Norwegian University of Science and Technology

Accuracy analysis of products obtained from UAV-borne photogrammetry influenced by various flight parameters

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BACKGROUND

Unmanned Aerial Vehicles (UAV) are more and more used in land surveying (geomatics) to obtain Digital Terrain Models (DTM) and other information of the surface of the earth. The final products are highly dependent on the choice of values of various parameters for the flight, and for the processing of the data.

TASK

The main objective of this thesis is to look into various parameters influence on the final accuracy of the products, when a low-cost UAV equipment is used. Main parameters are height above ground, overlaps, speed, and Ground Control Points (GCP). Another objective is to compare point clouds of a building acquired from vertical and oblique images from an UAV flight using the optimal set of parameters, with results obtained by using a laser scanner. See the task description below.

Theoretical part

The candidate shall describe and discuss the equipment, software and methods used in the thesis: Low-cost UAV, photogrammetric missions by using UAV, connection to classical photogrammetry, laser scanning, and data processing software packages.

Data capture and processing of the captured data

The fieldwork will be done at NTNU campus Dragvoll, where the student shall establish the study field.

The following instruments and software packages can be used: UAV (DJI Phantom 3 Advanced), laser scanner (Topcon GLS1000), GNSS (Leica Viva GNSS GS15), and total station (Leica TPS1201), the software packages Pix4D Mapper Professional, Agisoft PhotoScan Pro, CloudCompare, and ScanMaster.

Results of the processing of the captured data should be:

The accuracy of photogrammetric products from UAV by comparing different parameters and software.

Comparison of models of buildings measured by laser scanner and by UAV.

Results and conclusions

Interpretation, discussion and conclusions of the results achieved, and suggestions of improvements.

STARTUP AND SUBMISSION DEADLINES

Startup: January 15th 2017. Submission date: Digitally in DAIM at the latest June 11th 2017.

SUPERVISORS

Supervisor at NTNU: Terje Skogseth.

Co-supervisor: Tomasz Owerko, AGH University of Science and Technology, Krakow, Poland

Department of Civil and Environmental Engineering, NTNU. Date 15.01.2017 (revised May 2017).

Terje Skogseth (signature)

Preface

I would like to hereby thank my main supervisor Terje Skogseth for all the support, guidance and time that he devoted to help me to write this thesis.

Abstract

Rapidly developing technology Unmanned Aerial Vehicle – based photogrammetry is used in an increasing number of applications. They are employed in volume calculations, terrain mapping or generating 3D models of buildings. Conducting a successful mission with desired accuracy requires knowledge of influence of various flight settings.

The main purpose of this thesis is to assess accuracy that can be acquired with low-cost, commercially available UAV. It is influenced by flight parameters, such as height, forward and side overlap of images and speed of the aircraft. Additionally, various configurations of number and distribution of Ground Control Points are tested. The acquired accuracy is discussed with time and effort spent on the mission. The final result is always a compromise between economy and quality.

The second objective of the thesis is to compare 3D point cloud datasets acquired from laser scanning and UAV photogrammetry. The most optimal parameters of flight are used to perform a mission. Data is processed in two Structure from Motion software packages and compared to reference dataset. Results show that to some extent UAV-borne measurements can compete with Terrestrial Laser Scanning.

Abbreviations

AGL – Above Ground Level

ASIFT – Affine SIFT

BVLOS – Beyond Visual Line of Sight

CP – Control Points

CV – Computer Vision

DEM – Digital Elevation Model

EDM – Electronic Distance Measurements

EOE – Exterior Orientation Elements

EVOLS – Extended Visual Line of Sight

EXIF – Exchangeable Image File Format

GCP – Ground Control Point

GCS – Ground Control Station

GIS – Geographic Information System

GLS – Geodetic Laser Scanner

GNSS – Global Navigation Satellite System

GSD – Ground Sample Distance

IMU – Inertial Measurement Unit

INS – Inertial Navigation System

IOE – Interior Orientation Elements

MTOM – Maximum Take-Off Mass

MTP – Manual Tie Point

NTM – Norwegian UTM

PANSA – Polish Air Navigation Services Agency

RMSE – Root Mean Square Error

RPAS – Remotely Piloted Aircraft System

RTK – Real Time Kinematics

RTN – Real Time Network

SfM – Structure from Motion

SIFT – Scale Invariant Feature Transform

SURF – Speeded Up Robust Features

TLS – Terrestrial Laser Scanning

UAS – Unmanned Aerial System

UAV – Unmanned Aerial Vehicle

UTM – Universal Transverse Mercator

VLOS – Visual Line of Sight

WGS84 – World Geodetic System 1984

WMS – Web Map Service

Contents

1. INTRODUCTION

A cutting-edge Unmanned Aerial Vehicle (UAV) technology is becoming more enthusiastically employed by land surveyors for a variety of applications. Since few years drones became a low-cost, easily accessible tools which can be used for conducting measurements from the air. Recent development in sensors and flying platforms has significantly broadened the applications including volume calculations, creating orthophotomaps, generating 3D models, acquiring data for Geographic Information Systems (GIS), overseeing extraction in open-pit mines, conducting construction inspections, general mapping of terrain and much more. UAV shorten the time of performing surveys from several days to few hours, that have to be spent in a field. New products can be created that visually and graphically enhance the attractiveness of provided services such as colorful overview maps and detailed CAD models of buildings. They also, if properly used, increase the safety of people conducting measurements, because an operator can stay out of a dangerous zone.

UAV market is in constant development and new applications are just a matter of time and money. Improved copters are manufactured by global commercial giants such as DJI or eBee SenseFly but also by regional constructors like FlyTech UAV from Cracow, Poland who deliver personalized solutions for particular clients or application. Nowadays, more and more land surveying companies invest in an UAV technology. It is another, additional platform that is being applied in a field for data collection. Available, low-cost drones can generate sufficiently accurate products if used appropriately, but then the question arises how to conduct the photogrammetric mission in order to achieve possible highest accuracy in an optimal way.

Employment of new innovative technologies, especially in mapping and surveying is primarily based on their improvement of offered products in terms of accuracy and reliability but also the effectivity in time and money spent on measurements. Multirotor aircraft have limited duration flight endurance what should be taken into account when planning photogrammetric mission together with other flight parameters.

1.1. PROJECT OBJECTIVES

The main objective of this thesis is to examine the influence of different parameters on a final accuracy of a low-cost UAV-borne product. Many factors have to be taken into consideration when capturing data and the most important are: height on which UAV is flying, percentage of which adjacent images are overlapping and also speed of the aircraft while taking photos, as a sensor used for acquiring images is a rolling shutter camera. Moreover, indirect georeferencing plays an important role in bundle block adjustment, since reliability of camera calibration is based on accuracy of Ground Control Points (GCP). Thus, distribution and number of GCP were also a case of interest.

Several flights with variable parameters were performed over the area of interest. Eleven sets of images in total were captured. Each project was then processed in two commercial software packages, Agisoft PhotoScan and Pix4D Mapper Pro. The accuracy of results has been assessed as well as performance of workflow and time spent on processing. When the parameters have been evaluated, final mission with the best settings was flown again but additionally, oblique photos were taken manually. It was due to the secondary objective of this project which was general comparison of 3D point cloud of a building acquired from UAV-based photogrammetry and from Terrestrial Laser Scanning (TLS). Finally, 4 projects with different number and distribution of GCP over the area of interest were processed to analyze their influence on accuracy.

The thesis also considers actual information about Unmanned Aerial Systems especially in mapping applications, examines fundamental principles of UAV-based photogrammetry and describes software that can be used in processing the data.

1.2. THESIS ORGANIZATION

The thesis is divided into four bigger chapters: Introduction, Theoretical and Practical Part, and Summary. The first section gives a preface to the project and declares what is going to be done. Theoretical Part mentions how it can be achieved and underlines rules that should be followed. In Practical Part, the step by step workflow of the project is described. The last chapter summarizes the results and concludes the whole project.

2. THEORETICAL PART

2.1. UNMANNED AERIAL SYSTEMS

This chapter gives a theoretical background about Unmanned Aerial Systems (UAS). Base terms and definitions concerning the technology are explained. Followed by recalling some applications, especially in mapping and surveying domain. Later, different sensors for data gathering are described and general law regulations regarding conducting UAV flights are mentioned.

2.1.1. Terminology

UAV stands for Unmanned Aerial Vehicle which means that the pilot is not physically present in the aircraft. It can be controlled either remotely by human or by onboard computer. Terminology concerning unmanned aircraft is slightly wider and some abbreviations should be explained:

UAS – Unmanned Aerial Systems, term adopted by the United States Federal Aviation Administration (FAA), which consists of an Unmanned Aerial Vehicle (UAV), a ground control station (GCS) and a system to communicate between them. Thus, UAS refers to more general concept and includes all required components.

UAV – Unmanned Aerial Vehicle which corresponds only to the device that is flying in the air, so it has narrower meaning than UAS.

GCS – Ground Control Station to monitor flight parameters, display telemetry, so drone position, altitude, velocity, power consumption, visible satellites and much more. It also provides real-time preview from the onboard camera and enables the operator to safely pilot the aircraft.

RPAS – Remotely Piloted Aircraft System, RPV – Remotely Piloted Vehicle and RPAV – Remotely Piloted Aircraft Vehicle, drone – all meaning the same in general.

2.1.2. Applications

The advent of Unmanned Aerial Systems has revolutionized many sectors of economy. It has its roots in army, where it was first used for military purposes and where its most commonly known name comes from: "drone", but they have expanded into numerous civil and commercial applications. Nowadays UAS are used for example in precise agriculture for crop monitoring, spraying and health assessment of vegetation (Mesas-Carrascosa, et al., 2016) in archaeology for documentation of excavations (Thomas, 2016) or in cultural heritage for 3D modeling. They also found a utilization in Search and Rescue (SAR) services when rapid land reconnaissance in difficult to access areas under adverse weather conditions has to be accomplished in order to find lost people (Molina, et al., 2012) or in movie industry and entertainment to capture astonishing footages.

However, what is the most significant for this thesis, they are being widely used in geodesy and cartography. As it was stated in (Colomina & Molina, 2014) *Let them fly and they will create a new market.* The sentence is especially appropriate for mapping and surveying. UAS found their place in modern photogrammetry between close-range terrestrial photogrammetry and aerial photogrammetry. As it is illustrated in Figure 1, UAV tighten the gap between them two and let us acquire data in certain situations and areas with proper accuracy and density of points at relatively short time and low cost.

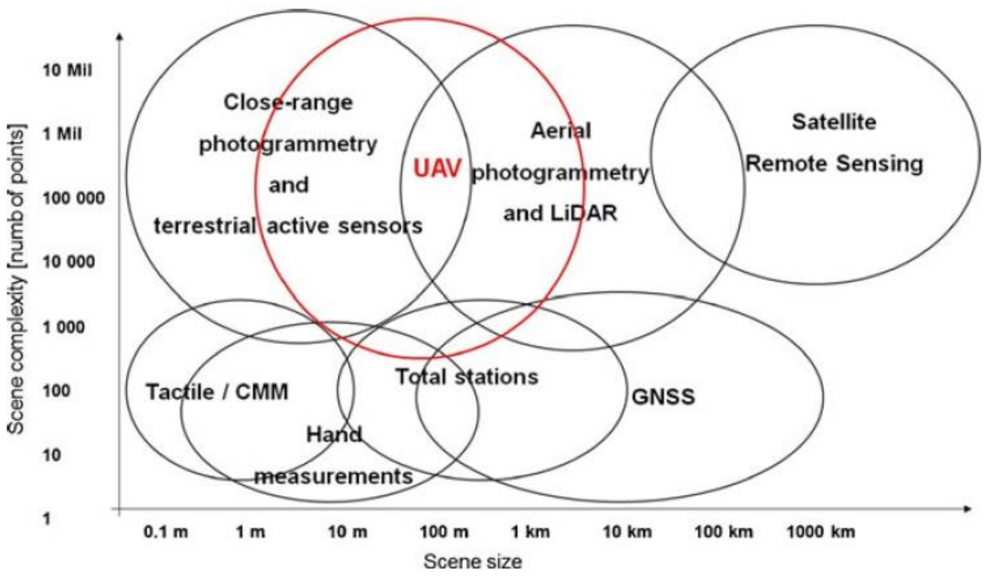

Figure 1 UAV among various surveying techniques based on scene complexity and size. Source: (Nex & Remondino, 2012)

Moreover, construction also benefits from this technology in Building Information Modeling, bridges inspections (Metni & Hamel, 2006) (Hallermann & Morgenthal, 2014) and deformation monitoring (Eling, et al., 2016) (Seier, et al., 2017). That means UAS are new source of data and are becoming more enthusiastically employed in numerous fields.

A great example of applying UAV technology on a construction site is E6 road project in Norway, Sor-Trondelag county between Trondheim and Melhus municipalities. It is a renovation of 8 km, 4 lane expressway with many advanced crossroads, crossings and one railway bridge. The project is supervised by National Public Roads Administration – Statens Vegvesen, which is responsible for overseeing the work progress and conducting inspections in the field to see whether construction advances as it was planned. In order to achieve it, frequent surveys have to be performed in a way that ensures sufficient accuracy of measurements and does not disturb the workers. The UAV-based photogrammetry seemed to fulfill these requirements and is being used to gather necessary data. First, it is applied to recording videos and capturing photos to visually assess the work and document week to week progress. However, its main application is mapping of the terrain to be able to check the data delivered by a contractor, a company that builds the road and compare it to the plan. There are many examples of how it is utilized and some of them are:

- make surface models for mass calculations

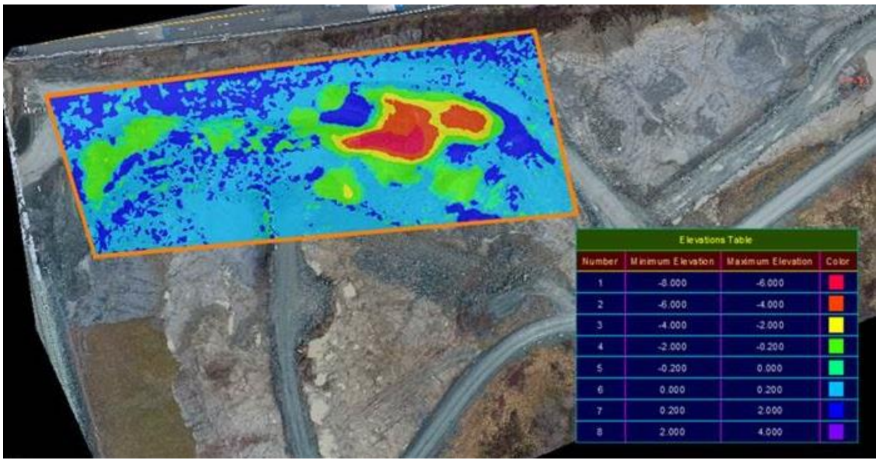

Figure 2 Surface model for mass calculation. Source: Statens Vegvesen.

- create surface models of filling and compare to 3D-models of completed works

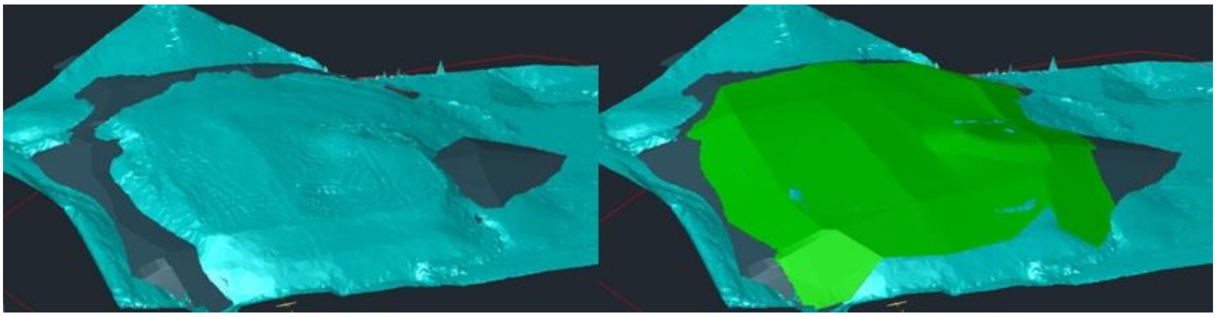

Figure 3 Surface model of filling and its comparison to 3D-model. Source: Statens Vegvesen.

- perform slope analyses and check masses slipping

Figure 4 Example of a mass slipping. Source: Statens Vegvesen.

Figure 5 Mass slipping seen on orthomosaic. Source: Statens Vegvesen.

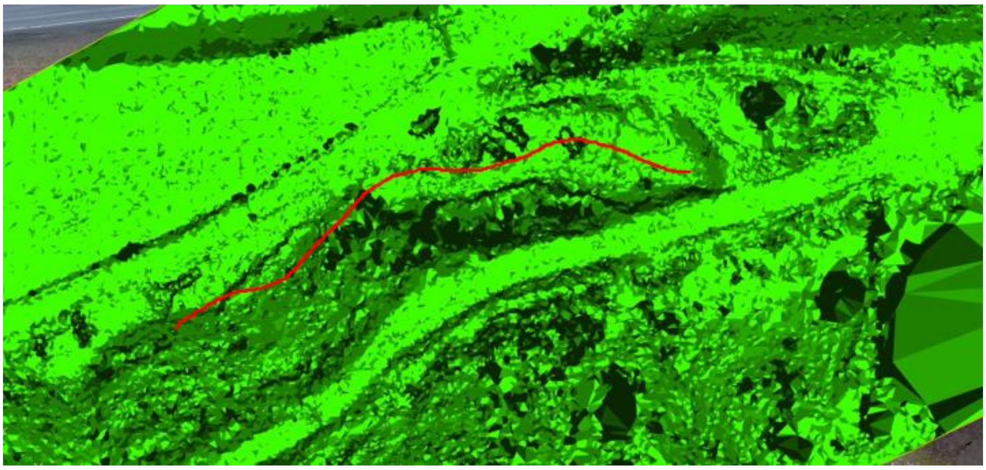

Figure 6 Analysis of mass slipping. Source: Statens Vegvesen.

- measure the surface area of a polygon

Figure 7 Surface measurements. Source: Statens Vegvesen.

- check lime cement stabilization and any other matters of interest

Figure 8 Lime cement stabilization. Source: Statens Vegvesen.

