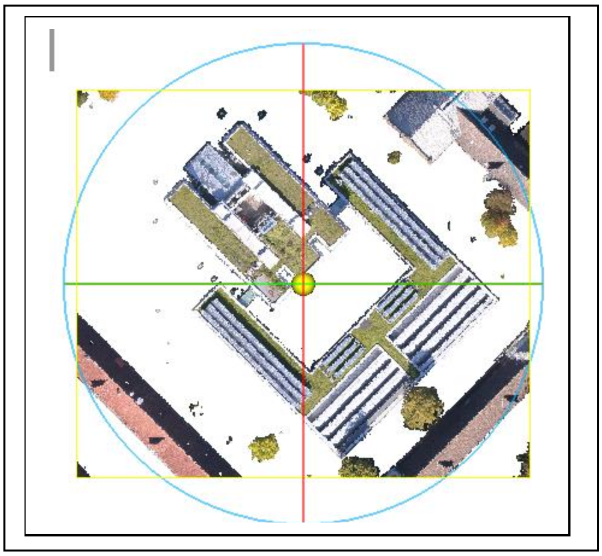


Figure 17: Automatic classification of 3D Point cloud using the Cloth Simulation Filter (CSF) plugin

The CSF plugin enabled the user to separate steep slopes, relief, flat areas, and other types of slopes when classifying the 3D Point cloud. This was important for cadastral mapping because it allowed for discriminating between features based on their relief properties. After the point cloud was classified, the ground features were removed leaving the buildings and tall trees.

There were numerous tools within CloudCompare to facilitate processing of the point cloud. Segmentation for example enabled cutting smaller portions of the point cloud since the data points were so dense. Figure 17 above shows a segmented point cloud which was then classified using the Cloth Simulation Filter plugin. After classification the ground features were removed by examining the histogram of the data and removing the areas with low-lying relief.

3.3.4.2 Meshing in CloudCompare, Meshlab and Meshmixer

The next step in the workflow process was to generate building volumes. To achieve this, the process of meshing was done to erect actual walls unto the buildings within the point clouds. Meshes were created inside CloudCompare, Meshlab and Meshmixer to ascertain which results were most suited for creating building volumes. Figure 18 illustrates the mesh applied to a building of the 3D point cloud using CloudCompare.

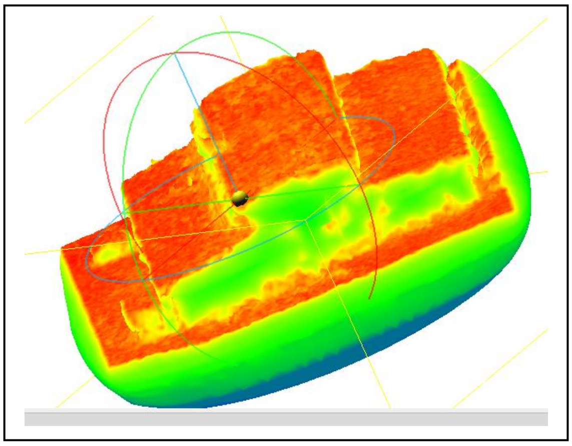


Figure 18: Meshing a building using CloudCompare

The points representing the building was segmented from the 3D point cloud (las format) to reduce processing time and to apply a mesh to the building. Normals were then calculated and a Poisson Reconstruction mesh applied. The result, seen in Figure 18 was a mesh that reconstructed the walls of the building saved as a stl file.

Upon importing the point cloud into CloudCompare, normals had to be calculated before the faces of the buildings could be determined.

[Filters > Normals, Curvatures and Orientation > Compute normals for Point sets]

Further processing was done in CloudCompare: to apply an appropriate mesh to the buildings within the classified point cloud, and to clean and sanitize the mesh to generate building volumes. The Poisson Reconstruction Mesh, Wiemann, Annuth, Lingemann & Hertzberg (2015), was applied, rendering the building volume seen in Figure 18.

A segment of the 3D point cloud was processed in Meshlab. This analysis was done using 2.5D buildings extruded from the 3D point cloud dataset. First normals were applied, then a Screened Poisson Surface Reconstruction algorithm afterwards, Kazhdan & Hoppe (2013).

[Filters > Remeshing, Simplification and Reconstruction > Screened Poisson Surface Reconstruction].

Figure 19 shows the results.

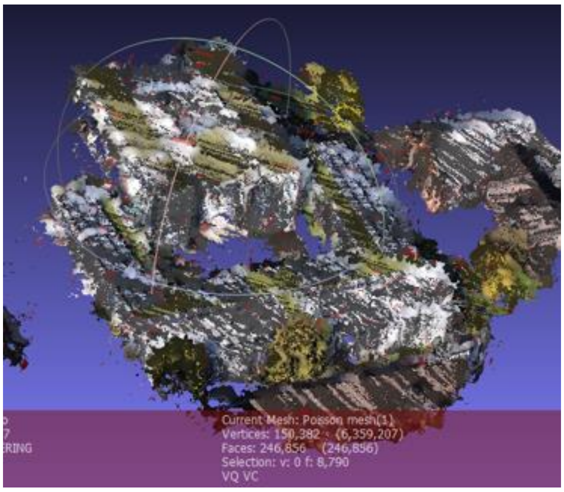


Figure 19: Screened Poisson mesh reconstructed over a 2.5D building in Meshlab

This building was extruded to a 2.5D (two-and-half dimension) surface, saved as a ply format and accessed within Meshlab. An iterative process of Poisson mesh application, mesh cleaning, removal of manifold edges and vertices, along with the closure of holes was carried out. Results are seen in Figure 19 saved as an stl file.

As Figure 19 shows, the meshing process did not generate a desirable result, so an iterative process of cleaning the mesh, removing manifold edges and vertices along with the closing of holes was carried out. The 2.5D building was quite challenging to mesh. Another analysis was done within Meshmixer to obtain better results.

The 3D buildings were imported as a ply file into Meshmixer to create the final building volumes. The resultant volume of this extracted building within Meshmixer can be seen in Figure 20. The volume was outputted in a stl format. An analysis of this result is outlined in the discussion section.

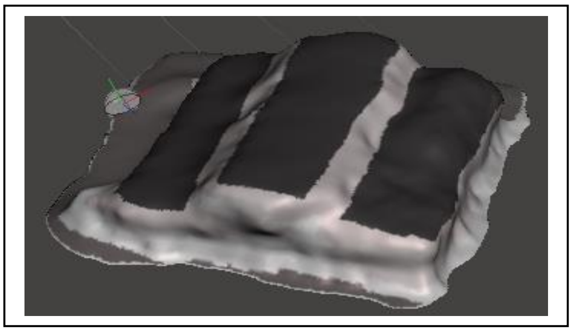


Figure 20: Building in Meshmixer with Poisson mesh applied.

The building object with mesh applied was imported into Meshmixer in ply format. Meshmixer had very good tools that were used to conduct further processing unto the building. Output file was stl. The stl format is good for 3D printing but was not a desirable format for the remaining processes of the thesis.

The results obtained from CloudCompare, Meshlab and Meshmixer, were good, however the resultant file formats were not desirable for the continuation of the workflow proposed by this thesis. The ply and stl file formats are widely used, and are ideal for 3D printing of models, but the required data format for the buildings moving forward was a vector data format that would allow users to select individual buildings and edit their attributes. The 3D building volumes in vector format is ideal for Cadastral Mapping as data is constantly edited and attributes constantly changed. The search continued therefore for a set of opensource tools that could render vector data format for the 3D building volumes.

3.4 3dfier Tool and the CityGML Standard

The search for an appropriate method of extracting the buildings as 3D volumes led to the use of the 3dfier tool, Biljecki & Sindram (2017), which yielded the resultant data format called gml via the CityGML standard, Kolbe, Gröger and Plümer, (2005).

The CityGML OGC standard for representing 3D data was used to create a tool called 3dfier, an opensource tool that was most suited to solving the challenge at hand. 3dfier allowed for the combination of the 2D vector layers that were created within QGIS to be combined with the 3D point clouds to create volumes of the buildings within the study area. The vector layers were prepared in a format necessary as input to the 3dfier executable, with a null height field in each 2D layer. These vector layers were used to generate the planar features (horizontal surface features) of the study area. The heights for extruding the buildings within the landscape were then taken from the 3D point cloud layer. An executable (3dfier) was run with the prepared 2D vector and 3D point cloud files along with a special yaml file (seen in appendix C) that was configured and programmed to give the 3dfier executable the instructions on how to treat each layer in the result.

The 3dfier tool, the yaml file, the input 2D vector and 3D point cloud files were all placed within the same folder. The 2D vector layers had to be edited so that each feature was a separate shapefile and that the attribute tables had unique identification fields such as gml_id and also a 'height' field.

The yaml file was then prepared within a text editor. The first parameter of the yaml file had the configuration of the ***Input polygons***. Each input 2D vector polygon (in shapefile format) had to be declared here, including the path to its location. The unique id number of the input layer had to be stated. Then, the CityGML feature to be lifted from this layer within the resultant 3D city model had to be declared, for example 'Terrain' or 'Road' or 'Building'. The 'Lifting' parameter gives the instruction to the 3dfier tool on how to treat the input layer within the City model. Another parameter was '***Height_field'***. This parameter was a mandatory attribute within the input 2D vector layer, even if the height field had null values. If more than one input vector layers were to be used to lift one particular feature type within the output City Model, an additional field had to be specified; namely 'handle_multiple_heights' and this had to be set to 'True'. An example of this can be seen in the yaml file in Appendix C.

The next parameter was '***Lifting options'***. These options allowed the user to specify how they desired for the City model to treat each City feature (Buildings, Roads, Terrain, Forest, Water and Separation features). For the building, the lifting options were 'roof height percentile' and 'floor height percentile'. The value given here should be between 1 and 100 (collectively). What this meant was that the 3dfier algorithm determined the heights of building roofs based on an average of the heights of the points from the 3D point cloud at the desired percentile. For this thesis, the building height percentile was kept as 90, so 90% of the 3D points representing the heights of building roofs were used to determine the actual height of the buildings within the output City model. This parameter was important as it allowed for the removal of outliers from the dataset or reduced the effect that features such as chimneys, had on the resultant height of each building.

Another lifting option was the 'Lod' or level of detail at which the output City Model was rendered. The default was Lod1. This rendered the buildings as simple block structures without details of roof structure, overhang, or wall details. This level of detail was quite acceptable for the mapping of buildings for cadastral purposes, however for other purposes such as building information modelling, a higher level of detail would be required.

The next important parameter for the 3dfier tool was the '***Input elevation'*** layer, and this also had to be specified within the yaml file. For this thesis, the input elevation layer was the dense 3D point cloud and was called "***Leocamp***". Its name and location had to be clearly specified, and it had to be a classified 3D point cloud layer according to the standard point cloud classification principles, LAS Specification (2011). The 'input elevation' parameter also allowed the user to omit LAS classes from the output City Model. This parameter was used to remove unclassified points from the output City model.

The final parameter was the '***Output***' parameter which allowed the user to specify the file format of the resultant City model. The options were 'Obj' and 'CityGML'. The obj file format created an object with the buildings as 3D volumes, however it does not allow for selecting individual buildings nor for editing the attributes of those buildings. The alternative was the CityGML file format which allowed for selecting individual buildings from the output 3D building volume along with the ability to alter its attributes. This was the preferred output format for this thesis as it allowed for the cadastral features to be managed in a dynamic manner. This spoke to the efficacy of the CityGML standard and the gml file format and the possibilities it opens for managing the Cadastral GI in 3D.

After the yaml file was configured, the 3dfier executable was initialized from the command line (Visual Studio command line was the preferred command line tool). To run the 3dfier executable, the folder housing the 2D vector layers, 3D point cloud and yaml files was accessed, then the command given below typed in the command line:

> *3dfier myconfig.yml -o output.ext* (On Windows)

> *$ ./3dfier myconfig.yml -o output.ext* (On OS x and Linux)

The parameter 'myconfig' was replaced with the file name of the output.ext, the output data format was specified as seen in the examples below.

> *3dfier leocampus.yml -o leooutput.obj* (Windows) or

> *3dfier leocampus.yml -o leooutput.gml* (Windows) when output folder is current location;

> *3dfier leocampus.yml -o C:\development\output.obj* (Windows) or

> *3dfier leocampus.yml -o C:\development\output.gml* (Windows) when output folder is another location.

The resultant gml file was viewed and manipulated within the opensource application FZK Viewer as seen in Figure 21.

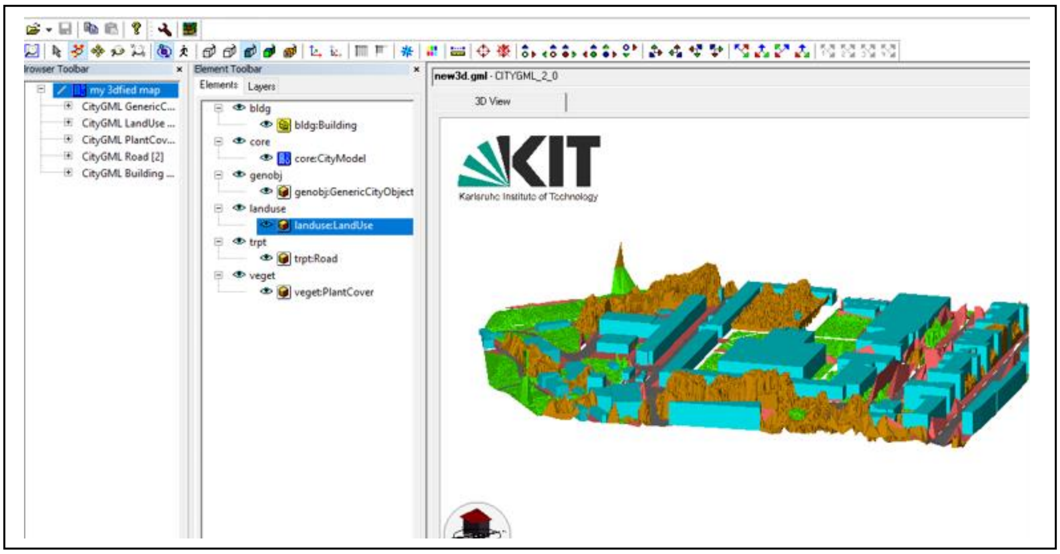


Figure 21: LoD1 City model generated by 3dfier with the CityGML format, viewed in FZK Viewer

The City model generated by the 3dfier tool captured the planar features of the 2D vector layers in shapefile format such as buildings, roads, forest, and terrain; and extruded the heights of those features using the heights of the corresponding points from the dense 3D point cloud. The final output was the gml format. This City model was viewed in the FZK viewer, an opensource application created by the Karlsruher Institute for Technology. Importantly, each element of the City model could then be individually selected and manipulated.

The 3dfier tool combined the planar 2D vector layers in shapefile format and the 3D point cloud in las format. The parameters specified within the yaml file allowed for the extrusion of city elements such as buildings, landuse, roads and vegetation as 3D features. The output file format was gml (CityGML). These City elements were all selectable and their attribute tables were editable which was necessary for the management of Cadastral GI in a 3D format. This was important because it allowed the Cadastral Experts to make changes to the attribute information stored within the database. It also provided an opportunity for the clients of the Cadastral Experts to make changes based on the actual setup of the final Web map on which the data was shared with the public. Further discussions on this can be seen in chapter 4. Section 3.4.1 explains the CityGML standard and how it handles 3D data.

3.4.1 CityGML and 3D volumes

The 3D data was stored as CityObjects; these were the CityGML root class based on the encoding standard of the OpenGIS City Geography Markup Language (CityGML) version 2.0. (Gröger, Kolbe, Nagel, & Häfele, 2012). A bounding box or envelope was drawn around the 3D volume that represented the building CityObject. The data within the landscape was represented in differing levels of detail (LoD), these were LoD0 to LoD4. The 3D buildings in this thesis were treated as LoD1 only, which represented the buildings as plain blocks or volumes without detailed surface or roof structure. The reason for this was that the 3D modelling for this thesis was intended for cadastral purposes, therefore higher levels of detail lay outside the scope of this research. Also, the 3DCityDB encoding offered support for LoD1 only. The ‘Future Work’ section of this thesis document speaks more about this. The resultant 3D model can be seen in Figure 22 with only the 3D building volumes being displayed, and a building selected with some of its attributes shown.