2.1.3. Classification

UAS can be of different types, what determines their usage and utilization. According to (Polish law, 2016), there are five categories of unmanned aircraft:

- unmanned airplane (A)
- unmanned helicopter (H)
- unmanned airship (AS)
- unmanned multirotor (MR)
- other unmanned aircraft (O).

They can be divided by Maximum Take-Off Mass (MTOM):

- up to 5 kg,
- from 5 kg to 25 kg,
- from 25 kg to 150 kg,
- more than 150 kg

and also by average altitude of flight or propulsion system (electric or combustion engine). The division can vary dependent on country or who makes it.

The two most widespread types used in geomatics field are fixed-wing and multirotor aircraft, both having their advantages and limitations. Fixed-wing UAV (Figure 9) can fly longer, thus cover wider areas. It is also faster and generally safer because it could still be prone to control it in emergency situations. However, an open space for take-off and landing must be provided for them, because they need to obtain velocity before flight or lose it afterward. Additionally, better cameras with adjustable shutter speed are recommended to avoid blurred images.

Multirotors (Figure 10) on the other hand do not require a lot of place and can take off and land almost everywhere. They can also hover in one spot if there is a necessity, for example, to take a photo and are generally more maneuverable, allowing to realize most of the trajectories. Nevertheless, rotary-wing copters are more limited in endurance and vulnerable to weather conditions and malfunctions. If one engine breaks down, there is almost nothing to be done to save the UAV.

Figure 9 Examples of fixed-wing UAV. Source: www.flight-evolved.com, www.cbc.ca, www.flytechuav.com.

Figure 10 Examples of multi-rotor UAV. Source: www.personal-drones.net, www.skytango.com, www.flytechuav.com.

2.1.4. Sensors

In order to perform data acquisition by UAV, there must be some kind of sensor mounted on it. It can be either camera or laser scanner (Figure 11).

Figure 11 UAV with mounted laser scanner (on the left), source: www.insideunmannedsystems.com, and professional camera (on the right), source: www.macnn.com.

The latter is generally more expensive and heavier which makes it less common choice than the former. However, laser scanners are capable of collecting point clouds with information about intensity and number of returns, what can be useful in some applications, such as terrain classification. On the other hand, cameras can capture imagery in wide electromagnetic spectrum. Thermal cameras can take photos in infrared or near-infrared, which enables creating different spectral compositions. Nevertheless, for most traditional photogrammetric purposes, such as generating orthophotomaps or Digital Elevation Models (DEM), RBG cameras are sufficient and cost-effective. It is accomplished with CCD or CMOS sensors that provide us with visible spectrum imaging. What is more, multi-cameras systems are becoming highly desirable for capturing oblique photos (Figure 12). However, in the future, more and more systems with laser scanners and cameras integrated together should be expected.

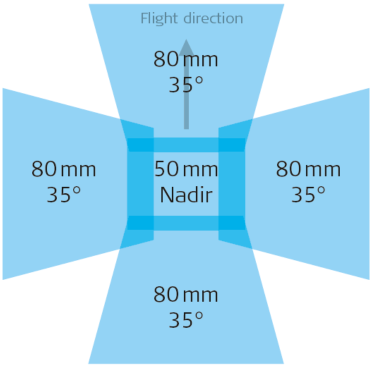

Figure 12 Multi-camera configuration formed by footprint of vertical and oblique images. Source: www.aerometrex.com.au.

The cost and quality of UAS are also affected by on-board instrumentation and auxiliary devices. To be able to perform autonomous flight with predefined waypoints a UAV must be equipped with GNSS receiver. The cheapest C/A receivers are enough to handle this task, but sometimes mounting more accurate equipment should be considered. GNSS is not only used for autonomous steering but also for georeferencing images. Real Time Kinematics (RTK) GNSS receivers are currently being tested in order to perform direct georeferencing and eliminate the necessity of using Ground Control Points or reduce their amount. Studies show that absolute block orientation accuracy can be enhanced significantly by using the onboard RTK solution (Gerke & Przybilla, 2016) (Wiacek, 2017). Applying position corrections can greatly improve reliability and save time spent on terrestrial measurements. The better the accuracy, to the higher extent information about coordinates of images can be used in further post-processing. Similarly, class of Inertial Navigation System (INS), as well as Inertial Measurement Unit (IMU) play an important role in a quality of a flight. The former consists of motion sensors (accelerometers), rotation sensors (gyroscopes) and magnetometers and the latter is responsible for collecting data about forces acting on the aircraft. There is also a barometer, which determines actual altitude of UAV over the starting point and they all together are essential for fixing UAV's position and providing highest possible accuracy of a final product.

2.1.5. Law regulations

Just like any other aircraft, an unmanned vehicle must always be flown in a safe manner, both with respect to people and properties on the ground and also to other airship in the air. Each country has at least one organization involved in the UAV regulations, that are oriented to enhance the reliability of the platforms and take care of the public safety. The offices responsible for defining the security criteria for UAV are in Norway *Luftfartstilsynet*, Norwegian Civil Aviation Authority and in Poland *Urząd Lotnictwa Cywilnego – ULC,* Polish Civil Aviation Authority together with Polish Air Navigation Services Agency – PANSA. Rules applicable to UAV are dependent on its dimensions, weight, and onboard technology but also on what the drone is used for so if it is a commercial project or leisure flight. The official acts in Norway concerning what regulations must be respected when flying a model aircraft are listed on CAA's website (Norwegian law, 2017) and say that:

- flights must be performed in a visual line of sight (VLOS) so such a way that the aircraft can be observed at all times without auxiliary aids
- flights must be conducted in a considerate manner so that there is no risk of harm to aircraft, people, birds, animals or property
- aircraft may only be flown during daylight hours and not higher than 120 m or close to other people
- model aircraft may not be flown over or in the vicinity of military areas, embassies or prisons
- nobody must fly a model aircraft under the influence of alcohol or other intoxicating or narcotic substance
- rotor-operated aircraft shall have a built-in system to ensure that the aircraft can land automatically in the event of loss of control

Regulations for leisure flying in Poland are almost the same as in Norway and in both countries, there are some more restrictions when it comes to commercial flying.

- before each flight, CAA should be notified with name, address and contact information of the pilot
- the operator should fulfill several roles at a time such as accountable manager, operations manager, and technical manager or have other persons that will do it
- operations manual must be prepared
- a log should be kept of all flight times
- aircraft should be marked with the operator's name and contact information

These are just the basic regulations that must be respected but in law one can find more rules for conducting UAV operations, including airspace management, right of air and rules of the air, safety distances and altitudes to aerodromes and other zones, insurance and different flying modes, like Extended Visual Line of Sight (EVLOS), Beyond Visual Line of Sight (BVLOS).

2.2. UAV PHOTOGRAMMETRY

In this section, the fundamental principles of photogrammetry are mentioned with the main emphasis on UAV-borne datasets. Essential drone-imagery processes are described underlining modern Structure from Motion algorithms and later advanced georeferencing techniques are presented. Finally, a brief summary of planning a proper photogrammetric mission is given with characterization of parameters that have importance.

2.2.1. Main characteristics

Photogrammetry is a science of performing measurements from photographs. The key problem is to find a 3D position of points of a scene from overlapping images. Normally, site measured by UAS cannot be taken with one photo, so it demands that the pictures are taken with proper forward and side overlap so that they can be later processed. This process is based on collinearity condition, in which a line originates from central projection of a camera and goes through a point in sensor plane (on the image) to the object point in the ground coordinate system. The intersection of many lines determines the location of three-dimensional points of a scene.

Image orientation and camera calibration are essential for reconstructing metric model from images. They can be achieved by two approaches: classical photogrammetric workflow or computer vision (CV) technique. The former relies on known camera positions and resolves the model by triangulation. If the camera positions are unknown, the solution is to place a set of reference markers with known 3D coordinates, identify them manually in the images and use resectioning to get camera positions. This process involves steps used in Digital Photogrammetric Workstation, that are shown on Figure 13. However, this approach is mostly applicable to high-level classical airborne photogrammetry (Bhandari, et al., 2015).

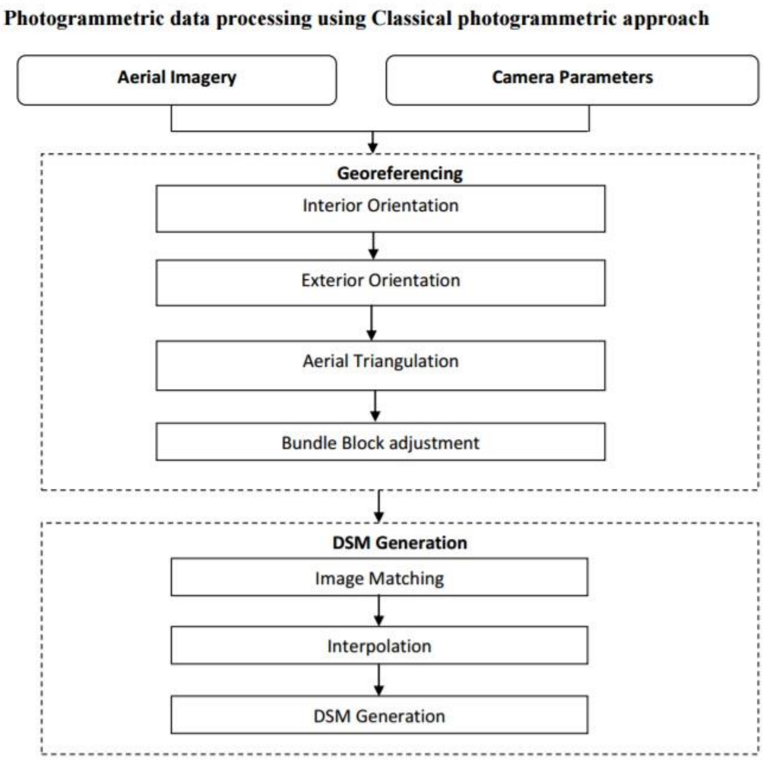

Figure 13 Processing steps of classical photogrammetric approach. Source: (Bhandari, et al., 2015).

Bundle Block Adjustment (Figure 14) is a method to directly compute the relations between image coordinates and object coordinates. It omits model coordinates as an intermediate step and thus the picture is a fundamental unit in the process (Kraus, 2007). Exterior Orientation Elements of all bundles in a block are computed simultaneously. When non-metric camera is used, it is also beneficial to include Interior Orientation Elements of a camera in equations as unknowns so they are determined within the process. Bundle Block Adjustment minimizes geometric cost functions by jointly optimizing both the camera and point parameters using non-linear least squares method (Snavely, 2008).

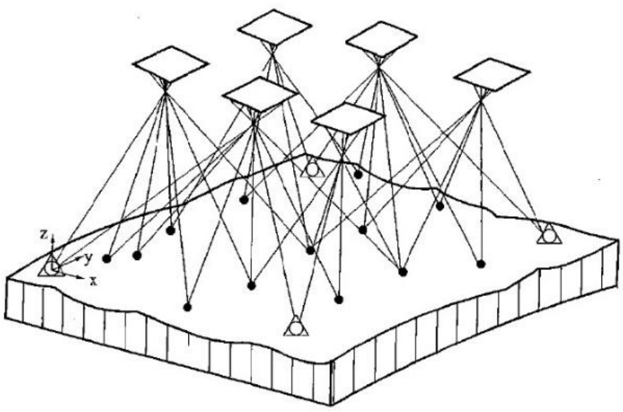

Figure 14 Principle of a bundle block adjustment. Source: (Kraus, 2007).

Camera calibration is a procedure that has a great impact on final accuracy of photogrammetric product. It is a process of estimating interior camera elements. In general, it is a separate task and used to be done in a laboratory before the photos were taken and aerotriangulation completed. Nevertheless, calibration and orientation can be computed at the same stage with reasonable results. This is called self-calibration or self-calibrating bundle adjustment. The whole process of determining camera parameters and 3D structure is called 'Structure from Motion' (Nex & Remondino, 2012).

To acquire approximate EOE, namely position of camera when the image was taken and its orientation, the measurements are performed during the flight by on-board equipment. This information greatly reduces computation time needed for image matching. Even UAV equipped with simple C/A receiver and low-cost INS system provides data that can be advantageous and useful. The accuracy of this devices and final required accuracy determine how EOE can be further used in bundle block adjustment, either as approximate values or for direct georeferencing.

2.2.2. Structure from Motion

With introduction of UAS as a surveying method, an intensive development of several Computer Vision (CV) algorithms can be seen. Various commercial software packages are available on the market, like Agisoft Photoscan, Pix4D Mapper and also open-source MicMac. They rely on tie point extraction, which is later used for Image Matching. Tie points are generated automatically based on feature-matching point detectors and descriptors of different types, such as Scale Invariant Feature Transform (SIFT), Speeded Up Robust Features (SURF), of Affine SIFT (ASIFT) (Colomina & Molina, 2014). The difference between classical photogrammetric approach and CV technique lies in fact that correspondences between images are computed almost always automatically and the camera positions together with the scene structure are calculated simultaneously (Snavely, 2008). They are usually obtained in an iterative bundle block adjustment that ensures statistically correct and robust solution. It is required that images are taken with sufficient overlap, so highly redundant number of connections is generated (Figure 15). However, there is also no need of using a metric camera, because its parameters are optimized during camera calibration procedure. The whole process is called Structure from Motion (SfM).

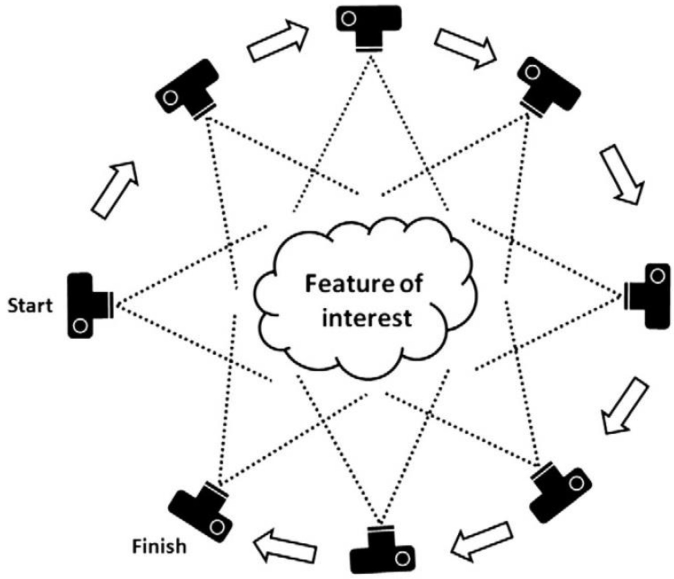

Figure 15 Multiple, overlapping images required as input to feature extraction and 3D reconstruction in Structure from Motion. Source: (Westoby, et al., 2012).

When the elemental model is derived from SfM without information about camera position or any other point coordinates, it lacks scale and orientation in object-space coordinate system. Therefore, a transformation from SfM image-space to real world coordinate system is required (Westoby, et al., 2012).

2.2.3. Georeferencing

To be able to perform measurements on the 3D model and its by-products, it has to be georeferenced or at least scaled. Scaling is used in rare, extraordinary cases when there is no information about geolocation of images or GCP. Distance, that is measured in real world, is passed into software to scale the model in arbitrary coordinate system.

The most common approach to geolocating measurements is to use Ground Control Points. This method is also called indirect georeferencing. GCP is a point with known coordinates, that is located in the area of interest and recognizable in the photos. They can be measured by conventional methods, i.e. tacheometry and GNSS or acquired from other available sources, like Web Map Service (WMS) or old maps. However, GNSS measurements are the most efficient way in terms of accuracy, reliability and time (Madawalagama, et al., 2016).

Once, the coordinates of the GCP are obtained, they can be processed in two ways in a bundle block adjustment. Firstly, they can be treated as weighted observations in the least squares method, which minimizes impact of possible systematic errors, helps in keeping the stability of the solution and improves determining the correct 3D shape of the scene. The second way is to add them at the end of bundle adjustment, in transformation to reference coordinate system (Nex & Remondino, 2012).

Direct georeferencing uses geolocation information only from GNSS receiver mounted on a UAV. Each photo has coordinates of its center written in EXIF format (Exchangeable Image File Format) (Figure 16). It keeps all metadata of a photo, like camera parameters, settings that were used when the photo was taken and the location information if camera was connected with GPS receiver.

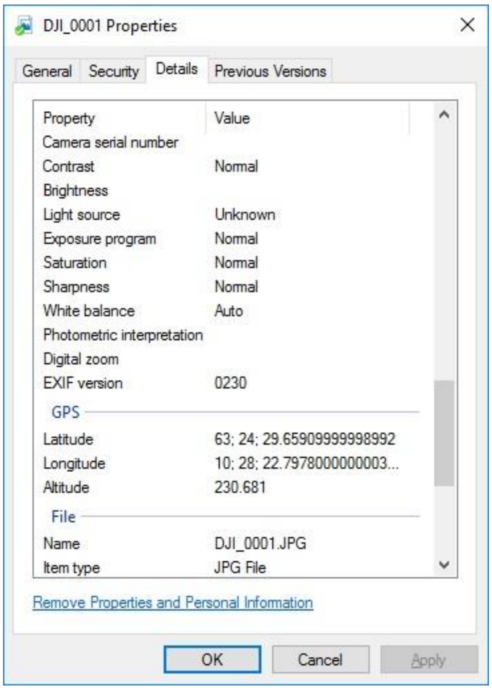

Figure 16 EXIF data of an image with GPS information.

The coordinates can be also accessed from a log file that is generated after each flight. This technique does not require GCP and final position of a model is affected by quality of a GNSS receiver. Direct georeferencing is used mainly when high accuracy is not needed, for example in Search and Rescue missions (Molina, et al., 2012). For geomatics purposes, this method is being developed employing RTK GNSS receivers mounted on a UAV. Corrections of position are computed in a receiver placed on a point with known coordinates (base station) and sent to the receiver in a UAV, which adapts them to adjust its position. It can be even improved when corrections from many base stations that work in a network (RTN) are used. Tests show that meter - accuracy when ordinary, non-RTK receivers are used can be improved to a couple of centimeters when RTK is applied (Wiacek, 2017).

Even if the coordinates of the photos are not accurate enough for direct georeferencing (accuracy of images reaching a couple of meters) it can be highly beneficial using them in computations. In the first step, when photos are aligned/matched to each other, this information can be applied and serve as additional data, so that the software knows on which pictures it should look for matches and which can be omitted. It can greatly improve performance and reduce time consumed for the process.