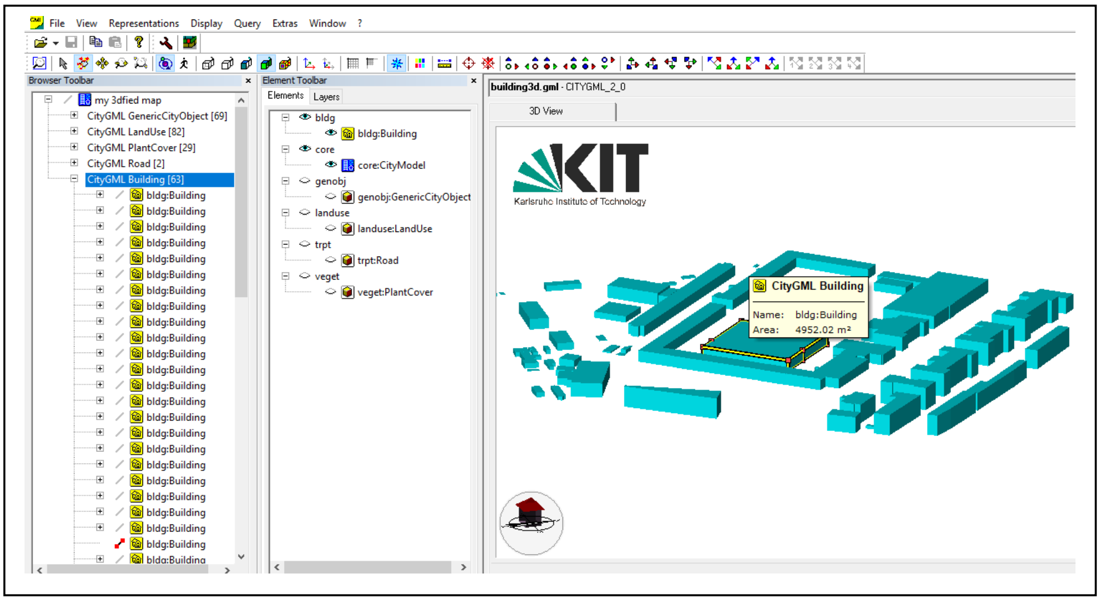


Figure 22: CityGML 3D building volumes in LoD1

The Leocamp buildings were displayed in an editable state. When the buildings were selected, their inherent polygonal topological structure was revealed. Each building could be individually edited, and attributes changed as required for the management of Cadastral GI.

The CityGML standard enabled increased management capabilities regarding Cadastral GI as the 3D building volumes in gml format could be managed in an editable format. In the case of City managers and NMAs, the cadastral data they maintain can be enriched with attributes regarding number of stories, building classification and ownership information, etc. The CityGML standard was a very good first step towards achieving a vast set of capabilities when managing the 3D building volumes as Cadastral GI. The 3D building volumes represented the **3rd order Cadastral GI and main final product** created by the Cadastral Expert from the input UAS dataset collected by the crowd.

3.4.2 Storage and Manipulation of 3D building volumes using the 3DCityDB suite of opensource tools

The proposed workflow of this thesis required that the building data be realised in a 3D volumetric format, and that the format be editable and interoperable so that the data can be easily managed and exchanged if necessary. The CityGML standard provided the ideal file format for these 3D building volumes. It was necessary therefore as the next step in the workflow, to manage this data as a City Manager or NMA would (includes making edits as the need arose), and to allow the data to be shared with the public. A set of tools was sought to manage the 3D building volume data, and the 3DCityDB suite of tools, 3DCityDB (2016), were identified. These tools were created specifically to manage data in the gml format, and comprised:

- 3DCityDB (the database itself);
- 3DCityDB Web Feature Service (WFS);
- 3DCityDB Web Map Client; and
- 3DCityDB Importer/Exporter tool.

Firstly, the 3DCityDB was installed on a Linux Virtual Server, Linux Virtual Server (1998). Configuration of the 3DCityDB itself required the establishment of the Coordinate Reference System (CRS) to be set using both European Petroleum Survey Group (EPSG) and another CRS identifier defined by the OGC GML standard. These were responsible for ensuring that the imported 3D model had the correct CRS assigned and read by the database. The coordinate system of the study area was EPSG code 32632 which corresponded to the WGS84 UTM Zone 32N CRS covering Muenster.

3D building volumes within 3DCityDB were held to be an aggregation of polyhedral surfaces. The buildings were stored both as a single solid (encapsulates the entire building) and as individual surfaces, (each face of a building represented a surface), which together constituted a building, 3DCityDB Documentation (2016). These building volumes (generated by the 3dfier tool) were imported into 3DCityDB using the Importer/Exporter tool and stored within the 3DCityDB as or gml files. They were later exported as collada files (see Figure 23), for upload to Google Earth Pro as seen in Figure 24 and gltf files (master JSON files) for upload to the 3DCityDB Web Map Client.

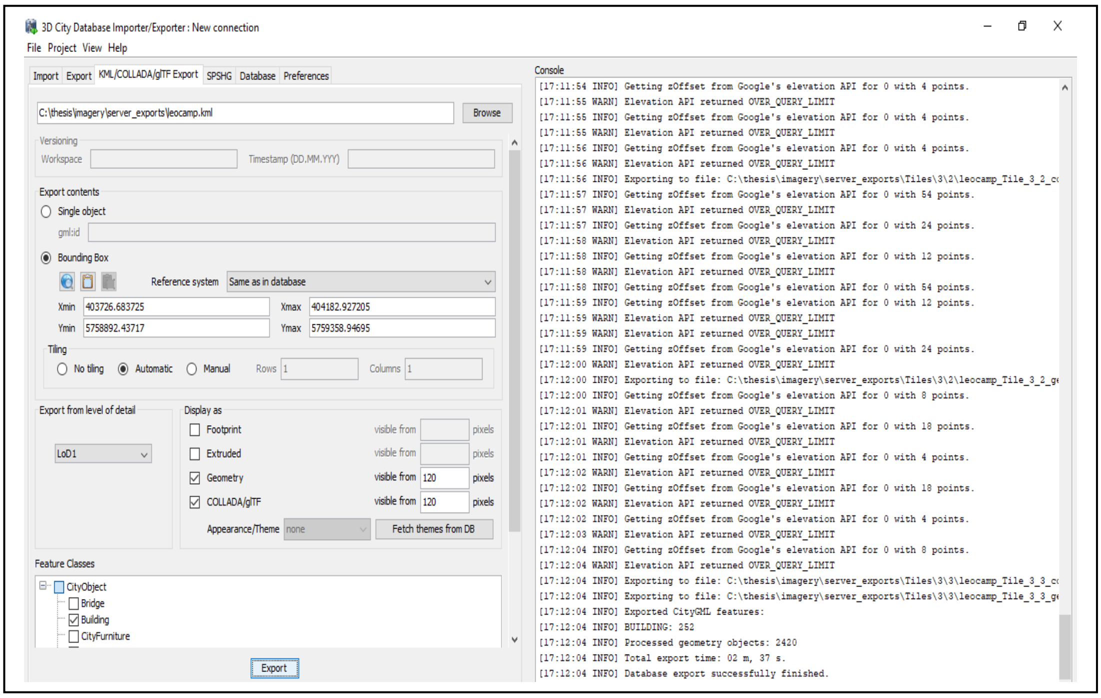


Figure 23: Importer/Exporter Tool with 3D CityGML building volumes being exported to Collada/glTF

The 3DCityDB Importer/Exporter Tool had multiple capabilities, from setting up of database, connecting and disconnecting to database, importing, and exporting of CityGML files, setting of Bounding Box for project and exporting of attribute layers as csv or excel files.

The first point of interacting with the 3DCityDB database is via the Importer/Exporter Tool. This tool is a graphical user interface designed to allow for multiple capabilities such as setting the database parameters (username, password, URL etc.), connecting and disconnecting to/from the database, importing, and exporting CityGML files, setting of Bounding Box for the project and a special plugin for exporting of attribute values as csv files or Google fusion tables. The plugin was very critical to the process of managing the data within the database as it allowed the Cadastral Expert to export the attribute tables of the 3D building volumes from the database. These tables were saved as Google Fusion Tables to be imported into the 3DCityDB Web Map Client, which enables editing of the 3D building attributes. When the crowd edits the attributes of the 3D buildings, their edits are not written directly back to the database but to the Google fusion tables instead, which makes managing the quality of the attributes submitted by the crowd possible.

Figure 24 illustrates the kml file of the study area exported using the Importer/Exporter Tool uploaded unto Google Earth Pro.

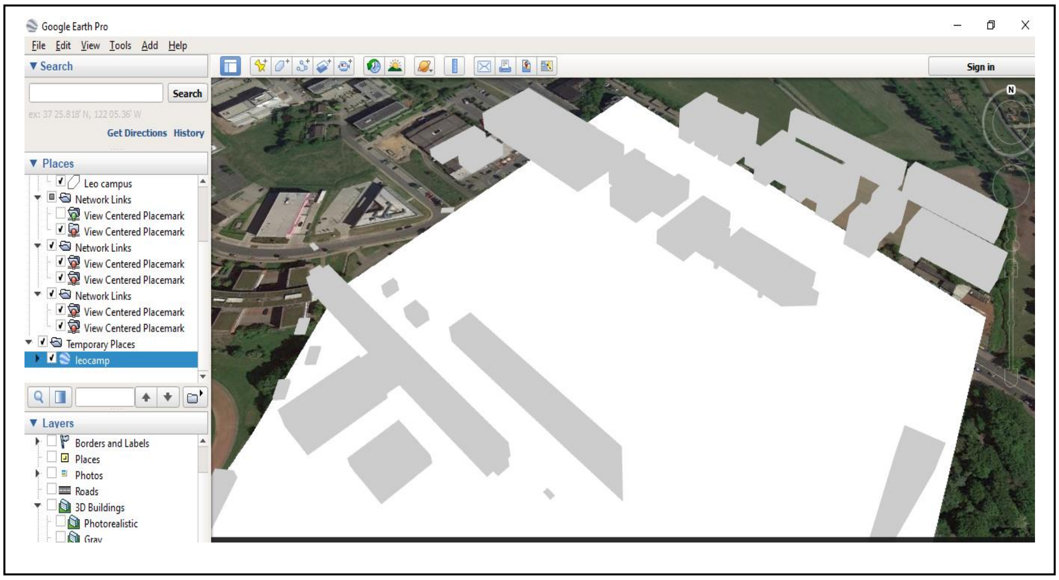


Figure 24: Leocamp 3D building volumes exported from the 3DCityDB (from gml to kml format) and uploaded to Google Earth Pro

The Importer/Exporter Tool allowed for data format conversion. The Leocamp data was converted from gml format to kml and was uploaded to Google Earth Pro. This opened additional possibilities for Cadastral Experts to host the data or offer services on Google Earth Pro according to their needs and business models.

Figure 24 illustrated the 3D building volume data imported into Google Earth Pro as a kml file. This is a **4th order Cadastral GI final output** as the layer could be offered as a service on Google Earth Pro by the Cadastral Experts, where clients can interact with the data freely and make changes to the attributes or just to see what 3D building volume data exists for their local area.

3.5 Web Feature Service (WFS) and Apache Tomcat Servlet

The WFS of the 3DCityDB was the conduit through which the 3D building volume data stored on the database was accessed as an xml feature service. Configuration of the WFS required an Apache Tomcat Server 8.5, Apache Tomcat v8.5 (2018), as the HTTP host server. This Apache Tomcat Server allowed for transferring of information to the Web Client as xml files. The WFS xml configuration file can be seen in Appendix D. This server also required the Java Runtime Environment and Java Development Kit, Java 8

(2018). The Apache Tomcat server manager can be seen in Figure 25 with the 3D citydb WFS and the 3D Web Map Client deployed.

Configuration of the Apache Tomcat Servlet necessitated editing four xml files within a development editor. In this case, the opensource text editor called Atom, Atom (2018), was used. The xml configuration files ‘context.xml’, ‘server.xml’, ‘tomcat-users.xml’ and ‘web.xml’ were edited to configure the capabilities of the server. The fully configured Apache Tomcat servlet was then managed from the command line. The URL used to host the Tomcat Apache servlet was **http://localhost:6001/.** (This version of Apache Tomcat servlet was hosted locally; however, it also could be hosted on the Linux Virtual Server). The 6001 in the URL above was an arbitrary number assigned to the port that was used.

After the CityDB-WFS was successfully deployed by the Apache Tomcat servlet, the context path was typed in the address bar of a new Google Chrome webpage. **http://localhost:6001/citydb-wfs/wfsclient**. Figure 25 illustrates the WFS client deployed by the Apache Tomcat servlet.

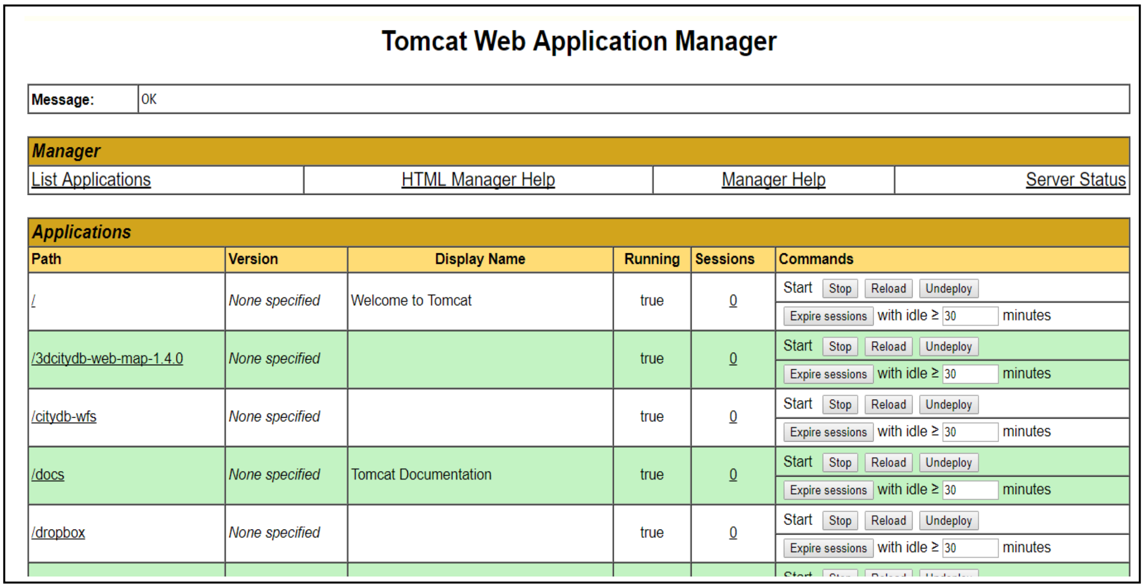


Figure 25: Apache Tomcat Servlet with the 'Citydb-wfs' successfully deployed

The Apache Tomcat Servlet was installed and configured locally for this thesis work, however for a production environment such as that hosted by a City Manager or NMA, it can be hosted on the Linux Virtual Server that also hosts the 3DCityDB database itself. After configuration of both the Apache Tomcat Servlet and the 3DCityDB WFS (‘citydb-wfs’), both were successfully installed. The Apache Tomcat Servlet was then used to deploy the WFS to connect to the database (3DCityDB) and the Web Map Client.

The WFS had a graphical user interface called the WFS client which allows users to input xml-based instructions when interacting with the 3DCityDB. The WFS Client is seen in Figure 26 below. The user will type a valid xml request within the ‘WFS Request box’ of the WFS Client. After the request is executed, a response is given in the ‘WFS Result box’ of the WFS Client.

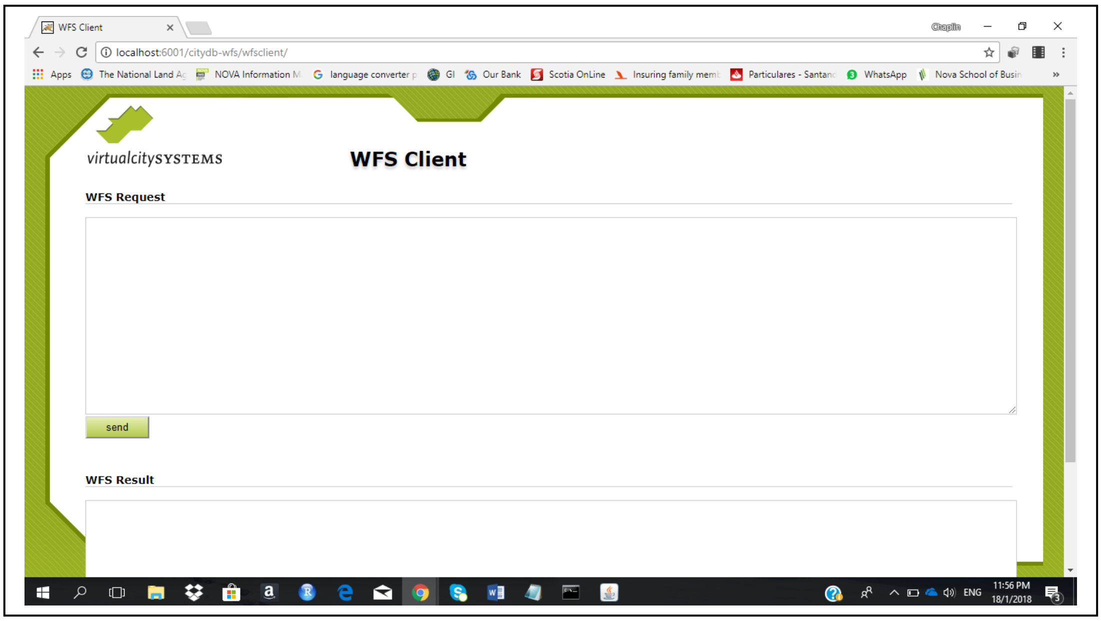


Figure 26: Graphical User Interface of the 3DCityDB WFS which allowed for sending and receiving data and metadata to/from the 3DCityDB

User can send requests to the 3DCityDB such as ‘GetCapabilities’, ‘DescribeFeatureType’, ListStoredQueries’, ‘DescribeStoredQuery’, ‘GetFeature’, ‘GetPropertyValue’, ‘LockFeature’, ‘GetFeatureWithLock’, ‘CreateStoredQuery’, ‘DropStoredQuery’ and ‘Transaction’, 3DcityDB Documentation (2016).