GCP should be evenly distributed over the area of interest, both on the edges and in the middle. They can be marked by removable signs, painted on the ground or could be other distinguishable natural objects (Figure 17). Their amount differs depending on terrain characteristics and complexity that is measured. GCP are used to transform coordinates of the model to global coordinate system. It is usually accomplished by Helmert 7 parameter transformation (3 translations along axes, 3 rotation angles and 1 scale factor) and while each point gives as many equations as measured coordinates it has, the minimal number of GCP is 2 points with all three coordinates and 1 point with known height only. However, as long as higher accuracy and its assessment are required, more GCP are needed, from 5-6 in simple cases to more than ten is complex situations.

Figure 17 Examples of artificial signs of Ground Control Points.

In order to check the accuracy of a model, Check Points (CP) must be measured employing the same rules like for GCP. They must have measured coordinates in known coordinate system and be visible in the photos. The only difference is that they are not taken into computations in bundle block adjustment but after the process is done, their measured coordinates are compared to those calculated ones.

2.2.4. Flight planning

The planning of a mission is usually done in office before the flight. The first considered issues are area of interest, required Ground Sample Distance (GSD) and intrinsic parameters of onboard camera. They normally remain fixed by pre-imposed requirements and other settings have to be adjusted to them to fulfill the desired accuracy. A typical airborne photogrammetric mission should take into consideration also other setting such as altitude of flight, percentage of frontal and sidereal overlap of images and speed of the aircraft. Additionally, images should be taken as *normal*, which means horizontally, but due to inaccurate stabilization systems it is almost never achieved and the photos are near *normal*. With variable applications and terrain characteristics one should consider choosing types of cameras with different fields of view or principal distances but since the cameras in UAV are usually not even metric sensors it is not a case for low-ceiling photogrammetry. At the end, an official document is prepared from with other auxiliary information such as weather forecast, project identification, and purpose, organizational details, proximity of international borders and aerodromes (Kraus, 2007).

Luckily, UAV flight planning is not so complicated and it comes to computing the coordinates of camera perspective centers (waypoints). As already described, the software in order to be able to perform image matching needs to find corresponding points on several photos. Thus, a high overlap should be chosen, for example, 80-60%. It is higher than in traditional aerial photogrammetry (60-30%) because a UAV is more vulnerable to wind gusts and sometimes there could be holes between the stripes. Altitude of flight is mainly dependent on desired GSD and camera constant. The better the GSD must be, the lower the UAV should fly. When the waypoints are computed, the flight is usually done in autonomous mode assisted by onboard computer and GNSS receiver.

2.3. SOFTWARE

This chapter presents software packages that were used for processing acquired data. Two first subsections treat of digital photogrammetric programs, Pix4D Mapper and Agisoft PhotoScan. General processing workflow and description of available settings are presented. Next, other used software are mentioned such as C-GEO, ScanMaster, CloudCompare, and Litchi.

2.3.1. Pix4D Mapper

Pix4D is a software used for drone-based mapping, created by Swiss company of the same name. It allows user to convert pictures taken from aerial vehicles or handheld cameras to georeferenced models and generate CAD and GIS outputs. Pix4D is divided into several products that are used for different purposes and applications, each of them being self-standing, independent software package. These are Pix4D Mapper, used in surveying for mapping or mining; Pix4D BIM for construction sites, earthworks, BIM and inspections; Pix4D Ag for agricultural purposes and Pix4D Model for real estate, 3D models. There is also Pix4D Capture, a mobile application for planning photogrammetry flight missions with appropriate overlap percentages, altitude or flight speed. It controls UAV while it is flying and collecting images so that the mission can be fully automated, but it is also possible to take over manual control in case of emergency situations.

Pix4D Mapper was used in post processing of the data as the most suitable tool among all Pix4D products for terrain mapping. While creating a new project, user can set two different coordinate systems, one for centers of images and the second one for Ground Control Points and output products. Geolocation of images can be imported straight from EXIF or coordinates of photos can also be acquired for example from flight logs from UAV and imported into the software from *.txt file. After creating a project, processing is restricted to 3 steps, that are followed one after another and each creates some output products (Pix4D, 2017). The general workflow is presented on the Figure 18.

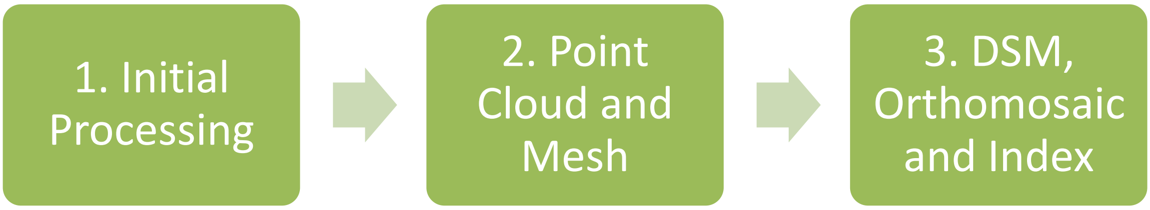

Figure 18 General workflow in Pix4D software.

In step 1. Initial Processing keypoints are extracted from overlapping images, that will be later used for image matching. The user can determine options (Figure 19 for matching by indicating type of path of the flight, time on which photos were taken, usage of image geolocation or image content for similarity matching. It is also possible to mark Manual Tie Points (MTP) in case when algorithms fail to match all the photos correctly. Camera calibration is also done in the first step. This process is crucial in order to achieve high accuracy of final products. Initial parameters for calibration are taken from software's database, where the information is stored for most of the today's commonly used cameras. The user can choose which options are to be optimized if they are all internal and external camera parameters, one of them or none. Most of the time while using commercial, low-cost cameras mounted on light-weight drones, both internal and external orientation elements should be calibrated "on-the-job" to improve quality of adjustment, because such cameras are much more sensitive to temperature or vibrations than real photogrammetric cameras. Optimized parameters are used in model reconstruction and can be also taken for creating undistorted images.

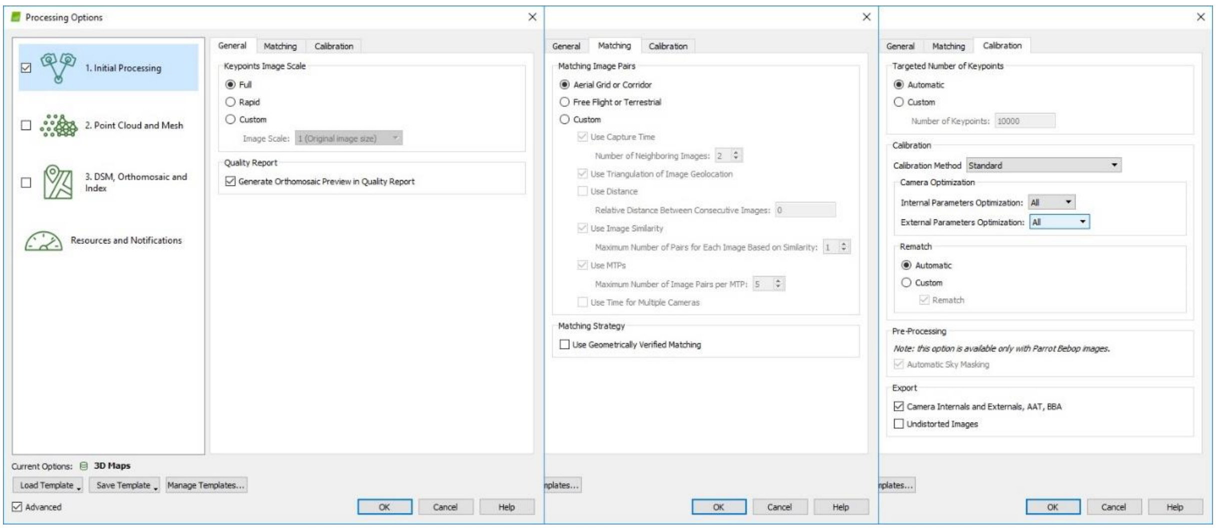

Figure 19 Processing options of the Initial Processing in Pix4D.

After Initial Processing is performed for the first time in a project, user should import coordinates of GCP. As mentioned before, they do not need to be in the same coordinate system as photos, because the software handles transformation between systems on the fly. Imported GCP are shown among other automatic tie points in rayCloud editor, they are displayed on sparse point cloud and in the photos. The more accurate geolocation of images was, the closer GCP are placed to their authentic position. The user has to indicate the exact location of the GCP in the images, so the final geolocation of the model is respectively high. It is accomplished by the help of software feature which, after at least two measurements of GCP have been done, suggests computed localization by the green mark (Figure 20).

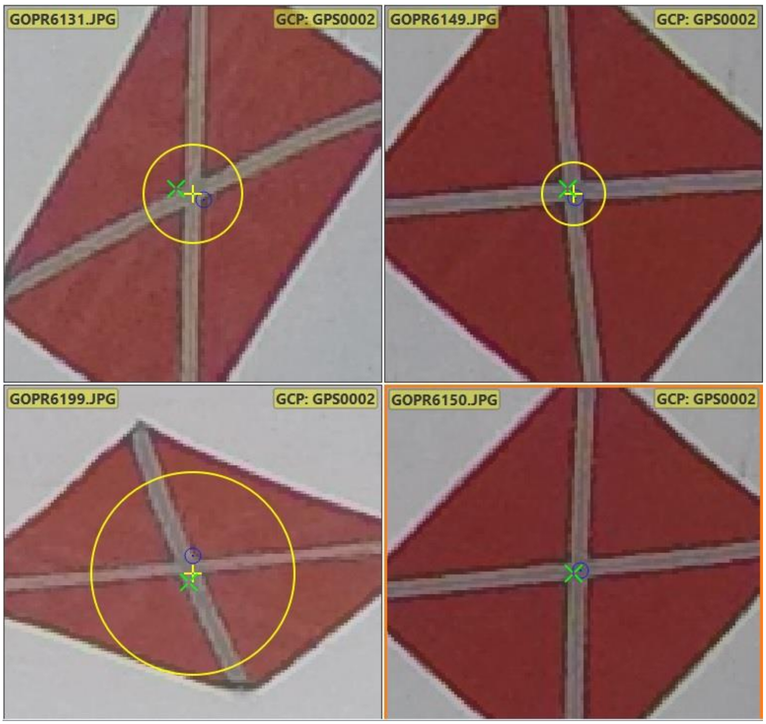

Figure 20 Pix4D feature for measuring GCP and CP.

The yellow cross indicates user's measurement, while yellow circle around it represents zoom of the photo, when measurement was made which is later treated as weight observation. When GCP is not well seen in the photo and software struggles with calibrating it correctly, one can add additional information by zooming out and pointing roughly the GCP. However, in that case, it would be worth considering adding Manual Tie Point in place where features are better visible. Blue mark shows initial, absolute position of GCP. Measuring GCP in the photos can be highly accelerated by features available in Pix4D. The size of all images, as well as their zoom, can be set by sliders and there is also a button for centering images on markers. All this together makes it effective and efficient when it comes to time and effort spent. After GCP have been added and measured, as well as Check Points, one of two features should be run: Reoptimize, which refines camera positions and internal camera parameters or Rematch and Optimize, which in addition computes more matches between images. Then, in Quality Report user can see Root Mean Square Errors for GCP and CP, so the accuracy can be assessed.

In the second step, point cloud densification is performed, followed by 3D textured mesh generation. Main options that can be set for densification are image scale at which points are computed, point density and a minimum number of matches, so a number of photos the point is visible in. Also, output file format of point cloud can be chosen and processing area to limit unnecessary computations. 3D textured mesh is an arbitrary output that can be generated.

In last, third step the software creates Digital Surface Model, orthomosaic, Digital Terrain Model and Reflectance Map. DSM can be filtered, deleting noises and correcting point's altitude to avoid erroneous data. It can be also smoothened, with different parameters Sharp – relevant for objects with corners and edges like buildings or with Smooth – to delete sharp features that are treated as noises and smooth areas to make them planar. For all of the products, resolution can be chosen as equal to integer value of Ground Sampling Distance or it can be arbitrary value. In Pix4D it is possible to calculate volume from surface drawn in special editor or imported from another software. The software also allows editing orthomosaics and DSM and generate contour lines.

It is worth noting that previous step cannot be rerun without deleting the next one (if step 1. is run again, results from step 2. and 3. will be deleted), so it is a good practice to export the output if one wants to keep it.

2.3.2. Agisoft PhotoScan

Agisoft PhotoScan is a stand-alone software package created and developed by Russian company Agisoft LCC founded in 2006. It is designed to cope with photogrammetric computer vision projects such as area mapping or 3D object digitization task. It found its application in field where digital photogrammetry is a fast and low-cost tool. There are numerous examples of using the software in archaeology for excavation documentation, in 3D scanning for video games or cultural heritage for conservation and documentation (Tokarczyk & Kwiatek, 2015). However, the most important application for this thesis is its topography reconstruction and mapping.

Workflow is Agisoft is not divided into bigger steps, but rather each process is run separately (Agisoft PhotoScan, 2017). First, after photos are imported into software, it is advantageous to exclude images that have bad quality. Build-in feature estimates the quality of the pictures and suggests the user to delete images that have this parameter lower than 0.5. The value of the parameter is calculated based on the sharpness level of the most focused part of the picture. Later, photos are aligned based on selected options (Figure 21).

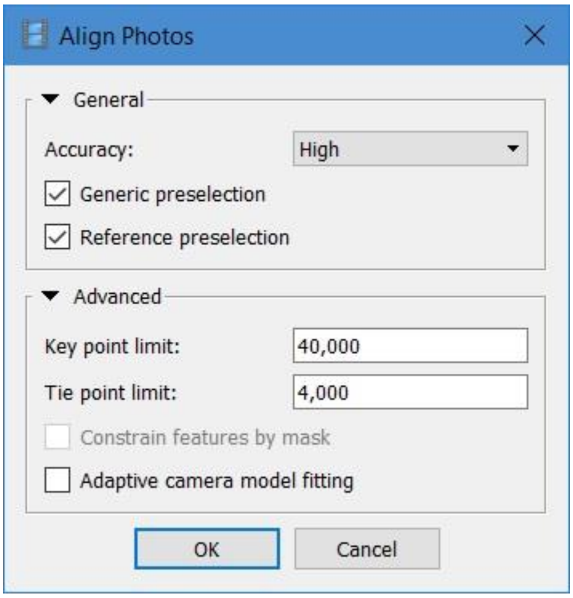

Figure 21 Parameters of aligning photos in Agisoft PhotoScan.

The accuracy of alignment influences scale of photos that is used when key points are extracted. The higher the scale, the better the accuracy, but also more time is needed for computations. Lower accuracy can be applied to obtain rough camera positions in shorter period of time if needed. Processing can be accelerated by using geolocation of images when Reference preselection is chosen, then the software will use coordinates of photos and angles yaw, pitch roll to find overlapping pairs of photos and extract information. When Generic preselection is checked, software will match photos on lower accuracy first to get the subset of photos corresponding to each other and then extract points based on general matches. It is also possible to limit the number of key points and tie points per image by selecting the particular figure or even set no limit (set 0 as an input) but it may lead to generate a big number of unreliable points. Changing these parameters requires deeper knowledge of a dataset and algorithm itself. Constraining features by mask means that the software will only take the areas on the photos that are of interest. It can be used when processed object is not stationary or user wants to exclude a background from computations. Using a mask requires importing it from external source or generating it in the software.

On sparse point cloud consisted of tie points, the most common step would be to generate dense point cloud. Before running the process, GCP should be imported into the project and marked in the images. When the geolocation of the photos is known, GCP are projected automatically in them. This projection is approximate, regarding the fact that accuracy of the images is not high enough and markers should be refined manually. However, what is important is that pictures and markers should be in the same coordinate system. If not, it is possible to transform one of them or both to appropriate system. Filtering the photos by markers speeds up the process because it shows only the images that the marker is located on.

Based on previously estimated or imported camera positions and parameters, the software calculates depth information for each camera and builds dense point cloud. The quality parameter is responsible for how detailed and accurate the geometry of point cloud will be. It refers to settings of accuracy of aligning photos described above. Depth filtering modes are: mild – for not excluding small, distinguishable details, aggressive – to sort out outliers, moderate – between both of them or disabled – not recommended. Finally, in Agisoft it is possible to create such outputs like:

- Mesh
- Texture
- Tiled Model
- DEM
- Orthomosaic

2.3.3. Other software

Postprocessing of tacheometric data was accomplished in C-GEO software developed by Polish company Softline Plus. Processing in the program is divided into separate modules. Each allows user to perform calculations from classical land surveying such as transformations, volume calculations, leveling, precise leveling and GNSS computations. Another advantage of the software is possibility of traversing adjustment with Least Square Method and acquiring plane coordinates and heights with their errors, which was used as the main application for this thesis. It is also compatible with most of the commonly used file extensions including AutoCAD *.dxf, ESRI *.shp or Leica *.gsi. What is more, after each process report can be generated with all necessary information like coordinates, accuracies and statistics.

Data captured in Topcon laser scanner GLS1000 can be easily handled in a dedicated software – ScanMaster. It enables a user to remote-control a scanner while conducting measurements and later post-process it. The most important feature is possibility to register point clouds captured from different stations. Based on common points – targets and their coordinates, the software fits scans together, computes translation and rotation of the whole scene and places it in a global coordinate system. Other tools that are available in software let the user perform angle and distance measurements, volume calculations, draw cross sections and extract features.

CloudCompare is an open-source and free point cloud processing software started in 2003 by Daniel Girardeau-Montaut. Initially, it was designed to compare and detect changes in 3D data. Afterward, it evolved into more generic processing project that allows the user to handle comprehensive tasks, such as:

- Registration
- Resampling
- Statistics computation
- Interactive and automatic segmentation
- And others

Litchi was used for flying one of the missions with pre-programmed waypoints. It is commercial application dedicated for DJI drones, with relatively low price. The software allows performing fully autonomous flights in many different modes such as tracking or orbiting around any object but also flying in strips for photogrammetric purposes. Ground Station editor supports also cable cams, selfies, 360° horizontal and spherical panoramas with real time. One of the advantages is automatic synchronization flight log files with online account, so the user can obtain drone positions just after the flight is finished.

3. PRACTICAL PART

3.1. DATA ACQUISITION

In this chapter, all issues concerning field data acquisition were taken care of. Area of interest is briefly characterized. Justification of chosen equipment and coordinate system is presented. Later, a step by step description of conducted fieldwork is given with the main emphasis on performed UAV flights.