3.6 3DCityDB Web Map Client

The 3DCityDB suite of products included a Web Map Client comprising WebGL, WebGL 2.0 (2018), HTML5, HTML5 (2018) and an adapted Cesium Virtual Globe, Cesium (2018). WebGL is an open standard available via the web that allows users to offer 3D graphics to their consumers. HTML5 is the latest version of the HTML markup language and this version allows much flexibility when interacting with data on the web. Cesium Virtual Globe is an openly accessible web browser that is designed to represent 3D data in a proficient manner. These three implementations were adapted and extended by the 3DCityDB creators to host and manipulate 3D volumetric data derived from the CityGML standard, which in this case, was a very good solution for visualizing and manipulating the data created during this thesis. Figure 27 below illustrates the Web Map Client hosting the final product of this thesis (Leocamp 3D building volumes).

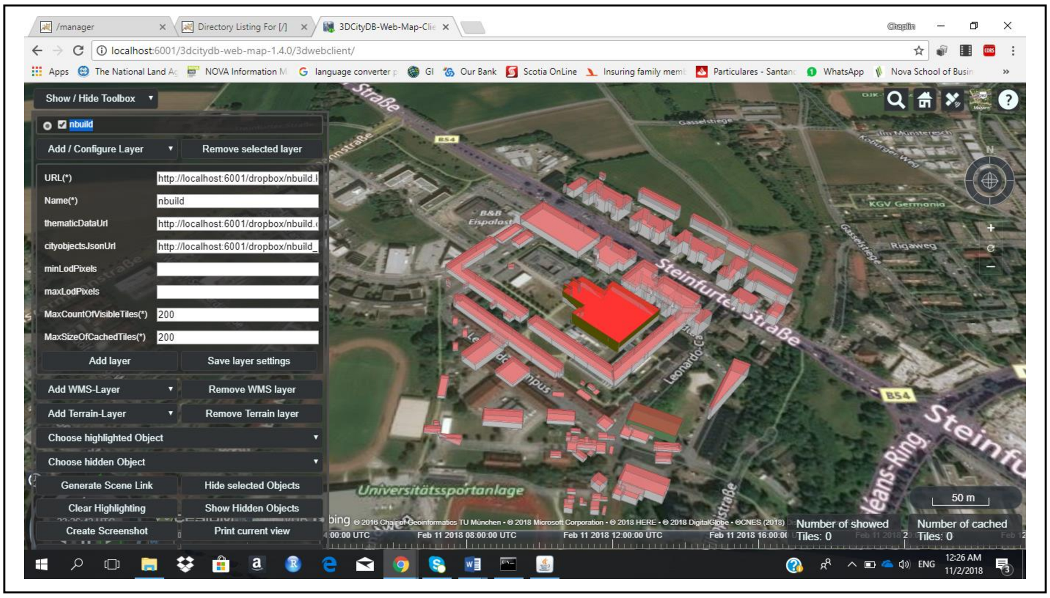


Figure 27: 3DCity Web Map Client with Leocamp data as WMS

The 3D building volume data hosted by the City Manager or NMA can be visualized and edited on the 3DCityDB Web Map Client. The data must first be exported from the 3DCityDB using the Importer/Exporter Tool as glTF/Collada. The data can then be sourced directly through the Apache Tomcat Servlet (webapps folder) or indirectly from a cloud server such as Google Drive with the Cross-Origin-Resource-Sharing (CORS) enabled and the data publicly shared. The City Manager or NMA can decide to allow external clients to edit the attributes of the 3D building volume dataset by uploading the csv or excel tables exported from the 3DCityDB as a Google Fusion Table. If this is done, the attribute data will not be written directly to the database but to the Google Fusion Table instead. This will allow for checks and balances to be implemented to monitor the changes made to the 3D building volume attributes.

The Web Map Client used a tiling system to view large 3D datasets such as the 'Leocamp' 3D building volumes generated by the CityGML 3dfier tool mentioned in 3.4. The tiling system allowed for data, which is closer to the user's viewpoint, to be seen based on a distance threshold pre-configured within the system. Data further away will disappear until the user pans or scrolls towards those areas. This system stores the data using a caching technique which allows for fast retrieval of the data and prevents having to constantly read the data from the database. This solution represents the **5th order Cadastral GI final output** achieved from this workflow.

4 Chapter 4 – Evaluation and Discussion

4.1 Data Formats, Standards & cadastral meaning

STANDARDS AND CAPABILITIES	
Standard	**Capabilities**
ISO TC211	GI standardization – managing GI Ontology, maintaining XML
OpenGIS City Geography Markup Language (CityGML)	XML-based and extendible. Allows virtual 3D city model data to be interoperable with various applications.

Table 3: Standards responsible for the development of the data formats and tools used in this thesis

The ISO TC211 and OpenGIS CityGML standards were the two main standards responsible for the data formats that were critical to the success of the workflow proposed by this thesis. The Extendible Markup Language (xml) format and the CityGML (gml) formats were both critical to the creation of 3D building volumes while preserving the geometric characteristics of the data and preserving the attribute data. The xml format was important for cadastral base map products because they allowed for the effective processing of the UAS data from one format to another until the final resultant 3D buildings were created. The CityGML standard was important for cadastral base maps be it allowed for handling the cadastral features as 3D which fits the reality of the built environment better than the 2D alternative.

Table 3 illustrates two of the standards that were responsible for the development of some of the data formats that were applied within this thesis. The collaborative efforts of the organisations involved (ISO, FIG and OpenGIS) has created data formats and standards that were critical to the creation and maintenance of the 3dfier tool, the CityGML (gml) data format, the yaml and xml configuration files used to derive the 3D building volumes. These standards were also the premise upon which the 3DCityDB suite of tools were created. Table 4 illustrates the tools used, licences and their associated privileges.

LICENCES, TOOLS AND CAPABILITIES	
License	**Tool and Capabilities**
Creative Commons Attribution-Sharealike Attribution 3.0	**QGIS** – Allows for sharing and adapting of material for any purpose including commercial.
General Public License version 3 (GPLv3)	**Mission Planner** – Allows freedom of use, adapting of material, sharing of code.
Restricted license of software use	**Precision Mapper** – limited free access to use application
Lesser General Public License version 2 (LGPLv2) and General Public License version 2 (GPLv2)	**CloudCompare** – Some aspects can be used in commercial or non-commercial products. Other aspects must be used in open-source projects.

General Public License version 3 (GPLv3)	**Meshlab** - Allows freedom of use, adapting of material, sharing of code.
Creative Commons License	**OAM** – Allows for copying, sharing and building upon tools.
MIT	**Meshmixer** – Ability to use, adapt, publish and redistribute code
GNU Affero General Public License	**CityGML** - Allows freedom of use, adapting of material, sharing of code.
Apache License version 2	**3DCityDB** – Access to copyright, patent, ability to redistribute and contribute to application.
GNU General Public License (GPL) version 2	**Linux Virtual Server** – Open source high performance servers
Apache License version 2	**Apache Tomcat server –** Opensource http server container
Oracle's Java license	**Java** – Build and configure 3DCityDB WFS
MIT license	**Atom –** Edit and debug configuration files for 3DCityDB WFS

Table 4: Licenses for the applications used in thesis

Table 4 highlights twelve (12) opensource licences and one (1) limited use licence that were used during this workflow. Of critical importance were the tools enabled by these licences, a majority of which were hackable and extendible as their source codes were openly shared. This was important for Cadastral GI because these opensource tools enabled the creation of the otherwise expensive 3D building volumes, yet with very limited costs involved.

If City Managers and NMAs are to overcome the high costs of creating and maintaining Cadastral GI as 3D building volumes, they must be able to identify inexpensive input data and tools. The tools listed in Table 4 are free and opensource (except for Precision Mapper which offered limited free use) and therefore provided an opportunity for Cadastral Experts to maximise their resources by reusing, hacking, deploying and otherwise engaging the use of these tools. This allowed for an impactful reduction in operating costs, since the most expensive input tool within this workflow was the DJI Mavic Pro UAS. Since the acquisition of such a UAS is a one-time cost, the benefits quickly accrue as the tool is increasingly used to capture cadastral data.

The Linux Virtual Server used in this thesis to house the 3DCityDB was free and opensource, however it must be housed on a PostgreSQL or Oracle database. This represents a cost that must be borne by the Cadastral Expert, however if that infrastructure already exists, the cost will not be a new expenditure but a recurrent one. This should be a consideration of the Cadastral Expert whom intends to implement the 3DCityDB suite of tools to manage their 3D building volume data.

PROCESS/TOOLS AND DATA FORMATS TABLE		
Process	**Input Data Format**	**Output Data Format**
Raw UAS Imagery	-	.jpg /.jpeg
Flight Survey field notes	-	text file
Pre-Processing in Precision Mapper	.jpeg	.tif, .las, .ply, .obj
QGIS	.tif / geotif	.tif, .shp
OAM	Jpeg2000 & geoTIFF	geoTIFF
CloudCompare	.las, .ply	.las, .ply
Meshlab	.las, .ply	.las, .ply, .stl
Meshmixer	.stl	.stl
CityGML	.shp, .las /. laz	.obj, .gml
3D CityDB & 3DCity DB WFS	.gml	.kml, collada (.gltf), MASTER JSON

Table 5: Process or tools used along with data formats

Table 5 illustrates the processes and tools applied to the data within this workflow. It also identifies the various file formats that were used as inputs and outputs from each process. The data formats inputted and outputted from these opensource applications reflected the stability that the standards mentioned in table 3 produced. This was very important for cadastral mapping as it allowed for many processes to be done to transform this data from one state to another, to obtain final file formats that were themselves widely used, interoperable, and allowed flexibility to share with others.

Tables 3-5 highlights the contribution of opensource standards to the successful achievement of this workflow. These standards gave provisions for numerous licences which allowed users to copy, hack, extend and redistribute the applications used within this project except for Precision Mapper. The applications used within this thesis utilised standard geospatial data formats such as TIFF, shapefile, and las files among others. Numerous processes were employed to process these datasets into new products, yielding multiple final datasets along the way that are beneficial to cadastral base mapping.

It was proven to be advantageous to collect UAS imagery for this small-scale project as the cost of acquiring the imagery was minimal (see UAS specification including cost in appendix A). The imagery was collected in under 20 minutes rendering 507 images with ground resolution of 3.2cm. The resolution of the imagery matches the very best that one can desire when compared to very high-resolution satellite imagery. A study conducted by (Harwin & Lucieer, 2012) proved that UAS imagery taken from 50 meters altitude produced imagery with an accuracy of 2.5-4cm. This is in-keeping with the results obtained in this thesis, as GCPs applied to the raw images allowed the improvement of the accuracy to sub meter levels.

Additional advantages of the UAS imagery included the lack of cloud cover when compared to satellite imagery, along with the ability of applying photogrammetric processes to produce the 3D dense point cloud. The photogrammetric process called multi-view stereopsis, Furukawa & Ponce (2009), when applied to 2D imagery that was taken with the requisite amount of overlap (usually 60-80% forward overlap and 60-70% lateral overlap), produces dense point clouds. The dense point cloud still retains the RGB digital numbers of the features they represented from the 2D imagery and can be visualised using a scalar field. Scalar field allows the user to view the points using different parameters other than the RGB registration such as the classified values of the point cloud. These photogrammetric methods were applied to the UAS 2D RGB imagery and produced this 3D Dense Point Cloud. This cloud free imagery and dense point cloud were both of great benefit for deriving cadastral features as they allowed for the features of the project area to be clearly seen and digitized using automatic or semi-automatic methods.

The analysis in CloudCompare, Meshlab and Meshmixer produced good results regarding point cloud segmentation, calculation of normals and classification. The file format of the 3D building volumes was good for 3D printing, but not ideal for managing the 3D volumes interactively in a vector format as required. Further research unveiled the CityGML file format and the 3dfier tool used earlier in section 3.4.

The 3dfier tool was a very effective tool that allowed for the programming of the yaml file seen in Appendix C. The parameters configured within this file helped to extrude the buildings (and other features within the study area landscape) as 3D volumes. The resultant volumes seen in Figures 21 and 22 were a much more desirable output than the output obtained from the analysis within CloudCompare, Meshlab and Meshmixer. The resultant 3D volumes in gml format (CityGML), allowed for the individual buildings to be selectable and editable which was necessary to manage them as Cadastral GI.

Overall, the CityGML tool and the gml file format provided an appropriate resultant 3D volumetric building layer which speaks well to the extendible nature of the OGC and ISO standards mentioned in Table 3. Additionally, these two standards seemed largely responsible for many of the tools, licenses and resultant capabilities listed in Table 4. These numerous open source tools made it possible to analyse the data used in this thesis and to successfully derive final products. Additionally, the licenses listed in Table 4 allowed for the public to use those tools, and to build on the capabilities of those tools by adapting their source code in whatever way they desired. The newly adapted code could then be republished, used to create new tools and products created either for other open source projects or even for commercial purposes. This level of freedom to use the listed software (Table 4) opens many doors for Cadastral Experts, City managers and National Mapping Agencies (NMA's) to adapt the applications to suit their purposes and reduce their underlying costs of project implementation.

Table 5 illustrated the various input and output data formats necessary for processing the data used in this project. The input data obtained from the UAS imagery was obtained in jpeg format. This data format underwent constant change throughout the processing steps until the final 3D volumes were obtained as CityGML files. This again reflected the numerous open source standards and file formats implemented by OGC and ISO to handle geographic data of all kinds. The CityGML files were later converted to kml and glTF/Collada (Master JSON + Tiles) for the final visualization and manipulation on the Web Map.

The final solution to hosting the 3D data on a web-based platform was realized via the 3DCityDB suite of tools, which included the 3DCity database, Web Feature Service, and the Web Map Client. The Web Map Client allowed the Cadastral Experts and their clients, (users from the crowd) to manipulate the attribute layers of the 3D buildings, albeit in different ways. The setup of the Web Map Client allowed the attribute data from the 3DCity Database to be appended to the 3D building volumes via csv files or as Google Fusion Tables. This meant that the Cadastral Experts and their users can make changes to the attribute data of the 3D building volumes without writing their edits directly to the database. The crowd can therefore participate in the process of maintaining the attributes of the 3D buildings by volunteering information such as building use, roof material, number of storeys, etc. This suggests that the solution implemented can be an effective tool to allow City managers and NMAs to host the 3D buildings within their jurisdiction and would facilitate the development of that dataset as a rich resource, hence providing an additional Cadastral GI.

4.2 Research questions revisited

A direct approach was employed in this thesis to answer the research questions and sub questions posed at the beginning. As a reminder, the questions are repeated here with the answers established throughout the research.

1. **How can crowd-sourced UAS imagery be used to improve the cadastral data available for base mapping?**
    a. ***In what ways can the crowd participate in this process****?*

It was ascertained that crowd-sourced UAS imagery can be used to improve the cadastral data available for base mapping by a partnership between the crowd and the Cadastral Experts. The crowd will share their UAS data on the OAM repository (2D data) and on the expert hosted 3D web map (3D Data). The expert will in turn conduct data verification techniques and if satisfied with the data quality, follow through with the workflow outlined in this thesis. At the end, the crowd will again participate by volunteering attribute data to the resultant 3D building volumes on the expert hosted Web Map.

    b. ***What processes are necessary to facilitate this participation by the crowd?***

It is necessary that the crowd uploads their data to the open online repositories. It is also necessary for the experts to establish the clear process chain to download, test and adjust the data, then follow the processing steps to achieve not only the traditional 2D vector cadastral data but also 3D building volumes.

c. What data formats will the crowd be required to submit?

The crowd will be required to submit their data in Jpeg2000 or geoTIFF format for the 2D RGB orthomosaic (data to be uploaded to OAM), and las or laz file format for the 3D point cloud files (data to be uploaded to the expert hosted Web Map).

d. Where does the contribution of the crowd end and where does that of the Cadastral Expert begin?

The contribution of the crowd towards this workflow initially ends at the time they upload their imagery or point cloud data to the open repositories. The crowd contribution resumes at the end when the final 3D building volumes are available on the 3D Web Map Client. The work of the Cadastral Expert strictly begins at the point they download that data from the open repositories, except when the Cadastral Experts themselves are contributors of the UAS data in the first place. The work of the Cadastral Expert continues through the remainder of the workflow.

e. What costs will be incurred by the crowd and the expert throughout this workflow?