3.1.1. Site characteristics

The measurements have been performed in an urban area on Dragvoll, which is one of the campuses of Norwegian University of Science and Technology. It is located in Trondheim, middle Norway (63.407157°N, 10.471235°E, datum WGS84, Figure 22). The site covers approximately 2 ha. The purpose of choosing the site was to fly over a road that is not too long in order to be able to perform several flights in a short time. Another determinant was presence of a building that could be scanned with a laser scanner and compared to its model obtained from photogrammetry. These requirements were met and even though Dragvoll sometimes can be a very crowdy area, it was overcome by flying late in the evening or during the weekend.

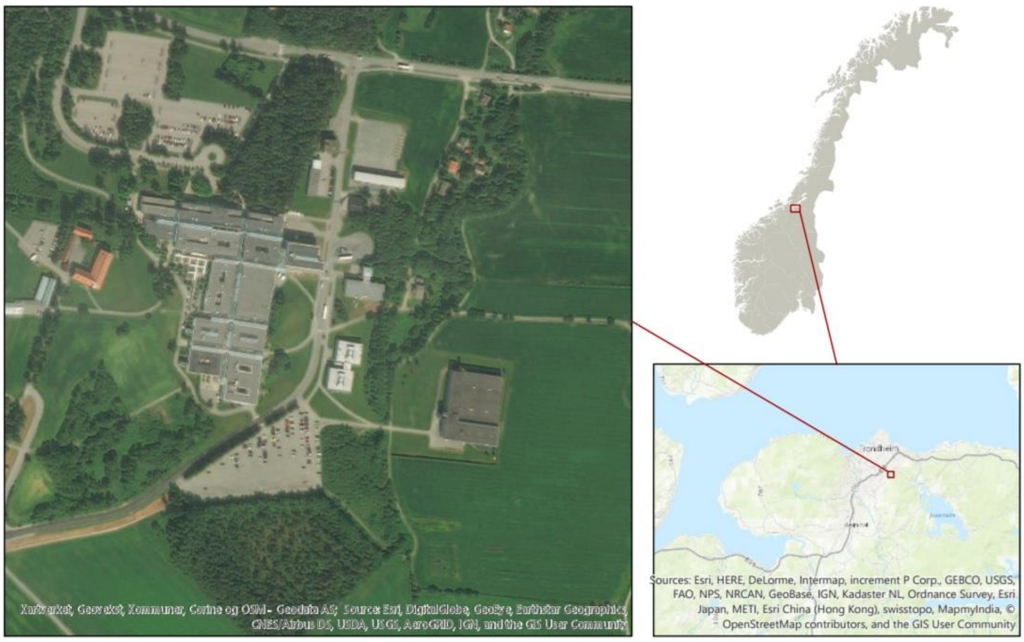

Figure 22 Localization of a studied site.

3.1.2. Equipment

Use of equipment was determined by its availability and suitability for a particular task. For traversing, Leica Viva GNSS receiver GS15 and total station TPS1200+ were adopted (Figure 23).

Figure 23 Total station (left), GNSS receiver (middle) and laser scanner (right) used in measurements.

The total station provides high accuracy of distance and angular measurements with different survey types like Automatic Tracking Recognition (ATR), Reflectorless Measurements (RL) or PowerSearch (PS) that make work easier. According to the manufacturer (Leica Geosystems, 2008), standard deviations of horizontal and vertical angles are 3^{cc} (Table 1) and 1 mm + 1.5 ppm for distances in standard Electronic Distance Measuring (EDM) mode (Table 2). The total station was used together with 360° prism.

Type	std. dev. Hz, V, ISO 17123-3		Display least count	
	["]	[mgon]	["]	[mgon]
1201+	1	0.3	0.1	0.1
1202+	2	0.6	0.1	0.1
1203+	3	1.0	0.1	0.5
1205+	5	1.5	0.1	0.5

Table 1 Accuracy of angular measurements with total station TPS series. Source: (Leica Geosystems, 2008).

EDM measuring mode	std. dev. ISO 17123-4, standard prism	std. dev. ISO 17123-4, tape	Measurement time, typical [s]
Standard	1 mm + 1.5 ppm	5 mm + 2 ppm	2.4
Fast	3 mm + 1.5 ppm	5 mm + 2 ppm	0.8
Tracking	3 mm + 1.5 ppm	5 mm + 2 ppm	< 0.15
Averaging	1 mm + 1.5 ppm	5 mm + 2 ppm	-

Table 2 Accuracy of distance measurements with total station TPS series. Source: (Leica Geosystems, 2008).

The accuracy of position determination by GNSS receiver is dependent on various factors including constellation geometry, observation time, number of satellites being tracked, multipath, resolved ambiguities and ephemeris accuracy (Leica Geosystems, 2012). It also varies with survey method that is applied. For differential phase observations in Real Time Kinematics mode, the accuracy is 10 mm + 1 ppm in horizontal coordinates and 20 mm + 1 ppm in height (Table 3).

Static		Kinematic	
Horizontal	Vertical	Horizontal	Vertical
5 mm + 0.5 ppm	10 mm + 0.5 ppm	10 mm + 1 ppm	20 mm + 1 ppm

Table 3 Accuracy of position determination by GNSS receiver Leica GS15. Source: (Leica Geosystems, 2012).

Another instrument that was used for collecting data is laser scanner GLS1000 from Topcon company. Two most widespread types of geodetic laser scanners are pulse-based and phase-based scanners. The former one sends a single pulse or train of pulses to the object and receives it back. As the light speed is well known and the time elapsed between emission and reception is registered, distance can be computed. Integration with high-resolution angular encoder measurements provides the three-dimensional location of a point. On the other hand, a phase-based scanner emits a wave, then receives a reflected one and compares it to the copy of transmitted signal. The shift in phase is proportional to the measured distance. Once it is acquired, coordinates are computed like in pulse-based scanner. There is a significant difference in capabilities of two mentioned scanners. The maximum range of measurement is higher for pulse-based (up to some kilometers) than phase-based devices (up to some hundreds of meters) because time of flight is long enough to be measured by electronic methods. On the other hand, pulse-based scanners capture hundreds or thousands of points per seconds, while phase-based scanners are faster, capturing hundreds of thousands of points per second and they also have higher resolution. Topcon GLS1000 scanner joins both types of technologies to achieve high accuracy and “clean” point cloud without noise. It measures 3000 points per second with maximum range of 330 m. The accuracy is 4 mm at a distance from 1 m to 150 m. The built-in 2-megapixel camera enables adding color information about the scene.

The last equipment used in this thesis was UAV Phantom 3 Advanced (Figure 24). It is a quadcopter manufactured by Chinese producer of flying and camera stabilization systems – DJI. Phantom is a small quadcopter that weights 1.3 kg with battery and propellers included. It has a 12.4 megapixel camera with 94° field of view lens. Chosen parameters of the camera and the drone are presented in Table 4. Drone’s main characteristic is its permanent integration with the camera. They cannot be separated, so it is impossible to use a better sensor. The main drawback of this solution is that it is a rolling shutter camera. These devices are considered as low-cost and low-power sensors and that is why they are commonly used in a cheaper equipment like commercial drones. A problem is they distort photographs of moving objects because the pictures are not all exposed at once but row by row with some time elapsed between. The effect is intensified by any vibrations that occur during exposures, so bad weather, especially wind gusts are not desired when flying. Rolling shutter is the main restriction of the sensor in tasks regarding reconstruction of scenes with moving objects (Ait-Aider, et al., 2006). And even if the object is stationary, like terrain, there is still an obstacle because of the UAV that is in motion. Fortunately, latest improvements in used SfM software (Agisoft PhotoScan and Pix4D Mapper) manage to model this effect and achieve satisfying accuracy with rolling shutter cameras (Vautherin, et al., 2016).

Figure 24 Phantom 3 Advanced.

Phantom 3 Advanced

Aircraft	Weight	1280 g
	Max speed	16 m/s
	Satellites Positioning Systems	GPS/GLONASS
	Max Flight Time	About 23 minutes
	Hover Accuracy Range	±0,3 m (with VPS)
Camera	Sensor	1/2,3" CMOS
	Lens	FOV 94°
	Focal Length	20 mm
	Shutter Speed	8-1/8000 s
Gimbal	Stabilization	3-axis (pitch, roll, yaw)
	Pitch Range	-90° to +30°
	Angular Control Accuracy	±0,02°
Battery	Capacity	4480 mAh
	Voltage	15,2 V
	Type	LiPo 4S

Table 4 Chosen parameters of Phantom 3 Advanced.

Phantom 3 Advanced receives signal from both GPS and GLONASS navigation satellite systems. The camera is connected with GNSS receiver, so photos that are taken have already coordinates written in EXIF format. Hence, there is no need to download flight logs to extract information about geolocation of images. Nevertheless, there could be sometimes problems with height coordinate of centers of pictures. Firstly, the information that is stored in EXIF shows altitude Above Ground Level (AGL), so it is not referenced to mean sea level or any other vertical coordinate system. Secondly, height is not measured by GNSS, but it is taken from barometric calculations and from time to time there could be big mistakes (up to several dozen meters), especially when calibration of a drone is not performed before the flight.

The UAV is also equipped with Vision Positioning System, which uses two ultrasound sensors and one camera facing downwards to keep the drone stable over the surface. It helps to hover over one spot steadily together with GNSS receiver. To be able to take images that are not blurred, camera is mounted on gimbal. This device stabilizes it in three axis direction (pitch, yaw and roll). UAV can fly with maximum speed up to 16 m/s and maximum flight time of approximately 23 minutes. It uses 4480 mAh, 15.2 V lithium polymer battery.

3.1.3. Coordinate Reference Systems

In order to compare datasets obtained through different measurement methods, they have to be referenced in space in one, uniform coordinate system. It would not be possible to measure the absolute differences of coordinates if reference system was unknown or missing and only the internal shape or dimensions could be assessed. However, what is crucial for that kind of comparisons is to know how collected data is geolocated in known and relevant coordinate system.

There were several possibilities to choose reference coordinate system both for X, Y coordinates and heights but they had some drawbacks and only one choice remained as the most proper one. One option was to establish new local coordinate system with origin and orientation referring to measured points or object. Nonetheless, it is usually implemented on larger construction sites that will be measured for longer period of time with very precise instruments so it did not find an application for this purpose. The second opportunity was to choose EUREF89 UTM, zone 32 – a regional datum used in Norway from 1994. It is linked to stable part of European continental plate and thus coordinates are not changing in time like it takes place in WGS84. Since it is an official Norwegian datum, its selection would be reasonable if not the fact that it has a relatively high distortion in distance because of a scale factor. It equals 0.9996 on a central meridian and can lead to 4 cm deviation on 100 m length. To avoid these inconveniences, NTM as an official datum was introduced with scale factor 1.0000 on central meridian and zone width of 1°. Henceforth projection error is not higher than 1,1 mm per 100m. This coordinate system is applied to construction sites and was also used for purposes of this thesis.

New vertical datum introduced in Norway in 2011, NN2000 was used as a height reference system. It was implemented because of the fact that Scandinavia is in the process of constant post-glacial uplift. In some places land raises by up to 5 mm per year. Compared to the old vertical datum NN1954, the real heights of benchmarks have changed by more than 30 cm during last 60 years (Kartverket, 2017). NN2000 takes it into consideration and models the uplift. Therefore, its utilization is fully justified.

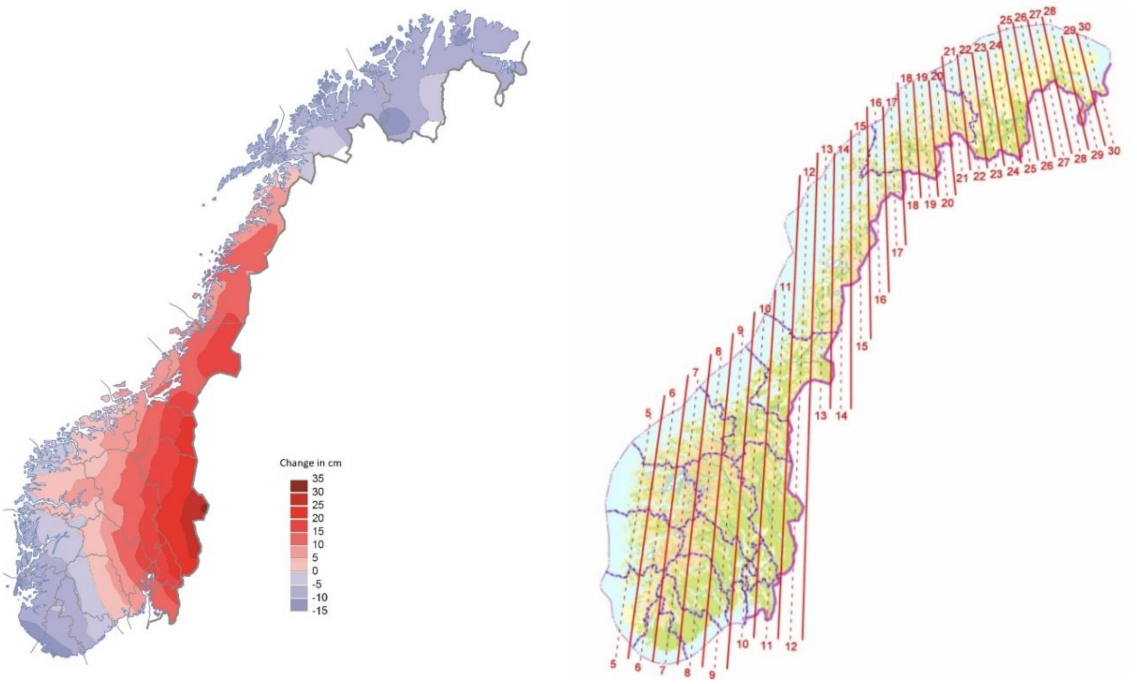

Figure 25 Map f changes in height at transition from NN1954 to NN2000 (left) and map of NTM zones. Source: www.kartverket.no

3.1.4. Fieldwork

Fieldwork consisted of three separate parts, each being a unique measurement technique, requiring dedicated equipment and producing different datasets. Firstly, control points which were used as stations for laser scanner were measured by traditional total station traversing. Secondly, laser scanning of a chosen building has been done, which would serve as reference model for comparison. Finally, numerous UAV flights were performed with different altitude, overlap and flight speed, so the best parameters could be emerged.

After general reconnaissance in field, it was decided that at least 6 points for laser scanner stations are needed to cover each part the scanned building. 4 of them in the corners of the building and 2 in the middle of longer sides because of a niche that could not be seen from the corners. Additionally, 2 points were added to enable scanning the whole road and 2 more were chosen at both ends as reference points. Together 10 control points in traverse had to be measured with high precision in a suitable coordinates reference system. In a first step, Ground Control Points and Check Points were also prepared, marked and measured at once during that process to save time and effort.

In order to ensure a correct scale of measured distances between points and thus acquire highest possible accuracy, GNSS measurements were combined with classical methods. Angles and distances were observed from each control point to other visible points to provide sufficient density of a network. Measurements were done both in face left and face right to remove the effect of systematic instrumental errors. To tie the observations to reference coordinate system, 2 points at each end of the traverse were measured with RTK GNSS method by Leica GS15 receiver as a rover. No additional receiver was needed as a base station because it was possible to work in a Leica SmartNet network, where corrections are downloaded in real time from closest permanently working stations. These are distributed over the whole country with maximum distance of 70 km to ensure proper coverage of observations. Corrections were streamed by Ntrip protocol (Networked Transport of RTCM via Internet Protocol) with an update rate of 1s intervals. Points were measured with 30 epochs duration and twice with few hours' time span to be sure that constellation of satellites changes and will not affect the results. All of the data has been stored digitally on a compact flash card so that it could be later imported directly to the processing software.

Laser scanning was accomplished with Topcon GLS1000. The goal was to acquire point cloud covering chosen building and a road. The rest of a landscape was not intended to be scanned very precisely and thus the coverage in that areas is not expected to be high. There were 8 stations from which measurements were performed. Measuring in GLS1000 is divided into two parts. The first one is target scanning to obtain information about points that will be used to join scans from different stations and to locate point cloud in a reference system. The second is 3D scanning to collect 3D data of a scanned object. The equipment recognizes only dedicated targets and only four were available so it was not possible to evenly spread them over the area of interest. Instead of this, targets were placed on points with known coordinates so that additional information about their position was provided. The scanner was mounted on a tripod above previously measured traverse points and its height was measured. After creating a project, a station was set up and measurements could be conducted. First, targets were scanned one after another and stored as separate files. Then 3D measurements of an area could be accomplished. The scanner does not enable to perform scanning of a whole 360° scene at once but rather choose an object or area of interest to be scanned, so the upper left and lower right corner were indicated each time. Resolution and distance to object were set in equipment before each scan. Also, pictures were taken to acquire information about colors.

3.1.5. Photogrammetric missions

Planning UAV missions with proper parameters was accomplished in Pix4D Capture, an application on mobile devices that enables to design a photogrammetric flight. In the application, it is possible to choose a mission between several possibilities (Figure 26). There is a *Polygon* mission to plan a project over an arbitrary, irregular area with many vertices, a Grid mission to perform a flight over rectangular field and a *Double Grid* mission to also fly over a rectangle but in both directions. The last options are *Circular Flight* and *Free Flight*.

Figure 26 Possible mission options in Pix4D Capture.