The crowd should have minimal or no direct costs to bear with regards to this workflow. Direct cost to the crowd will be the cost of UAS ownership and the cost accrued due to conducting the survey. The cost to the Cadastral Expert would be the cost of quality checks and quality assurance regarding the input data. This may include the acquisition of GCPs for the area covered by the imagery. Other costs to the expert would be that of hosting the Linux Virtual Server which must be housed either on a PostgreSQL Database or an Oracle Database. If these Databases were already a part of the existing infrastructure of the Cadastral Expert, this cost would be absorbed as a recurring one.

f. Can the quality of data submitted by the crowd be trusted?

The quality of data submitted by the crowd will vary. The conclusion taken by Haklay and Weber (2008) applies here, in that the benefits of having the data outweighs the ills of poor data quality. In this regard, the expert has the duty to test the quality of the data, apply expert methods to adjusting data such as collecting and using GCPs to aid in improving the absolute accuracy of the input UAS imagery. If the expert believes that the data is erroneous then that data should not be used to generate 3D building volumes nor any other Cadastral GI.

2. **What tools and techniques exist, or can be implemented to aid in making cadastral geospatial information more open and accessible?**
    a. ***Are the necessary tools freely available?***

The online repositories for initial data upload already exists such as OAM. As it regards upload of point clouds as las files, these can be directly uploaded to the instance of the 3DCity Web Map Client implemented and hosted by the Cadastral Experts.

The tools are freely available, and the licences are facilitative of using, hacking, adapting, and sharing those tools as illustrated by Table 4.

    b. ***Are the necessary standards and data formats already implemented?***

The standards and data formats necessary for full implementation of this workflow already exists. The data formats were used in this thesis to successfully achieve the desired 3D building volumes. Tables 3 and 5 illustrated this fact.

    c. ***What final formats will be created by the Cadastral Experts and will they be shared openly also?***

The Cadastral Expert had a multiplier effect regarding the benefits gained from this process chain. Cadastral GI of five levels were obtained throughout this process. The **1st order Cadastral GI** was the 2D orthomosaic and the 3D point cloud themselves. These are valuable resources to cadastral mapping. **2nd order Cadastral GI** obtained was the 2D vector layers which are like traditional cadastral data. The classified 3D point cloud data was also an added benefit that would not otherwise have been realised if the initial dataset was just satellite imagery. The **3rd order Cadastral GI** obtained was the 3D building volumes which facilitates maintaining the cadastre in 3D. The **4th order Cadastral GI** obtained was the kml file imported to Google Earth Pro. This can be offered as a service by the Cadastral Experts to their clients. A **5th order Cadastral GI** is the 3DCityDB database and Web Map, which allowed the Cadastral Experts to manage and share their 3D building volume data with the crowd. This meant that the Cadastral Experts benefitted five times from the same input dataset, freely obtained from the crowd.

Conclusion

This thesis demonstrated that the workflow adopted, successfully produced 3D building volumes from the initial UAS imagery. These 3D buildings are a necessary resource for the Cadastral Experts to manage the cadastre in 3D, which better fits the reality of the built environment.

The process chain facilitated the Cadastral Experts acquiring input data freely from the repositories on which the crowd deposited it. This was in contrast with the traditional expensive data gathering methods such as ground surveying, aerial photography, and satellite imagery.

The benefits of the proposed workflow to the Cadastral Experts were exponential. Not only were the 3D buildings final products of this chain of processes, but additional benefits were the 2D imagery itself, the 3D point cloud, the 2D vector layers, the 3D buildings imported to Google Earth Pro, and the 3D buildings hosted on the 3DCity database and Web Map.

If the workflow posited by this thesis is implemented, the Cadastral Expert would have the necessary datasets to fast-track the completion of the cadastral map, especially in developing countries like Jamaica where resources are very scarce to do so. The Cadastral Experts would benefit from a partnership with the crowd, where they utilise the GI constantly being created by the crowd to improve their cadastral base map data, while re-engaging the crowd to enrich the attributes of the newly created 3D building dataset. The Cadastral Experts would also benefit from the pool of opensource tools freely available such as QGIS, CloudCompare, 3Dfier and the 3DCityDB suite of tools. This exponential list of benefits opposed the expected high cost of obtaining and maintaining cadastral data in 3D format suggested by Paasch et al., (2016). The accrued benefits outlined would aid NMAs to develop the needed Cadastral GI to buildout the cadastral map, and to manage the 3D building volumes as a first step to upgrading from a 2D cadastre to a 3D cadastre, Stoter, Salzmann, van Oosterom & van der Molen (2002).

City managers and NMAs constantly operate under strict financial constraints, therefore the huge reduction in costs realized by either using their own UAS to capture data or receiving UAS data from openly accessible online platforms offers a welcomed change to the historic high cost of input data such as high-resolution aerial photographs or satellite imagery. A small DJI UAS such as the one used in this thesis or a more rugged, fit-for-purpose UAS will offset the high costs for the alternatives, and ensure greater economies of scale for the entities involved.

The effect of obtaining and maintaining the cadastral information in 3D cannot be overlooked. For some jurisdictions such as Jamaica, a concurrent problem for Cadastral Experts is how to efficiently manage the reality of high-rise buildings created for commercial or residential purposes, while managing the cadastral data regarding these buildings in a 2D cadastral management system. Challenges sometimes arose regarding representing ownership below ground, and above ground, and further challenges arose regarding effective taxation, especially in complex developments, Stoter & Ploeger (2002). A 3D solution such as the one implemented in this thesis is therefore perceived by the author to be a welcomed solution to this problem as it facilitates the Cadastral Experts managing and sharing 3D building data with the public.

Additionally, this thesis has proven, as seen in Tables 3-5, that there are well developed open standards, interoperable data file formats and data structures, along with many unrestricted licences that affords users such as Cadastral Experts the ability to create their strategies of how to derive the solution that fits their need.

The author believes that the solutions implemented in this research has far reaching benefits to City managers and NMAs such as cost reduction in data acquisition, data processing, data storage and sharing. If implemented, the solution should align City managers and NMAs along a feasible path to manage the cadastre in 3D while improving the quality of their offerings to the public.

The Cadastral Experts must decide if they desire all or some portions of the solutions provided by this thesis. They can for example use the 3DCityDB to house the data strictly for internal use without the need for the web map client, however they have, freely available at their disposal, the Web Map Client on which to share their data with the public. In a strict sense, this depends on the purpose for which the data is used and the business model of the Cadastral Expert, City manager or NMA.

Limitations

This project highlighted a workflow that can be adopted by City managers and NMAs to build their Cadastral GI store. There are however certain limitations to the work done here based both on the scope of work and the time constraints to complete this project. These limitations should be mitigated to maximize the final solution implemented for other use cases. The notable limitations are:

- The Precision Mapper application does not offer the service of GCP error reporting, so that report is missing from this document. If a GCP error is needed, a proprietary application may be used to pre-process the UAS data instead.
- The UAS data collection exercise should have been repeated while flying from a lower altitude, with attention paid to capturing all information surrounding each building. This would have increased the data points stored within the 3D point cloud and may have facilitated a better result from the analysis done in CloudCompare, Meshlab and Meshmixer.
- The author acknowledges that UAS is just one method of capturing this type of data, and another method such as lidar could have rendered even better results, albeit at a higher cost.

Future Work

The more recent development of Real Time Kinematic (RTK) technology mounted on UAS will increase the absolute accuracy of UAS imagery. Further studies can be done to see if these RTK tools can replace the regular surveying methods when collecting Cadastral GI.

This thesis treats the 3D buildings as volumetric surfaces at the Level of Detail One (LoD1) because this is the level of detail necessary to represent building data for cadastral purposes. Other researchers may see great benefit however both in capturing greater levels of detail when conducting the UAS flight survey, and subsequently representing the 3D buildings as LoD2 - LoD4 as described in Gröger, Kolbe, Nagel & Häfele (2012). They may however be forced to develop additional capabilities onto their instance of the 3DCityDB as it currently only supports 3D buildings at LoD1.

The author envisions that City Managers and NMAs can explore ways to use the solution implemented in this thesis to further develop their cadastre in 3D. This would entail accounting for 3D building data underground, along with applying Building Information Modelling (BIM) principles to derive more information about the inside of the buildings. This accounts for ownership information such as in the case of high-rise apartments.