Missions that were to compare different altitudes, overlaps and speed were flown in a *Grid* mode. Their values could be easily fixed in settings menu just by moving the appropriate slider. (Figure 27)

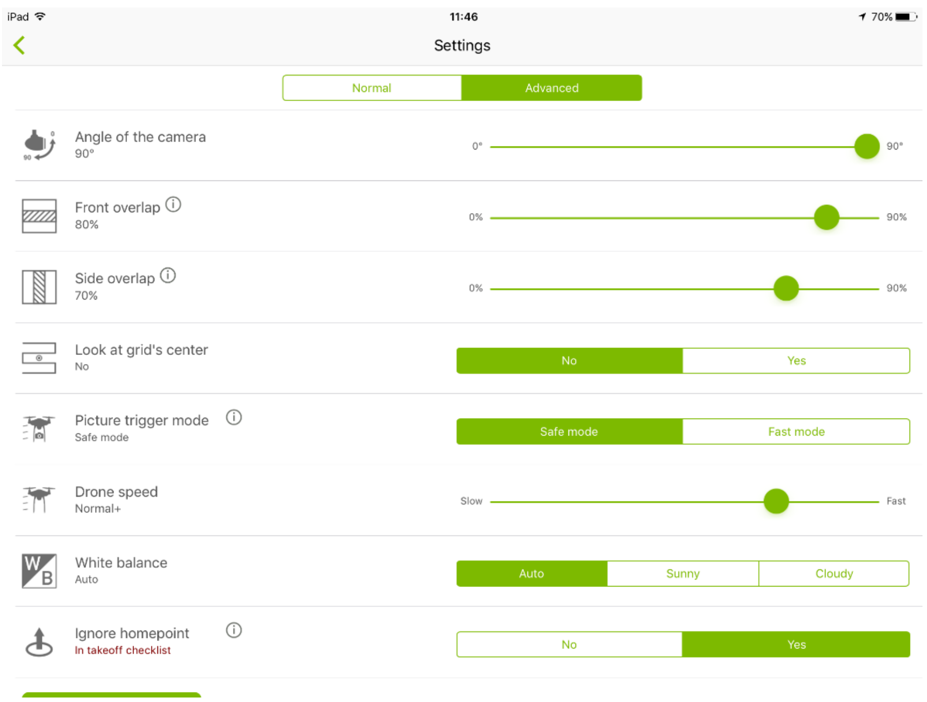

Figure 27 Settings of a new mission in Pix4D Capture.

First, four missions were programmed with 40, 50, 60 and 80 m above the starting point. The other parameters were set to 80% of front overlap, 70% of side overlap, picture trigger mode to *Fast*, which means that the UAV does not stop on a waypoint and takes a picture in flight. Drone speed was set to normal which resulted in approximately 5.2 m/s in all missions. This was also the highest possible velocity of the airborne vehicle with that overlaps and heights settings because otherwise, the aircraft will not manage to save a photo before taking the next one due to the speed of the SD card and its connection with the camera. Secondly, overlap missions were designed with 70x60, 80x70 and 90x80 percentages. Altitude of the missions was chosen to be 40 m as it was regarded as height that provides the best accuracy of a final product among others and it would not alter the results very much. UAV flew with 5.2 m/s speed in two missions with lowest overlaps and 2.6 m/s in the highest one. It could not fly faster because of the factor described above. Therefore, if accuracy of that mission is expected to be the highest, it could not only be because of the fact that these percentages really provide it. What could have an influence is that the pictures were taken at lowest speed so are not that blurred and rolling shutter effect is not so strong.

Since the idea was to compare the parameters in as similar conditions as it was possible, including weather, all *height*-missions were flown one after another during the same day. It was also applied to *overlap*-missions. As a result, there were two missions that were completed with the same parameters, 40 m altitude and 80x70% overlap. Regarding that fact, there was an opportunity to conduct one more analysis of the gathered data. When comparing two sets of photos taken with identical options, it was possible to check how the weather conditions can influence acquired results and if measurements of one area can be repeatable.

Finally, the speed of the drone while taking photos could be checked. Three missions were prepared for this purpose. All of them were at 40 m altitude and with 80x70% overlap. As already described, the highest possible speed that could be chosen was 5.2 m/s. Then, half of this velocity was picked, so 2.6 m/s and eventually a flight with the UAV stopping at each waypoint was planned. The last one was unfortunately impossible to perform with the help of Pix4D Capture application because of some limitations. Phantom 3 Advanced does not support missions that have more than 99 waypoints and since there were about 126 pictures to be taken, the flight had to be separated into two parts. It was then not possible to implement in the application because once a mission is canceled, it must be started from the scratch. It also cannot be divided into sub-missions but only boundaries of an area can be manually changed, so few smaller tasks could be prepared. It was not desired because some parameters could be imbalanced. For this reason, another mobile application was adopted for performing data acquisition – Litchi. It is not a special photogrammetric tool but it was rather designed for steering a drone in different flight modes. One of them automatically leads an aircraft through a set of previously selected waypoints but they had to be calculated in another software. To accomplish this, a code in MATLAB computing environment was written. It was based on the rules introduced in *Flight planning* chapter. After the coordinates of the points of image acquisition were generated in MATLAB, they were divided into two *.csv files with no more than 99 waypoints in each. Then the files could be imported into Litchi Mission Hub and flown one after another.

The number of photos taken for each mission is presented in Table 5.

Height	Photos	Overlap	Photos	Speed	Photos
40 m	126	90x80	360	5 m/s	126
50 m	85	80x70	126	2 m/s	126
60 m	70	70x60	70	stops	124
80 m	44				

Table 5 Number of photos taken in each mission.

Workflow in field of performing the UAV flights was almost the same for every planned task. The only difference was the mission itself and the fact that one lasted longer that another. Before each measurement day, a compass in the UAV was calibrated to ensure safety of flights. It should be done, because the magnetic north is determined by electronic sensors, which have to be calibrated in new place or when long time elapsed since the last calibration to show correct direction, since magnetic north varies in time and space. Also, weather conditions were checked so that for example the wind was not too strong. Phantom 3 can fly up to 16 m/s so theoretically the wind should not be higher than this, but in author's practice and as the producer, DJI company suggests it should not exceed level 4 in Beaufort scale, which is 7.9 m/s. What is more, the lower the speed of wind, the sharper pictures taken and the better photogrammetric parameters of flight realized, so 2-5 m/s was desired. Additionally, kp index was taken care of. It indicates geomagnetic disruption of solar activity from 0 (calm) to 9 (major storm). It affects the position determined by GNSS receivers including the one that is mounted in UAV. Solar activity interferes with GPS signals in two ways, both due to disruptions in the ionosphere. First, it changes the propagation delay through the ionosphere, making GPS positioning inaccurate even if the receiver has all satellites locked. Second, it decreases the signal-to-noise ratio and affects carrier frequency, causing the receiver to lose lock on some satellites. So, for example, instead of 9 satellites, receiver might lock only 6, or the number might fluctuate from second to second (Uavforecast, 2017). Usually, if the index is under 5, it is safe to fly. Other things that one should have in mind were precipitation and temperature. When it is raining or snowing, it is highly unrecommended to fly a UAV, because it may lead to damage of its electronic components and if the temperature is below 0° C, batteries should be kept in warmth before takeoff.

What affects visual aspect of final photogrammetry products is lightning. If it is sunny, objects in the photos will be well visible but there also will be shadows. On the other hand, when the sun is not shining and it is cloudy, the terrain is uniformly exposed but also pale. A compromise between two approaches must be made to capture appropriate images. The first missions with variable height were conducted just before sunset when it was already getting dark and that is why sometimes it is hard to precisely indicate the center of a manhole that was a Check Point what could have an influence on accuracy in some projects. The *overlap*-based images were taken in better weather conditions for a photogrammetric mission. The sky was overcast so the shadows were not present but there was also enough lightning. The third measurement day was chosen so that the sun was shining very bright but was low on the horizon, so influence of these weather conditions could be checked. It resulted in long shadows in the pictures. Examples of the photos are presented in Figure 28.

Figure 28 Difference in lighting on photos.

In general, right, even lighting allows having a small aperture to reduce the image’s depth of field. Shallow depth-of-field is not a desired thing for photogrammetry, because blurred details confuse the software. In order to have high-detail, sharp, and flat imagery, a closing of the aperture is required, which means more light is needed. Good lighting will also allow lowering the ISO which will reduce grain, and will result in having a high shutter speed which reduces motion blur.

Finally, when the mission on 40 m altitude with 80x70% turned out to fit initial assumptions the best, so to provide the highest accuracy, reliability and could be flown on this terrain with the help of only one battery, it was performed once again. This time, in addition to taking normal, horizontal photos in autonomous flying mode, oblique imageries were captured manually around the building that was formerly scanned with the laser scanner. It enabled detailed 3D reconstruction of its shape by photogrammetric methods and compare to the model acquired by terrestrial laser scanning.

3.2. DATA PROCESSING

In this chapter, the workflow of processing the data has been introduced. First, management of measurements from total station and laser scanner is shortly described. The images have been processed in two Structure from Motion software packages. Options used as well as performance of the programs is presented. Finally, the results from all missions are compared in terms of accuracy and effectivity.

3.2.1. Network adjustment

Calculation of coordinates of control points was conducted in C-GEO software. Coordinates of four reference points and their errors were extracted from *.KOF file from RTK measurement by Leica GNSS receiver. They were to be used to tie the whole network to the reference coordinate system. Observations of angles and distances stored in *.GSI file were imported to C-GEO in *Tacheometry* module. They had to be sorted manually into separate stations and exported to *Rigorous 3D traverse and GNSS adjustment*. Based on all measurements and instrumental errors, network has been computed and the points were later used again in *Tacheometry* module to acquire coordinates of GCP and CP. Coordinates of all points are in Table 6 and sketch of the network is in Figure 29.

No.	X	Y	H	mxy	mh
101	1602405.601	98452.426	158.125	0.009	
102	1602457.472	98518.194	159.356	0.010	
103	1602465.049	98563.002	158.780	0.009	0.002
104	1602455.042	98617.174	157.284	0.011	0.002
105	1602490.780	98622.422	158.019	0.012	0.003
106	1602528.996	98626.804	158.830	0.012	0.002
107	1602529.679	98586.955	160.446	0.009	0.002
108	1602499.795	98574.228	159.398	0.009	0.002
109	1602592.785	98574.554	160.003	0.010	
110	1602714.985	98600.379	157.840	0.011	
GCP1	1602457.611	98503.284	159.501	0.003	0.003
GCP2	1602432.553	98571.025	158.110	0.002	0.002
GCP3	1602440.039	98605.265	157.088	0.003	0.002
GCP4	1602510.618	98541.663	162.697	0.003	0.002
GCP5	1602547.427	98619.312	160.960	0.002	0.001

GCP6	1602523.889	98578.909	159.552	0.002	0.001
GCP7	1602612.283	98611.823	159.419	0.002	0.002
GCP8	1602601.439	98556.024	161.779	0.002	0.001
CP1	1602449.889	98500.990	159.037	0.003	0.003
CP2	1602456.094	98559.645	158.329	0.002	0.000
CP3	1602529.318	98566.361	159.573	0.003	0.003
CP5	1602486.970	98616.192	158.896	0.002	0.002
CP6	1602492.790	98617.663	158.920	0.002	0.002
CP7	1602531.676	98577.241	159.491	0.002	0.001
CP8	1602535.636	98572.280	159.452	0.002	0.001
CP9	1602503.311	98578.294	158.641	0.002	0.000
CP10	1602590.764	98586.568	159.654	0.002	0.001
CP11	1602595.008	98579.507	159.665	0.002	0.000
CP12	1602605.403	98560.621	161.422	0.002	0.001
CP13	1602608.181	98611.793	159.860	0.002	0.002

Table 6 Coordinates and errors of points measured in the network.

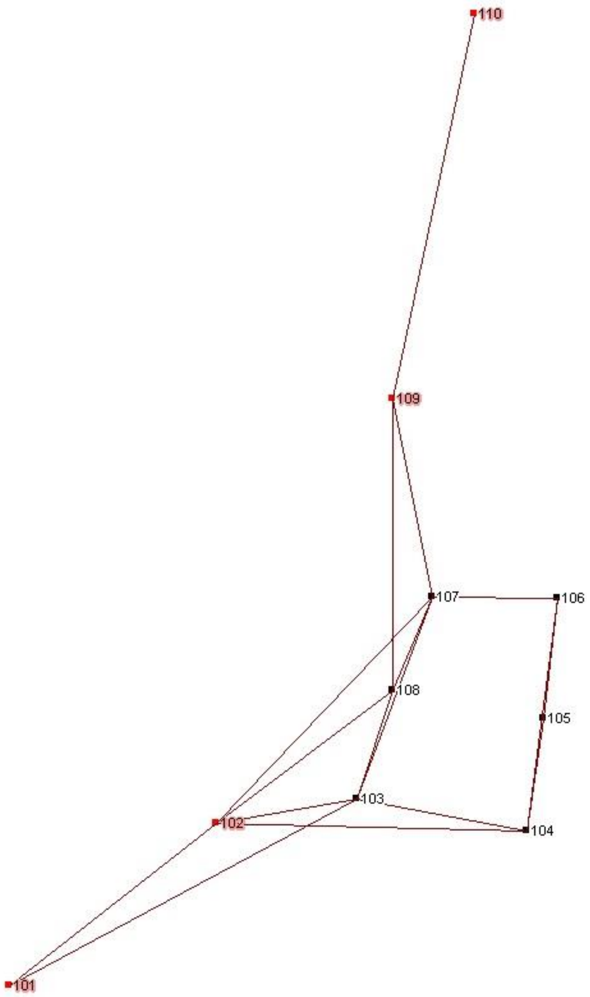

Figure 29 Localization of Control Points in measured network.

3.2.2. Point cloud registration

As previously mentioned Topcon GLS1000 is delivered with dedicated software for controlling the scanner while performing measurements and for post-processing of acquired material. Thus, Topcon ScanMaster was used for handling the scanned 3D data in terms of registration of scan positions, georeferencing it in a chosen coordinate system and creating a point cloud with common file extension. ScanMaster is a comprehensive tool that enables performing advanced analyses on a dataset including drawing cross sections, creating meshes and primitives, measuring angles and distances. However, these tools were not used, but just simple station registration and point cloud generation.

A project created in a scanner has all the data about the measurement arranged in a way that is recognizable by the software. Therefore, after importing the project to ScanMaster, it was already sorted into scan stations. All of them contained 3D scene measurements, target measurements, height of instrument and photos taken. First, it was necessary to create a tie point for each station, so called Backsight (BS), which was one of the targets scanned. Then coordinates of control points were imported and set to the tie points. Also, Occupation (OCC) point was assigned coordinates. Additionally, information about instrument and target height was entered. When all information about station and target connections have been provided, it was possible to run Registration Manager and register the scans (Figure 30).

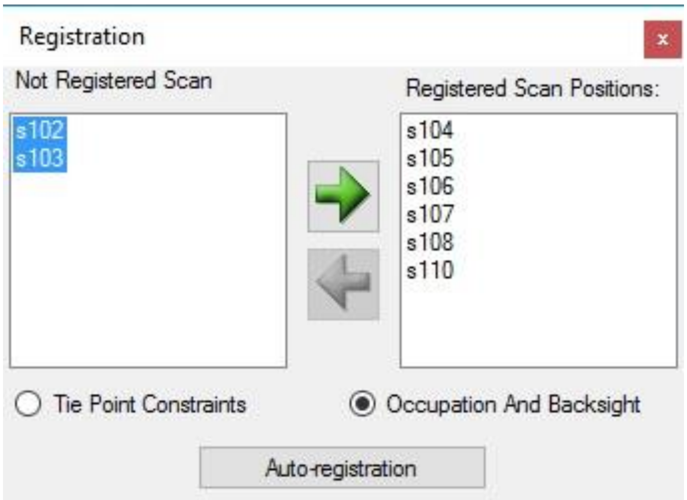

Figure 30 Registration of scan positions in ScanMaster software.

As mentioned before, there were not enough available targets to be able to join scans based on *Tie Point Constraints*. The software requires minimum 3 common points between two separate scanner stations to apply this procedure. As long as there was no visibility between two control points that were adjacent to the control point on the corner of the building (for example between points number 102 and 104), it was demanded that at least 6 targets are scanned from that point (number 103). Since only 4 targets were available it would be too time and effort consuming to constantly move them. That is why a less demanding but still giving reliable results method *Occupation and Backsight* was chosen. After registration of scanner stations, a point cloud of the whole scene was created and exported to *.las file.

3.2.3. Image processing

Photos from all of the missions were processed in both Pix4D and Agisoft Photoscan software. There were different sets of comparisons and the purpose was to select the best parameter that ensures the highest accuracy but also a reliable amount of time spent on capturing and post-processing the data. The first checked parameters were height of flight, overlaps and speed of a drone while taking the photos. Later, when best configuration of settings emerged, a few more projects were processed in the context of number of GCP used and their distribution over the area of interest in order to see how it affects the final accuracy.

Before photos could be processed, there were some preparations of data that must have been done, like creating a project and choosing correct reference coordinate system. In Pix4D after importing photos and reading the EXIF information, datum WGS84 was chosen for geolocation of images and ETRS89 NTM zone 10 as output coordinate system. In Agisoft on the other hand coordinates of photos had to be transformed directly to NTM zone 10, what was accomplished by build-in feature *Convert*. To maintain the greatest possible similarity in processing workflows in both Pix4D and Agisoft and keep the results as consistent as they could be, the options had to be set properly in each step in the programs. The Pix4D's general options in Initial Processing included Keypoints Image Scale which was set to Full meaning that it kept original image size (scale = 1) and the same was for Photoscan's accuracy in aligning photos when the setting was chosen to be High. Although it was possible to upscale this parameter (double image size in Pix4D or Highest accuracy in Photoscan), it would become time-consuming and very sharp image data would be desired for that kind of processing. Matching in Pix4D was chosen as *Aerial Grid or Corridor* and in Agisoft *Generic Preselection* and *Reference Preselection* were checked. The meaning of options was described above in chapter treating of software. The number of key points and tie points was unlimited. Masking the photos in Agisoft was not chosen as well as *Adaptive camera model fitting*. It would automatically select which camera parameters are to be included in adjustment based on their reliability estimates, so it was not desirable, because a fixed set of parameters was preferable, including focal length, coordinates of principal point, three radial distortion coefficients and two tangential distortion coefficients. The same was applied in Pix4D when choosing *Calibration Method* as standard.

After the first step, which was *Initial Processing* or *Align Photos*, it was time to measure GCP and CP. For every project, all eight Ground Control Points were measured and eight out of twelve Check Points were chosen. Not all CP were measured because some of them were too close to each other or hard to identify on the pictures, so their appearance would not contribute anything or even perturb the results, but remaining amount was enough to assess the accuracy properly. Distribution of GCP and CP is presented on a map (Figure 31). They were indicated by the author manually and separately in both software. There was an idea of exporting the markers from one program to another in a common format so that measurements on pictures would not influence acquired results. Though it was possible to export them from Pix4D to *.xml file, the plan was not realized, because there was no direct way to do the same it Agisoft Photoscan. The software gives an opportunity to write own scripts in Python language and implement them in the programming environment but author decided that for the purpose of the thesis he will do his best when measuring manually and leave programming part as opportunity for further potential improvements. The accuracy of imported Ground Control Points and Check Points was to set 0.020 m and not to the one acquired from adjustment. It was so, because of the fact that accuracy generated in C-GEO was very high but relatively to the points that were taken as reference. What is more, the targets marked on the ground were squares with 15 cm side and on some pictures it was not possible to clearly identify the middle of it. Therefore, to obtain more reliable results, errors on GCP were chosen to be 2 cm.

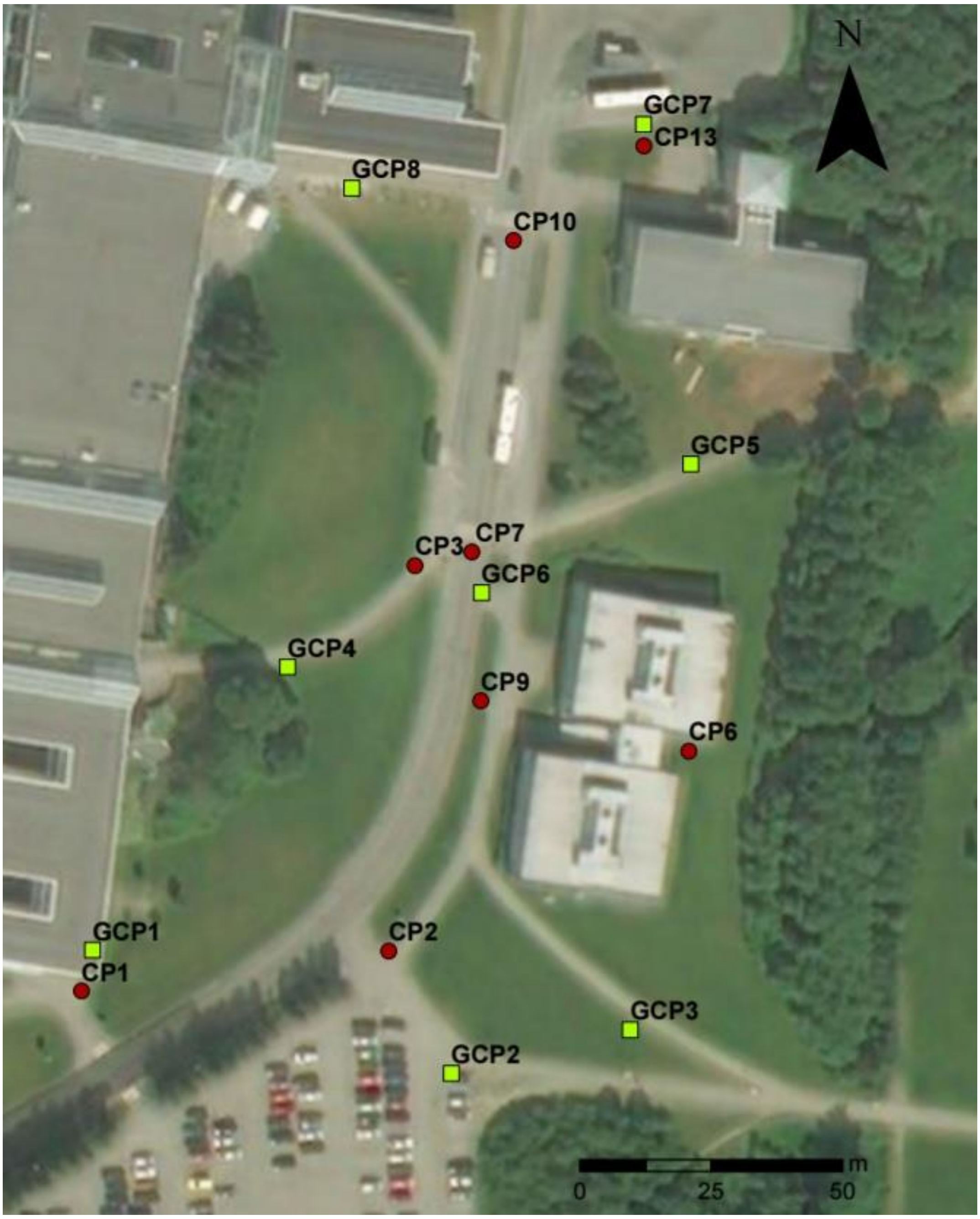

Figure 31 Localization of GCP and CP over an area of interest.

When the points were measured on all of the photos, an optimization procedure based on Ground Control Points only was run to refine internal and external camera parameters. It computes bundle block adjustment once again but uses only previously chosen GCP which are very accurate compared to geolocation of images. Whether a high error was present at any point, it was checked and remeasured if needed. Finally, quality report was generated with information such as project summary, camera calibration details, accuracy of Ground Control Points and Check Points and other processing options.

The last, final mission with 40 m altitude and 80x70% overlap was processed together with oblique photos in order to get full 3D model of the building. Both software packages had difficulties with automatic aligning some of the oblique images. Pix4D could not match pictures of south wall of the building and Agisoft had problems with eastern part. There were strong sun lights that were shining from west, because the sun was going down and taken photos were overexposed what could be the reason. Therefore, the images had to be calibrated manually. This process requires additional measurements in the photos. Manual tie points (MTP) were indicated on all uncalibrated cameras and also on some calibrated ones to join them together. When at least four points were measured on each uncalibrated photo, the calibration and optimization process were run once again with success. After image alignment, point cloud was built with half of image size scale for densification. It is an optimal setting, because it usually generates point cloud with sufficient coverage and not too redundant. Point clouds were later exported to *.las files and compared to dataset acquired from terrestrial laser scanning.

3.2.4. Influence of parameters

A sensor mounted in Phantom 3 Advanced is a rolling shutter camera. As previously mentioned, it is a cheaper equivalent of a global shutter camera but the price has to be paid in quality of photos. They are taken row by row with a time delay, so not all parts of the image of the scene are recorded at exactly the same instant. This produces some distortions, especially when capturing fast-moving objects. When high accuracy of a 3D reconstruction is to be acquired, the effect of a rolling shutter should be modeled. In February 2016, such an option has been added to in Pix4D Mapper 2.1 and since October the same year, this process could be accomplished in Agisoft Photoscan 1.3.

In Table 7 and Table 8, there are results from flight at 40 m altitude with 80x70% overlap processed in two software packages with and without modeling rolling shutter effect. The flight was performed at 5.2 m/s speed and the same manual measurements were used in both projects. The only difference was if the mentioned rolling shutter was taken into account or not. In Table 7, it can be seen that all parameters are comparable except one, which is XYZ RMSE on Ground Control Points. The error without modeling rolling shutter is in two programs about 14 cm, so they both adjusted 3D model equally on GCP and both did it not very accurate. However, when rolling shutter option was used, RMSE reduced significantly in Pix4D to about 1 cm, while in Photoscan only to 8 cm.

Software	Pix4D				Agisoft Photoscan			
Mission	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]
without rs	1,60	140,9	0,789	0,777	1,79	138,7	0,590	0,709
with rs	1,60	11,1	0,683	0,736	1,80	80,5	0,526	0,652

Table 7 Results from flight on 40 m with 80x70% overlap with and without modelling rolling shutter.

Errors on Control Points follow the same pattern as those on GCP. They are decreasing when rolling shutter is modeled. Here also Pix4D provides higher accuracy than Agisoft and lowers the errors by more than the factor of two when the effect is not modeled. Therefore, the conclusion can be drawn that Pix4D Mapper significantly better handles modeling the effect. On the other hand, Agisoft provides more reliable results without taking into consideration rolling shutter, what is also stated by other authors, including (Sona, et al., 2014).

Software	Pix4D				Agisoft Photoscan			
Mission	X [mm]	Y [mm]	Z [mm]	XYZ [mm]	X [mm]	Y [mm]	Z [mm]	XYZ [mm]
without rs	82,3	67,4	72,6	**128,8**	82,6	46,8	41,3	**103,5**
with rs	19,9	40,4	23,0	**50,6**	60,2	35,0	30,6	**76,1**

Table 8 RMSE on CP from flight on 40 m with 80x70% overlap with and without modelling rolling shutter.

General information about height missions is presented in Table 9. It can be seen that Ground Sampling Distance (GSD) is increasing with the height which confirms a well-known photogrammetric rule: the higher the altitude of the flight, the bigger the GSD value. However, it is worth noting that GSD is better by more than 0.2 cm/pix in Pix4D for every project. It can be because of in-software algorithms that are implemented. There is also a significant difference of final accuracy on all 3 XYZ coordinates of GCP between the programs. Pix4D fits the model better on Ground Control Points than Agisoft even by the factor of 7 (11.1 mm compared to 80.5 mm in 40 m altitude flight). This could be due to the fact that these missions were performed without stopping on waypoints but in constant movement and rolling shutter had to be modeled. It is clearly seen that Pix4D resolves it better and the error is in general increasing with the height. On the other hand, in Agisoft it is on constant level of about 8 cm and decreases on 80 m to about 5 cm. It may be also a consequence of a rolling shutter camera and the fact that the effect reduces on higher altitude as (Candiago, et al., 2015) reports. Projection errors on both Ground Control Points and Check Points are not higher than 0.8 pix what means that measurements were accurate enough.

Software		Pix4D				Agisoft Photoscan			
Mission		GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]
height	40	1,60	11,1	0,683	0,736	1,80	80,5	0,526	0,652
	50	1,98	15,6	0,728	0,771	2,23	78,1	0,439	0,572
	60	2,36	12,5	0,637	0,712	2,67	81,6	0,522	0,708
	80	3,14	18,4	0,792	0,533	3,54	53,7	0,506	0,581

Table 9 Results from flights on various heights.

Root mean square errors on Check Points for height missions of each coordinate separately and XYZ together are showed in Table 10. At the beginning, worth noting is the fact that stripes in which the missions were flown are more or less along meridians, so Y error automatically represents an error in direction of flight and could be expected to be higher than X error because of UAV speed and rolling shutter effect. This is confirmed by Pix4D results, when RMSE of Y coordinates is 2-3 times bigger than RMSE of X. The outcome X and Y RMSE from Agisoft do not seem to concur with this remark and have a more random behavior. They are also higher than the ones generated by Pix4D. The same applies to Z RMSE which is sometimes two times worse in Agisoft. All these result in final location RMSE that is better in Pix4D, starting from 5 cm on 40 m and rising to about 7 cm on other altitudes, so there is no big difference between 50, 60, and 80 m flight heights. On the other hand, in Agisoft Root Mean Square Error on XYZ coordinates ranges from about 7 cm on the lowest altitude to 12 cm on 50 and 60 m and up to 14 cm on 80 m. Two main conclusions can be drawn from this observation. First Pix4D better handles the dataset and provides more reliable results without accidental discrepancies. Second, a general rule can be formulated that accuracy decreases with higher altitude.

Software		Pix4D				Agisoft Photoscan			
Mission		X [mm]	Y [mm]	Z [mm]	XYZ [mm]	X [mm]	Y [mm]	Z [mm]	XYZ [mm]
height	40	19,9	40,4	23,0	**50,6**	60,2	35,0	30,6	**76,1**
	50	18,1	60,2	38,5	**73,7**	67,9	71,2	76,8	**124,8**

	60	20,8	60,3	34,9	**72,7**	59,7	79,7	79,3	**127,3**
	80	24,5	42,4	54,5	**73,3**	63,8	50,8	115,7	**141,6**

Table 10 RMSE on CP from flights on various heights.

Results from comparison of different overlap percentages are displayed in Table 11. They were flown on 40 m altitude and therefore can be contrasted with the mission done before on the same height. As previously, GSD is around 1.6 pix/cm in Pix4D and 0.2 pix/cm higher in Agisoft. RMSE on GCP in Pix4D is around 2 cm which is very satisfying compared to results from Agisoft where it is about 10 cm in 70x60% and 80x70%. It is thought-provoking why the GCP error of mission with 90x80% overlap in Agisoft has such a big value. The cause lies in Ground Control Point number 1, which has a 30 cm error on X coordinate. It has been re-measured several times and examined for any other potential blunders but nothing was found. Nevertheless, even if the point is not taken into bundle block adjustment, the overall accuracy is 12.9 cm, so there is an improvement but not very significant. For the purpose of the thesis, it was decided that the point will remain in computations. Measurements on the images are better than in the previous set of missions, probably due to the lightning and the fact that overlap missions were flown in preferable weather conditions like clear sky and not as in height missions when the sun was already going down and it was getting dark.

Software		Pix4D				Agisoft Photoscan			
Mission		GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]
overlap	70x60	1,67	24,5	0,539	0,650	1,90	98,8	0,332	0,449
	80x70	1,66	16,6	0,563	0,526	1,88	116,3	0,513	0,517
	90x80	1,64	18,3	0,573	0,418	1,85	160,5	0,539	0,667

Table 11 Results from flights with various overlaps.

All overlap settings in Pix4D show RMSE not higher than 4 cm. In Photoscan, there is the same outlier for CP as it was for GCP, the 90x80% overlap mission has significantly greater RMSE value than the other flights. It is due to the Control Point 1 which is located nearby GCP1 and has an error of almost 40 cm. When it would be excluded from computations, RMSE would be 13.9 cm what would be consistent with the rest of the missions from Agisoft. It is confirmed again that Pix4D provides better results than Photoscan. However, the errors of different percentage overlap projects in the same software are very similar to each other. This fact implies that overlap setting do not have an influence on accuracy if they are high enough.

It is not worth flying with very highly overlying images, because it is a waste of time spent on acquiring the data and later postprocessing it. Authors of (Mesas-Carrascosa, et al., 2016) stated the opposite when evaluating this parameter and proved a high importance of overlapping the images in UAV projects. However, they checked 70x40% and 60x30% settings, so their side overlaps were very distant from those applied in this thesis, what could be a reason.

Software		Pix4D				Agisoft Photoscan			
Mission		X [mm]	Y [mm]	Z [mm]	XYZ [mm]	X [mm]	Y [mm]	Z [mm]	XYZ [mm]
overlap	70x60	19,6	24,5	23,4	**39,1**	91,5	54,1	29,2	**110,2**
	80x70	13,3	18,9	25,5	**34,4**	112,2	69,8	43,8	**139,2**
	90x80	15,1	21,0	27,0	**37,4**	153,3	105,8	49,8	**192,8**

Table 12 RMSE on CP from flights with various overlaps.

The last checked parameter was speed of the UAV while flying and taking photos. The main assumption while examining any of the parameters was to perform the missions during one day due to maintaining the same influence of weather conditions. Unfortunately, this could not be accomplished for the speed-missions case, because there were some problems with one of the batteries during that measurement day and only two flights were performed, first one with 2.6 m/s speed and second one with stopping on waypoints. Outcomes for 5.2 m/s speed had to be copied from 40 m height mission. Projects “in motion” were processed with rolling shutter effect taken into consideration, while for “stationary” mission it was neglected.

The results are consistent with the previous ones when it comes to GSD and projection accuracy. What is worth noting is the fact that RMSE on GCP is decreasing with lower speed, so 1 cm on 5.2 m/s becomes 2 cm on 2.6 m/s in Pix4D and 8 cm and 9 cm respectively for Agisoft. This could be due to fact that that rolling shutter is best modeled at medium to high speeds, while its influence at low speed is smaller, as reported in (Vautherin, et al., 2016) and it is harder to model it correctly. Interesting phenomenon are higher RMSE on GCP when the drone was stopping on waypoints. They are slightly worse than errors when the aircraft was in motion. The question should be asked if modeling rolling shutter effect does not distort results for its favor. Comparing to global shutter camera could probably give an answer.

Software	Pix4D				Agisoft Photoscan			
Mission	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]

speed	5mps	1,60	11,1	0,683	0,736	1,80	80,5	0,526	0,652
	2mps	1,67	22,1	0,752	0,649	1,89	92,0	0,408	0,515
	stops	1,61	42,2	0,455	0,457	1,81	111,6	0,441	0,475

Table 13 Results from flights with various speed.

The accuracy of Check Points is not that coherent among different speeds and it is hard to present one general rule, because results do not fall into any specific pattern. The speed of a UAV does not seem to have an influence on final accuracy, when rolling shutter is taken into consideration. However, in this case, Pix4D again produces better results which range from 3 to 5 cm, while RMSE in Agisoft is up to 11 cm.

Software		Pix4D				Agisoft Photoscan			
Mission		X [mm]	Y [mm]	Z [mm]	XYZ [mm]	X [mm]	Y [mm]	Z [mm]	XYZ [mm]
speed	5.2 mps	19,9	40,4	23,0	**50,6**	60,2	35,0	30,6	**76,1**
	2.6 mps	20,0	15,1	20,8	**32,3**	91,1	57,9	30,2	**112,1**
	stops	35,1	20,9	22,0	**46,4**	63,9	53,5	45,0	**94,7**

Table 14 RMSE on CP from flights with various speed.

Furthermore, because of the fact that two projects with the same options were flown when comparing altitude and overlap parameters and third, final mission with the same, most preferred settings was performed, it was possible to check if accuracy acquired from UAV photogrammetry is repeatable. The missions were conducted on 40 m altitude with 80x70% overlap. Results are presented in Table 15 and Table 16.

Software	Pix4D				Agisoft Photoscan			
Mission	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]
height	1,60	11,1	0,683	0,736	1,80	80,5	0,526	0,652
overlap	1,66	16,6	0,563	0,526	1,88	116,3	0,513	0,517
final	1,70	18,2	0,691	0,533	1,91	78,2	0,364	0,398

Table 15 Results from flights with the same parameters completed in different days.

It can be seen that accuracy is very similar in all three projects when it comes to results from Pix4D. The difference of RMSE on X and Z coordinates do not exceed 1 cm and on Y coordinate it is about 2 cm. It proves that UAV-based measurements can be repeated and the achieved accuracy will be consistent. On the other hand, results from Agisoft present more random behavior. Errors on particular coordinates show irregular distribution but it cannot be noticed if one of the missions has any blunders, because values are not outlying. The difference in RMSE reaches 6 cm, so it is higher than final errors from Pix4D. Therefore, it is not so straightforward to state if it is possible to obtain the same accuracy each time when using this software.

Software	Pix4D				Agisoft Photoscan			
Mission	X [mm]	Y [mm]	Z [mm]	XYZ [mm]	X [mm]	Y [mm]	Z [mm]	XYZ [mm]
height	19,9	40,4	23,0	**50,6**	60,2	35,0	30,6	**76,1**
overlap	13,3	18,9	25,5	**34,4**	112,2	69,8	43,8	**139,2**
final	19,3	30,8	23,5	**43,3**	71,2	34,5	57,4	**97,7**

Table 16 RMSE on CP from flights with the same parameters completed in different days.