APPENDIX A – UAS Specification

1. Type of UAS used – DJI Mavic (most common civilian UAS)
2. Camera's focal length – Lens – FOV 78.8^0 28mm (35mm format equivalent)
3. Size of the camera sensor – Sensor type – 1/ 2.3" (CMOS). 12.35M effective pixels (12.71M total pixels)
4. Image size – 4000*3000
5. Electronic shutter speed – 8s – 1/8000s
6. ISO Range for photographs – 100-1600
7. Still Photography modes – single shot, burst shooting at 3/5/7 frames or auto exposure bracketing at 3/5 bracketed intervals
8. Flight time possible by UAS based on battery power – Approximately 21 minutes
9. Range of UAS as it relates to remote control by operator
10. Maximum speed of UAS – maximum possible 65 km/h
11. Satellite positioning systems available – GPS/Glonass
12. Approximate costs (euros) - €1000

APPENDIX B – GCPs for Leocampus survey

Type	Correction Type	GPS Date	GPS Time	GPS Height	Horizontal Precision (m)	Latitude	Longitude
pt 1	Postprocessed Carrier Float	2017-10-15	12:52:49pm	61,611	0,1	5758964,98	403787,7489
pt 2	Postprocessed Carrier Float	2017-10-15	12:55:23pm	60,54	0,1	5759028,652	403817,3598
pt 3	Uncorrected	2017-10-15	12:59:23pm	60,061	0,1	5759008,972	403912,5253
pt 4	Postprocessed Carrier Float	2017-10-15	01:02:31pm	60,175	0,1	5759099,204	403872,7106
pt 5	Postprocessed Carrier Float	2017-10-15	01:04:46pm	60,104	0,1	5759086,921	403902,7026
pt 6	Postprocessed Carrier Float	2017-10-15	01:08:55pm	60,427	0,1	5759158,666	403776,5094
pt 7	Postprocessed Carrier Float	2017-10-15	01:11:22pm	60,63	0,1	5759230,426	403775,1891
pt 8	Postprocessed Carrier Float	2017-10-15	01:13:41pm	59,885	0,1	5759228,655	403822,9035
pt 9	Postprocessed Carrier Float	2017-10-15	01:16:17pm	59,793	0,1	5759227,568	403879,5849
pt 10	Postprocessed Carrier Float	2017-10-15	01:18:37pm	59,591	0,1	5759176,124	403855,4297
pt 11	Postprocessed Carrier Float	2017-10-15	01:21:19pm	59,94	0,1	5759188,667	403919,1393
pt 12	Postprocessed Carrier Float	2017-10-15	01:25:13pm	59,586	0,2	5759146,417	403965,9854
pt 13	Postprocessed Carrier Float	2017-10-15	01:27:38pm	59,701	0,1	5759085,233	403999,5772
pt 14	Postprocessed Carrier Float	2017-10-15	01:30:52pm	59,776	0,1	5759038,891	403940,5026
pt 15	Postprocessed Carrier Float	2017-10-15	01:35:55pm	59,84	0,1	5759003,834	403952,7736
pt 16	Postprocessed Carrier Float	2017-10-15	01:39:21pm	58,268	0,1	5758947,809	404027,2243
pt 17	Postprocessed Carrier Float	2017-10-15	01:41:17pm	57,805	0,1	5759003,454	404043,3498
pt 18	Postprocessed Carrier Float	2017-10-15	01:43:26pm	58,321	0,1	5759070,436	404074,829
pt 19	Postprocessed Carrier Float	2017-10-15	01:48:20pm	59,166	0,1	5759122,831	404051,7545
pt 20	Postprocessed Carrier Float	2017-10-15	01:51:09pm	59,368	0,1	5759159,814	404018,189
pt 21	Postprocessed Carrier Float	2017-10-15	01:55:09pm	59,711	0,2	5759221,186	403962,6385
pt 22	Postprocessed Carrier Float	2017-10-15	01:58:09pm	59,547	0,1	5759302,453	403900,2187

pt 23	Postprocessed Carrier Float	2017-10-15	01:59:59pm	58,861	0,1	5759332,96	403936,4181
pt 24	Postprocessed Carrier Float	2017-10-15	02:03:50pm	58,691	0,1	5759280,886	404007,9161
pt 25	Postprocessed Carrier Float	2017-10-15	02:06:50pm	58,46	0,1	5759227,049	404041,0542
pt 26	Postprocessed Carrier Float	2017-10-15	02:10:02pm	58,917	0,1	5759148,762	404073,0694
pt 27	Postprocessed Carrier Float	2017-10-15	02:16:29pm	59,835	0,1	5758944,802	403945,8715
pt 28	Postprocessed Carrier Float	2017-10-15	02:19:20pm	60,482	0,1	5758970,287	403864,0671
pt 30	Postprocessed Carrier Float	2017-10-15	02:23:00pm	61,435	0,1	5758951,233	403758,625
pt 31	Postprocessed Carrier Float	2017-10-15	02:24:59pm	61,633	0,1	5758940,873	403824,1753

APPENDIX C – Yaml File used in 3dfier (Precise format required)


```yaml
input_polygons:
  - datasets:
      - leocamp_layers/Grass.shp
      - leocamp_layers/Playground.shp
      - leocamp_layers/Bareground.shp
    uniqueid: Id
    lifting: Terrain
    height_field: Height
    handle_multiple_heights: true
  - datasets:
      - leocamp_layers/Roads.shp
    uniqueid: Id
    lifting: Road
    height_field: Height
  - datasets:
      - leocamp_layers/Buildings.shp
    uniqueid: gml_id
    lifting: Building
    height_field: Height
  - datasets:
      - leocamp_layers/Greenarea.shp
```

```yaml
    uniqueid: Id
    lifting: Forest
    height_field: Height
  - datasets:
      - leocamp_layers/Concrete.shp
    uniqueid: Id
    lifting: Separation
    height_field: Height
lifting_options:
  Building:
    height_roof: percentile-50
    height_floor: percentile-10
    lod: 1
  Terrain:
    simplification: 10
  Forest:
    simplification: 10
  Water:
    height: percentile-10
  Road:
    height: percentile-50
  Separation:
    height: percentile-80
```

```yaml
  Bridge/Overpass:
    height: percentile-50

input_elevation:

  - datasets:
      - leocamp/leo_classified.las
    omit_LAS_classes:
      - 1 # unclassified
    thinning: 0

options:
  building_radius_vertex_elevation: 3.0
  radius_vertex_elevation: 1.0
  threshold_jump_edges: 0.5

output:
  format: CityGML
  # format: CityGML
  building_floor: false
  vertical_exaggeration: 0
```

APPENDIX D – 3DCityDB WFS xml configuration file

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<wfs xmlns="http://www.3dcitydb.org/importer-exporter/config"
xmlns:ows="http://www.opengis.net/ows/1.1" xmlns:xlink="http://www.w3.org/1999/xlink"
 xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.3dcitydb.org/importer-exporter/config
schemas/config/config.xsd">
 <capabilities>
  <owsMetadata>
   <ows:ServiceIdentification>
    <ows:Title>3DCityDB Web Feature Service</ows:Title>
    <ows:ServiceType>WFS</ows:ServiceType>
    <ows:ServiceTypeVersion>2.0.0</ows:ServiceTypeVersion>
    <ows:ServiceTypeVersion>2.0.2</ows:ServiceTypeVersion>
   </ows:ServiceIdentification>
   <ows:ServiceProvider>
    <ows:ProviderName/>
    <ows:ServiceContact/>
   </ows:ServiceProvider>
  </owsMetadata>
 </capabilities>
 <featureTypes>
  <featureType>
   <name>Building</name>
   <ows:WGS84BoundingBox>
    <ows:LowerCorner>-180 -90</ows:LowerCorner>
    <ows:UpperCorner>180 90</ows:UpperCorner>
   </ows:WGS84BoundingBox>
  </featureType>
```

```
  <version isDefault="true">2.0</version>
  <version>1.0</version>
</featureTypes>
<operations>
  <useXMLValidation>true</useXMLValidation>
  <GetFeature>
    <outputFormat>application/gml+xml; version=3.1</outputFormat>
    <outputFormat>GML3.1+GZIP</outputFormat>
  </GetFeature>
</operations>
<database>
  <connection
    initialSize="10"
    maxActive="100"
    maxIdle="50"
    minIdle="0"
    suspectTimeout="60"
    timeBetweenEvictionRunsMillis="30000"
    minEvictableIdleTimeMillis="60000">
    <description/>
    <type>PostGIS</type>
    <server>http://giv-project14.uni-muenster.de</server>
    <port>5432</port>
    <sid>threedcity</sid>
    <user>c_will20</user>
    <password>…..</password> (Password removed)
  </connection>
</database>
<server>
```

```
    <externalServiceURL>http://localhost:6001/citydb-wfs</externalServiceURL>
    <maxParallelRequests>30</maxParallelRequests>
    <waitTimeout>60</waitTimeout>
    <enableCORS>true</enableCORS>
  </server>
  <uidCache>
    <mode>local</mode>
  </uidCache>
  <logging>
    <file logLevel="info"/>
  </logging>
</wfs>
```

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