Finally, the number and distribution of Ground Control Points have been assessed. The *final* project was used for this purpose. Four different configurations were checked and the fifth one with all GCP as a reference set was taken. Each time the same manual measurements of GCP and CP were used so that it would not affect the results. Additionally, in every project, all of the CP took part in computations so the whole area was covered with points and checked. Projects were processed both in Pix4D and Agisoft. The map in Figure 32 shows placement of Ground Control Points in the terrain.

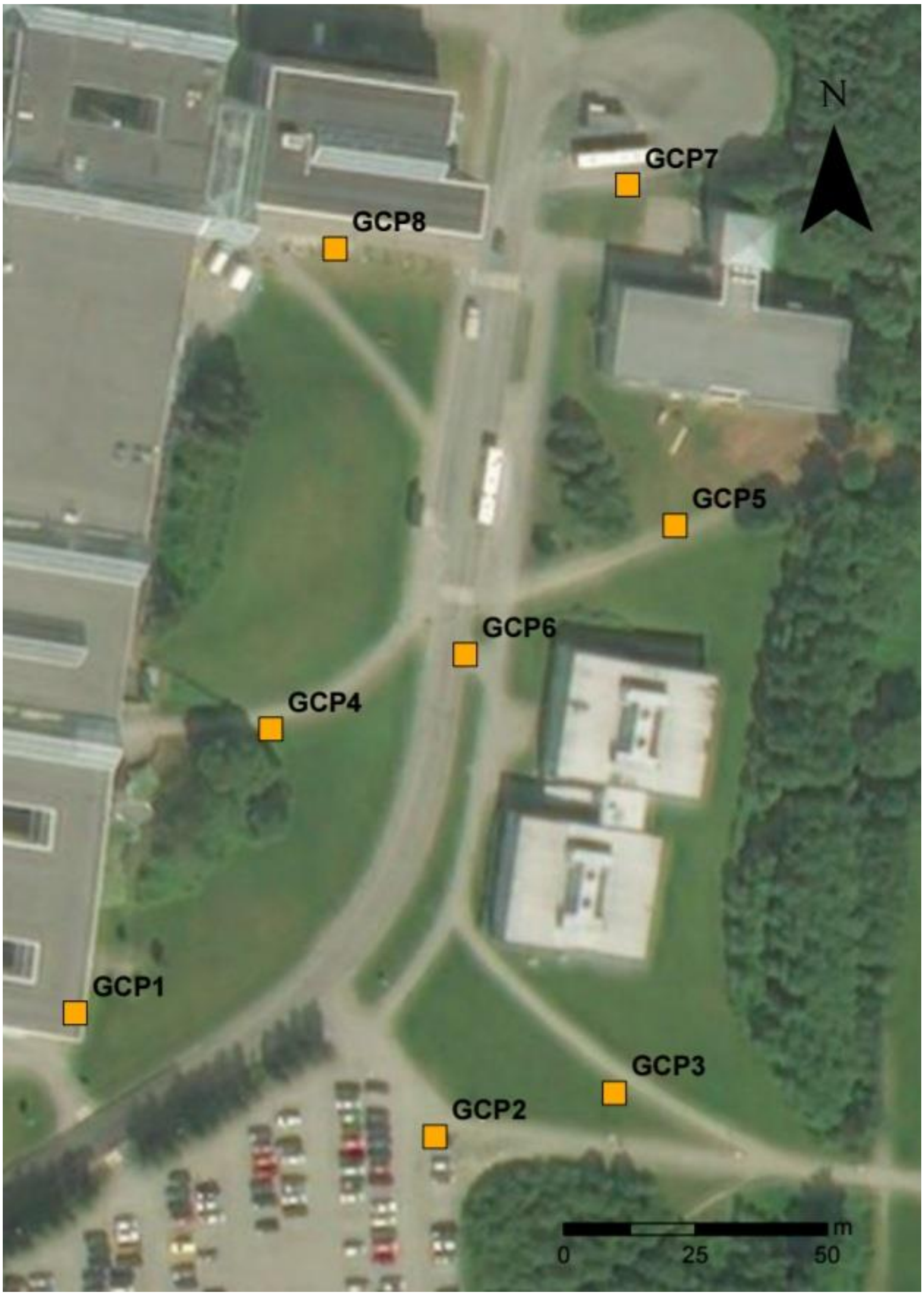

Figure 32 Localization of GCP over the area of interest.

In the first project with all GCP, the points are spread evenly over each part of mapped area. It is expected to provide the highest accuracy but takes most of the time to measure both during fieldwork and in postprocessing. The next mission excluded points number 2 and 6 from the middle part of the site and left six points only on sides. Later, a project with one point in the center of area and four on the edges was prepared. Then, the last two configurations checked performance of four points only. The first one with GCP located more or less in corners of area and the second with GCP in the middle of sides. Figure 33 presents the distribution of Ground Control Points.

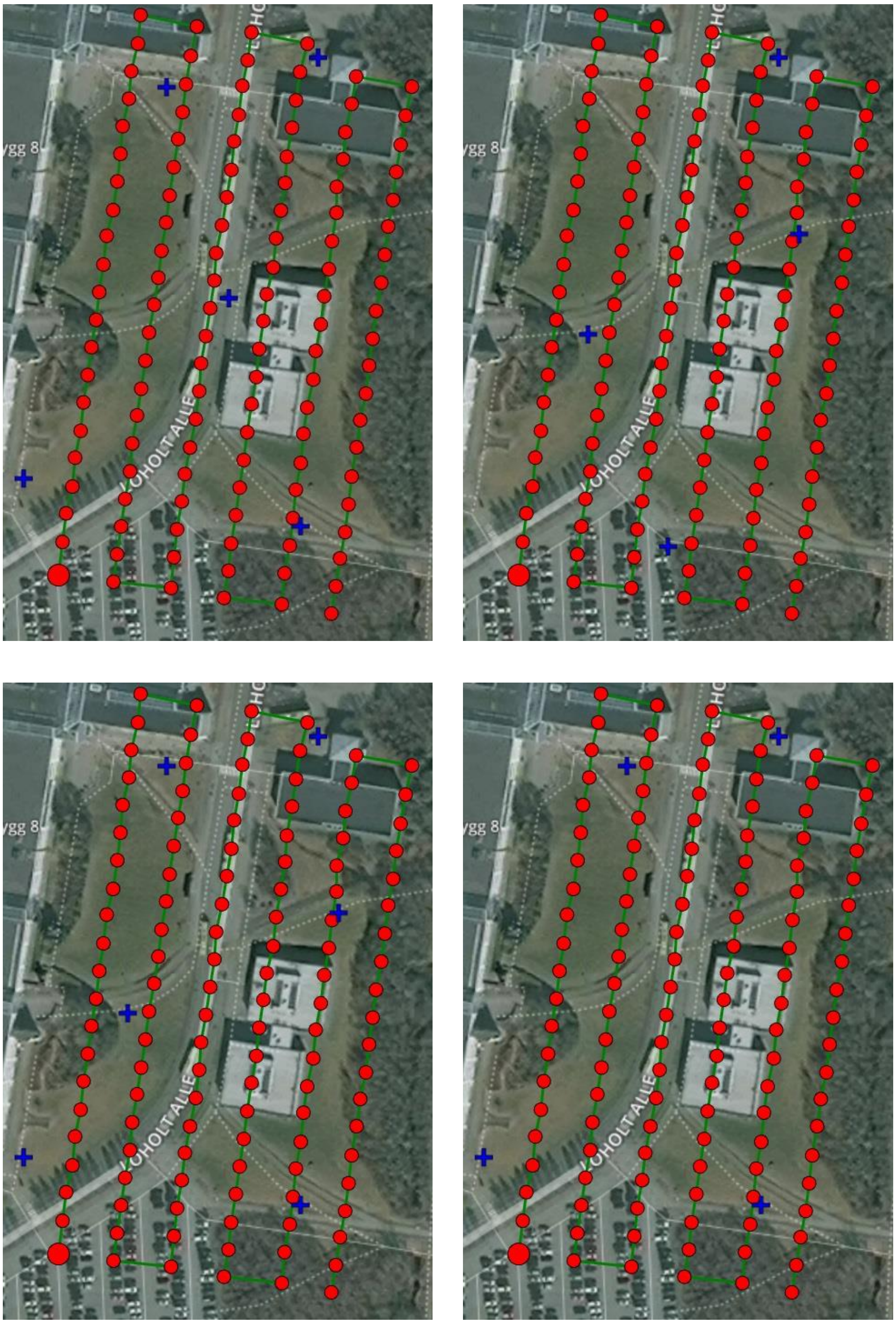

Figure 33 Distribution of GCP in tested configurations.

Software	Pix4D				Agisoft Photoscan			
GCP	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]	GSD [cm/pix]	GCP XYZ [mm]	GCP proj. [pix]	CP proj. [pix]
all	1,70	18,2	0,691	0,533	1,91	78,2	0,364	0,398
1 3 4 5 7 8	1,70	10,5	0,658	0,541	1,92	85,4	0,356	0,389
1 3 6 7 8	1,70	5,8	0,611	0,545	1,91	54,5	0,329	0,398
1 3 7 8	1,70	6,1	0,620	0,548	1,92	56,6	0,313	0,388
2 4 5 7	1,70	7,6	0,820	0,540	1,92	93,3	0,384	0,386

Table 17 Results from mission processed with various number and distribution of GCP.

A conspicuous rule can be formulated at the beginning that the more the GCP the higher the accuracy. In general, the RMSE decreases with subtraction of GCP, however, their distribution also has an influence. The difference between second and third configuration shows that it is better to have fewer points in every part of terrain, so in the corners and in the middle than have more points but only on sides. There is also a significant discrepancy between fourth and fifth project that have the same number of points. Results from both programs show 5 cm difference so again it is proved that placement of GCP should be considered. The time elapsed on measuring more points is not a wasted time and it is undoubtedly worth it to spend in order to achieve higher accuracy.

Software	Pix4D				Agisoft Photoscan			
GCP	X [mm]	Y [mm]	Z [mm]	XYZ [mm]	X [mm]	Y [mm]	Z [mm]	XYZ [mm]
all (1)	19,3	30,8	23,5	**43,3**	71,2	34,5	57,4	**97,7**
1 3 4 5 7 8 (2)	19,4	33,0	77,9	**86,8**	74,6	34,8	110,7	**138,0**
1 3 6 7 8 (3)	28,1	34,3	35,5	**56,8**	91,1	58,1	82,6	**136,0**
1 3 7 8 (4)	31,0	35,4	67,1	**82,0**	97,2	64,1	140,0	**182,1**
2 4 5 7 (5)	19,8	33,2	130,0	**135,6**	130,6	63,5	186,1	**236,1**

Table 18 RMSE on CP from mission processed with various number and distribution of GCP.

3.2.5. Comparison of models

The comparison of point clouds of a building was performed in CloudCompare software. There were three datasets, one acquired from Terrestrial Laser Scanning (Figure 34), which is a reference model that the others will be compared to and two point clouds obtained from oblique images in Agisoft PhotoScan (Figure 35) and Pix4D (Figure 36).

The point clouds representing the whole scene were imported into the software. Once it was completed, they were segmented so that only the walls of the building remained. The ceiling was cut form Pix4D and Agisoft datasets because it could not be scanned by TLS and therefore there would not be any reference. However, it is a first difference in favor of the UAV-borne photogrammetry that the whole scene can be represented including roof and if one wanted to scan it by TLS, an additional instrument station should be placed on the top of the building.

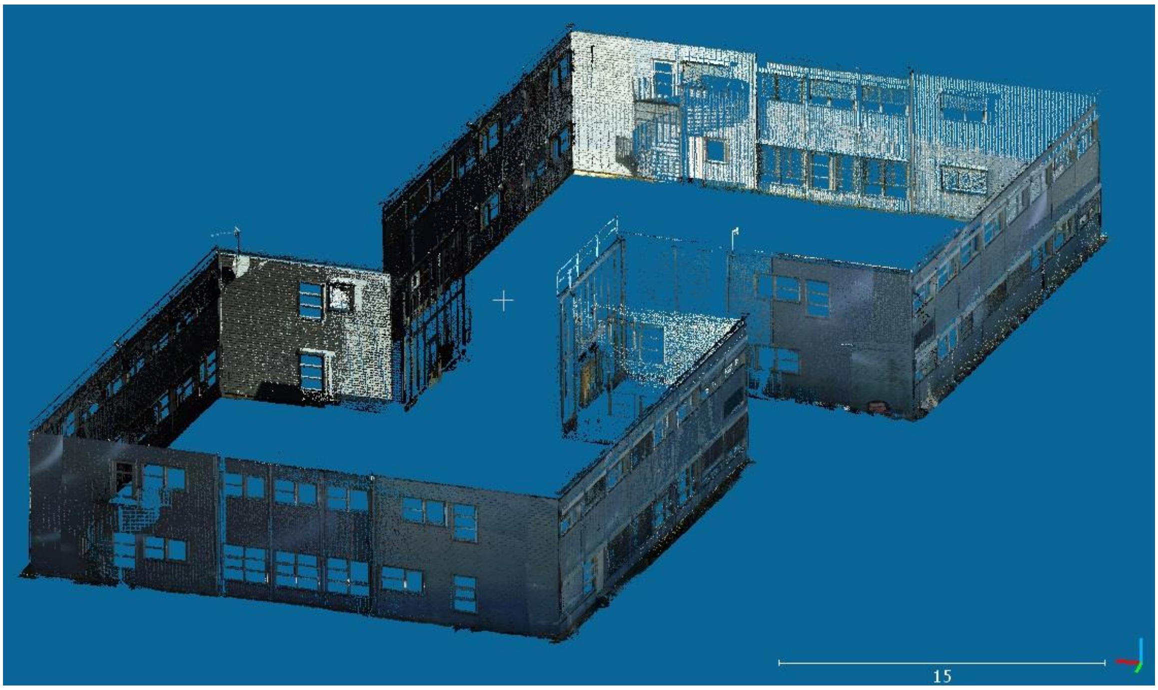

Figure 34 Point cloud representing a building obtained from laser scanner.

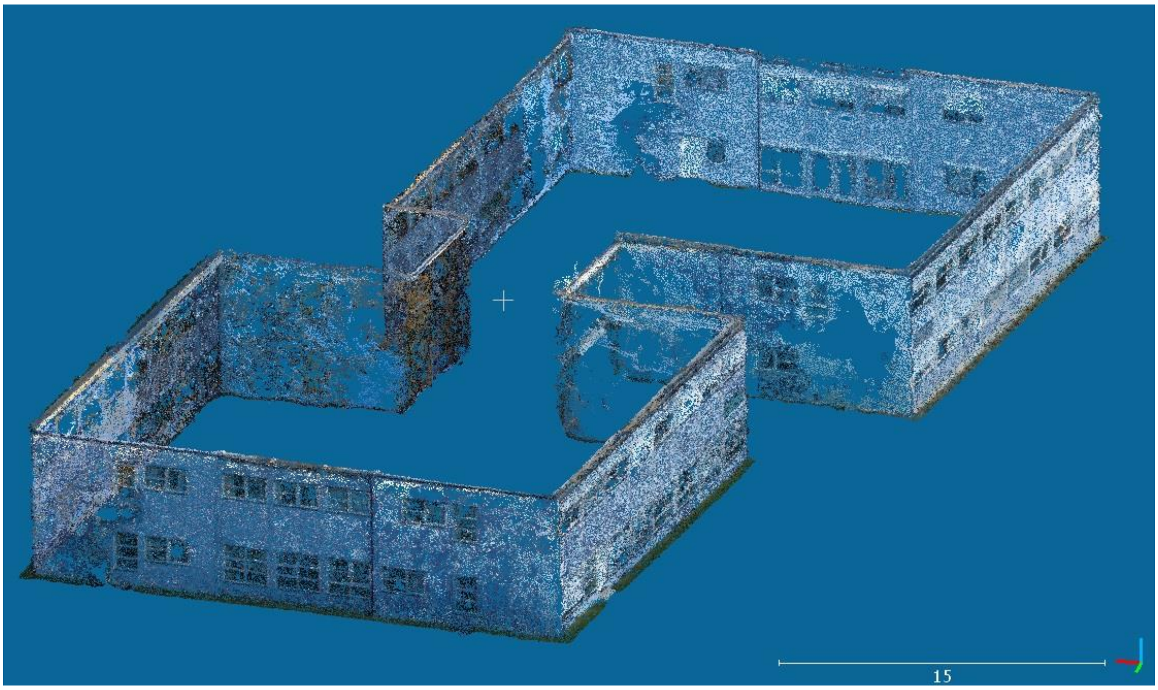

Figure 35 Point cloud representing a building acquired from oblique photos and processed in Agisoft PhotoScan.

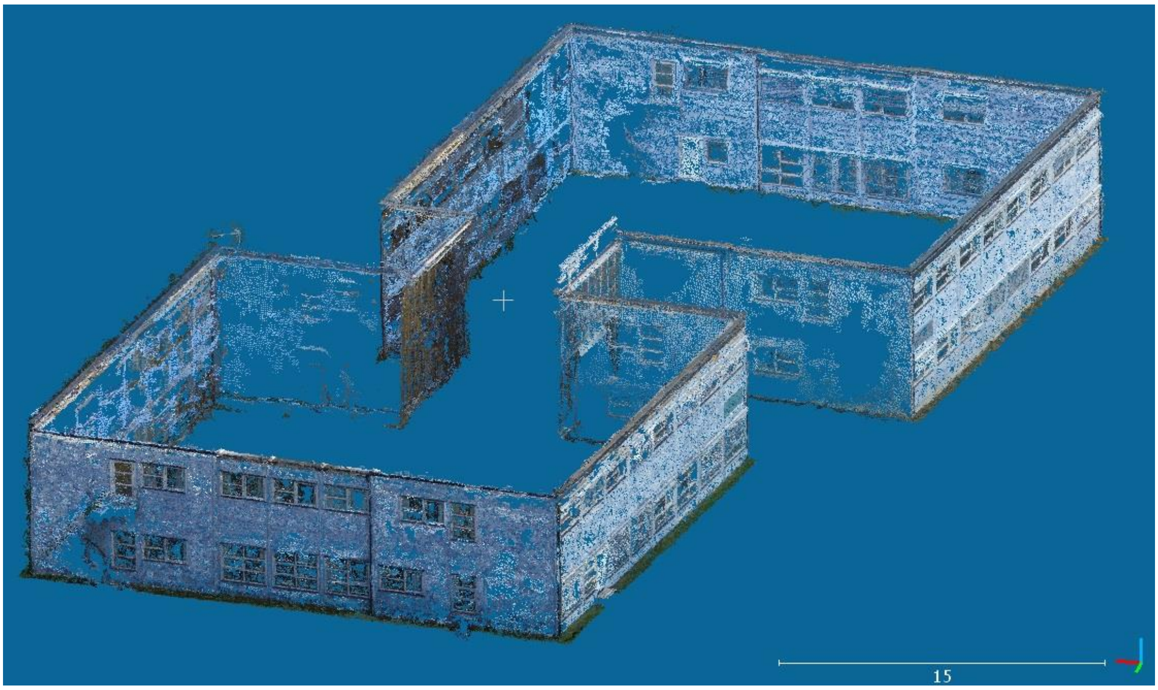

Figure 36 Point cloud representing a building acquired from oblique photos and processed in Pix4D..

By the visual inspection one can notice that the point cloud from laser scanning is more orderly. The distance between points is equal to the one set in resolution settings when the measurements were performed. There are not a lot of noises or artificial elements made by mistake and it could be assumed that it represents the building as is. On the other hand, point clouds obtained through photogrammetry in both cases are noisier, especially near more complicated features or in detailed spots (Figure 37). Pix4D does slightly better near windows than Agisoft but both struggle more when blinds are covered. They also have holes in some parts probably because the overlap there was not sufficient. The color of point cloud from TSL could be better in some places if not the low resolution built-in camera. The scanner extracts color information from photographs and some of them were very dark. This is not a case for point clouds from photogrammetry since camera in a UAV can have adjustable options and take better pictures.

Figure 37 A wall represented by point cloud obtained from laser scanning (upper), Agisoft PhotoScan (middle) and Pix4D (lower).

In order to present the variations between reference dataset and point clouds derived from UAV-based photogrammetry, maps with distance differences have been done. The distances have been computed in cloud to cloud mode and presented by colors. Values higher than 0.200 m were excluded from visualizations because after inspection they were stated to be blunders or outlying points and would bring confusion. The cloud from Agisoft is presented in Figure 38. It can be noticed that three of the walls are blue so the difference is lower than 5 cm but there are also other bigger parts that can range 10 cm (green color). Occasionally, the difference is up to 20 cm but it is near window jambs or wall edges so it could be because the photos were taken on another day than scanning and window blinds could be moved. The same applied to point cloud from Pix4D (Figure 39), where red color is mostly on edges. However, there is only one spot with green color (difference of about 10 cm) and it is the wall which in Agisoft seems to not have a big difference. The rest of the building is mostly blue so the difference is not higher than 5 cm and can be assumed as a precise result.

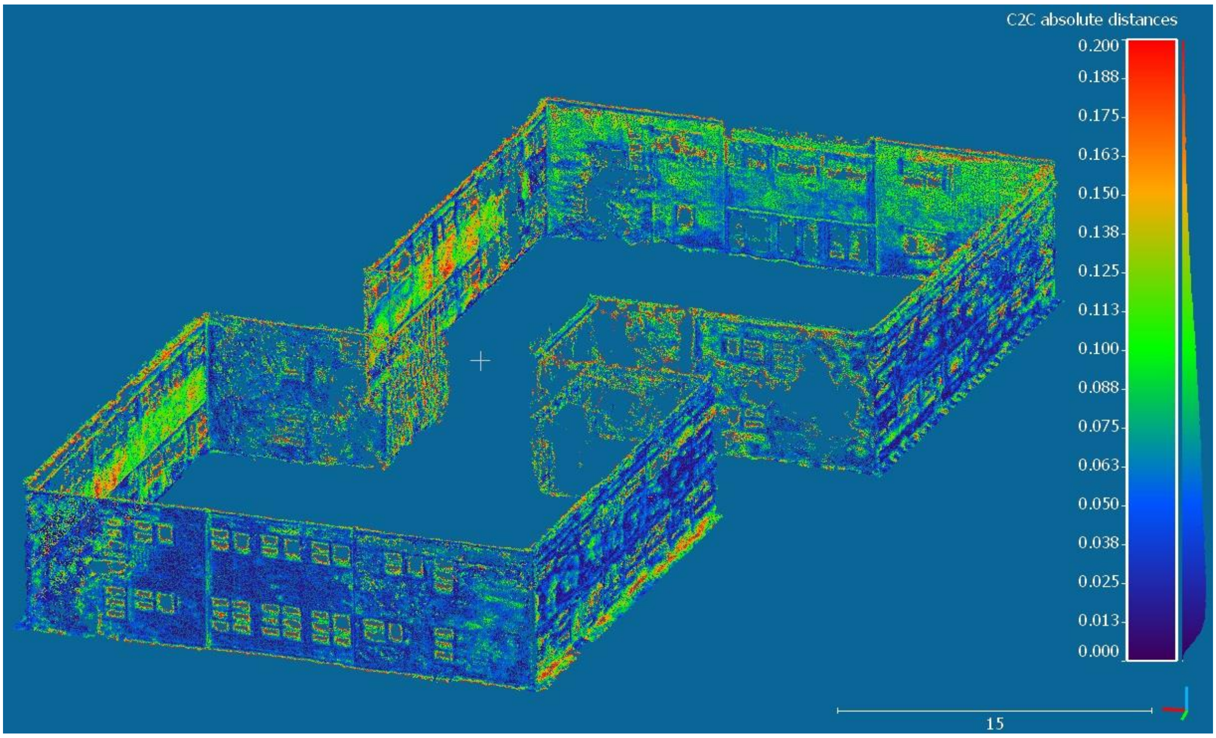

Figure 38 Map of comparison Agisoft point cloud to reference dataset.

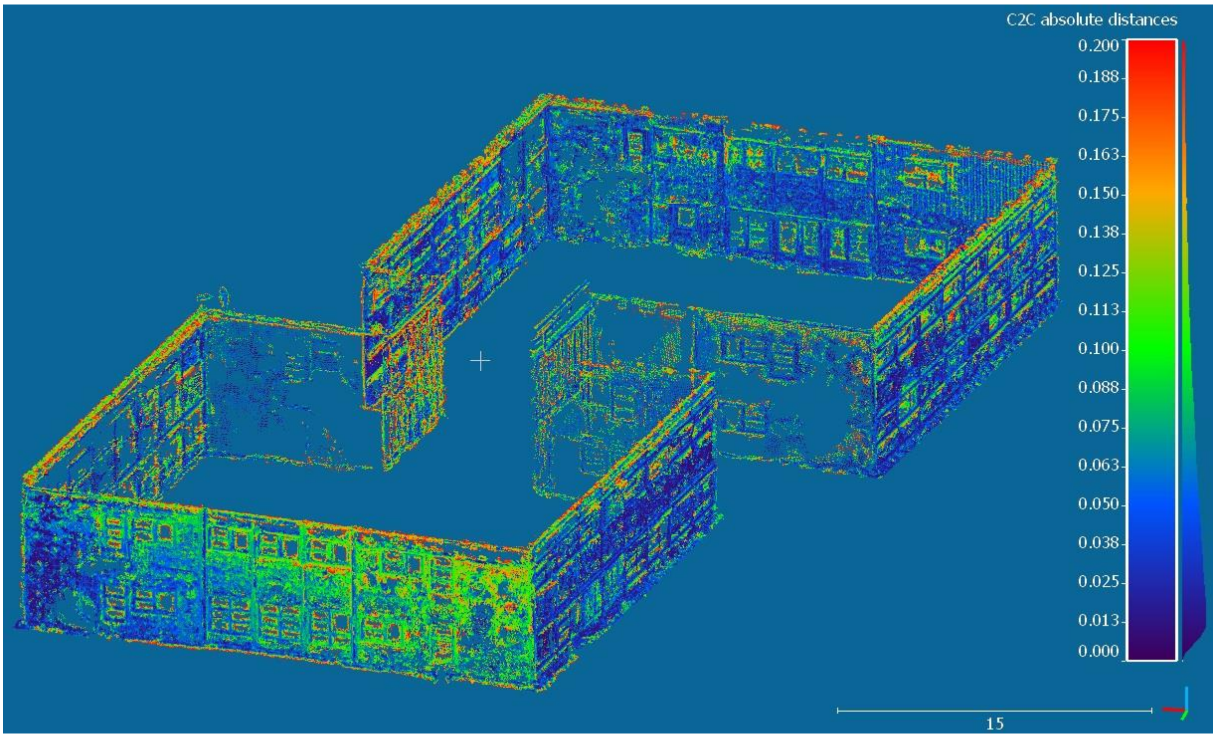

Figure 39 Map of comparison Pix4D point cloud to reference dataset.

Finally, three cross sections were prepared in places indicated in Figure 40. The reference point cloud from TLS is red, point cloud from Agisoft is blue and dataset from Pix4D is green. Cross section 1 was chosen to be on flat surface to see how the software manages in simple cases. This is also a place where Pix4D had problems described above. Here it is confirmed again that the wall is a bit moved outside the building and there are some holes in Pix4D point cloud. Output from Agisoft fits the TLS better but still does not overcome the very even surface obtained from scanning. The second cross section was marked in place where PhotoScan seemed to have problems. The point cloud from TLS there is also not very dense in upper part of the wall because the corners of scanned scene were not correctly indicated in scanner on that station. However, both Pix4D and Agisoft fit well in lower part of the wall and there is only small displacement of PhotoScan dataset in upper part. The third cross section is located where there are parts of windows and cornices to see how the programs can handle more difficult areas. In the upper part, even laser scanner appears to produce erroneous points but these are measured shutters. There is also a difference between Pix4D and Agisoft because one dataset is moved toward outside of the building and another one inside. In the lower section of the wall, there are small windows and both photogrammetric software have some problems with correct point projection.

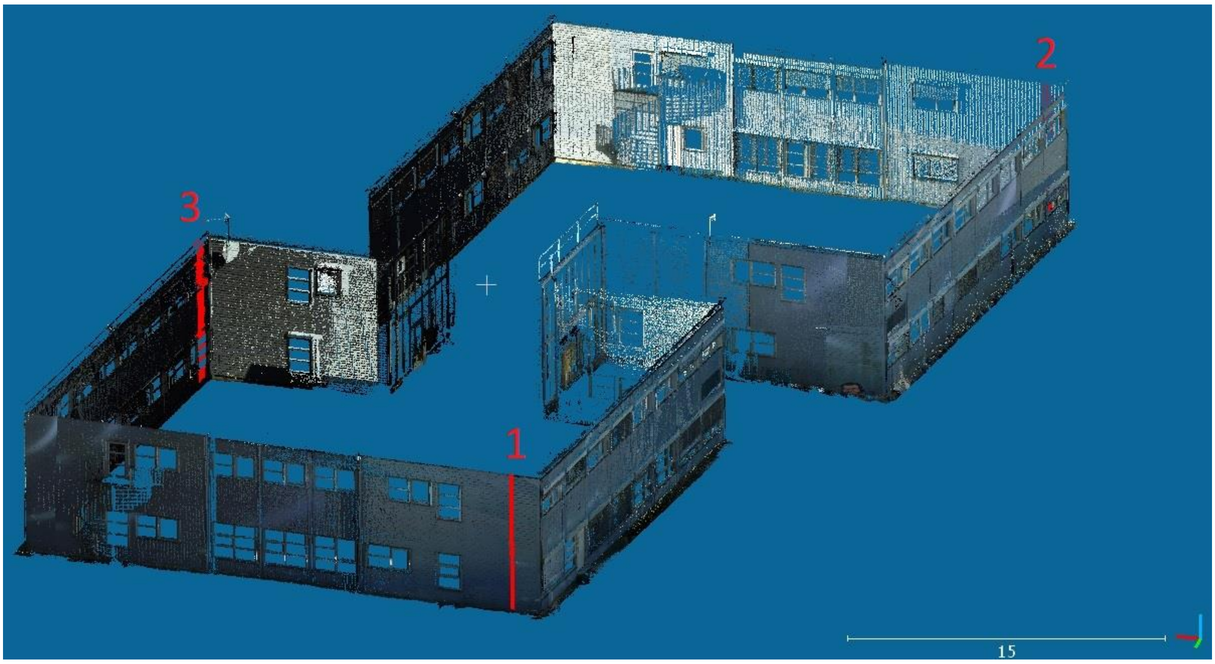

Figure 40 Placement of cross sections.

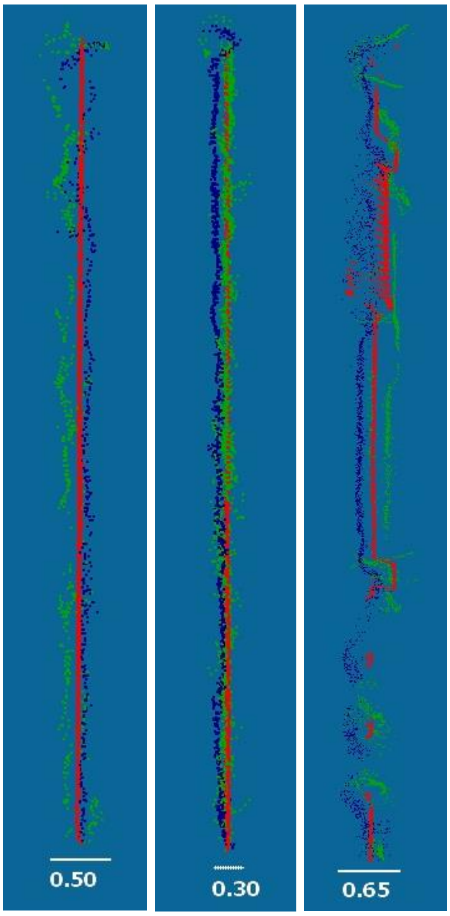

Figure 41 Chosen cross sections of all three datasets: reference (red), Pix4D (green) and Agisoft (blue).

4. SUMMARY

In this chapter, final conclusions are presented, briefly summing up what was already stated. The main emphasis is put on knowledge of influence of flight parameters on accuracy and time of conducting measurements by Unmanned Aerial Vehicles. Finally, potential improvements of workflow and chosen tests are presented underlining what could have been done better or different.

4.1. Discussion and conclusions

In the thesis, a brief introduction to Unmanned Aerial Systems and low-ceiling photogrammetry has been shown. Preparatory procedures before and during the flight have been described with emphasis on acquiring possible high accuracy and with reasonable workload. Two Structure from Motion software packages have been used, Agisoft PhotoScan and Pix4D Mapper Pro. The presented workflow in software and obtained results underlined what should be taken into consideration when planning a photogrammetric mission. Finally, a 3D point cloud was generated from oblique images and compared with dataset obtained by Terrestrial Laser Scanner.

What affects a way of performing a photogrammetric flight and does not depend on a UAV operator are weather conditions. Strong wind disturbs UAV in realizing a perfect, pre-planned flight projects. Small aircraft are also vulnerable to wind gusts which can cause that there will be holes in overlap between images. As shown in previous chapters, the sunlight affects the quality of the images that are taken and too bright or dark lightning can lead to difficulties for software in post-processing in aligning the photos. What is more, kp index can have an impact on accuracy or even on safety of property and people when it is too high and the activity of the sun affects the position determined by GNSS receivers. To avoid such problems, weather forecast should be included as one of the parameters that are taken into consideration before the flight.

The results in the form of Root Mean Square Errors of numerous UAV photogrammetric missions with various parameters showed some dependencies. Knowledge of their influence on different aspects while preparing flight plan for specific project can greatly improve reliability and effectiveness of conducting such a task. First of all, modelling rolling shutter effect enables using low-cost cameras mounted in commercial aircraft to be used in projects when land surveying accuracy is required, so errors from tens of centimeters reduce to couple of centimeters. This is the most significant improvement that was seen in the thesis. Modelling of the effect costs almost nothing because no additional efforts must be spent in field but it only extends computations by some time. Next, a height of a flight plays a role when it comes to time spent for measurements and achieved accuracy. It is strictly associated with acquired Ground Sampling Distance of orthophotomap and the value of height should be calculated based on assumed GSD and focal length of a camera to meet the requirements. However, when there is a margin, a higher altitude could be considered so that the less time in the air is spent and lower number of batteries is used to perform the flight. As the results show, the side and forward overlap of images is not essential to acquire a higher accuracy and greatly increases the time that has to be spent for acquiring images and processing them in the software. However, following other scientific articles, this parameter is crucial when reliable results should be obtained. The possible difference in conclusions of these two approaches could be that in the thesis, the overlaps that were tested were high enough to provide good results. This, in turn, shows that there is no point in increasing the overlaps to a very high extent because it would not provide any improvement and only extend the time. To sum up, a considerable overlap of the images should be applied of about 70x60% in good weather conditions, smaller values can reduce time but also accuracy and higher values are not necessarily needed. The speed of an aircraft has been tested to see if it is significant when planning a UAV mission with a rolling shutter camera. It would not be a case for a fixed-wing UAV because it cannot hover in the air and stop on a waypoint. However, when multirotors are used it is possible to do so and one could wonder if it improved the accuracy. The results present that it is not a significant setting and slower speed does not improve accuracy. On the contrary, it is beneficial to apply faster speeds because the flight will last shorter and fewer batteries can be used. It was shown that results acquired by UAV measurements can be reasonably repeated and will not differ significantly. It is a useful information when one would want to conduct periodical measurement campaigns and keep consistency between them. Finally, tests with various number and localization of Ground Control Points show that it is still one of the most important parameters. GCP should be evenly distributed over the area of interest and generally the more GCP, the better results.

Finally, it can be stated that 3D point clouds obtained from UAV-borne photogrammetry can be reasonably compared to Terrestrial Laser Scanning data. They are still not as accurate as TLS and have more noise but provide sufficient information about the object and can be used in many applications. It depends on the purpose of the project and if the highest possible accuracy is desired, then TLS is the best choice, but when time and economy of work count, UAV can be employed.

The thesis showed that centimeter-level results can be achieved with UAV technology what is sufficient for a great mayority of projects. It is a time-effective method for data acquisition. Unmanned systems overcome manned flights in many applications and can compete with terrestial measurements. Having the knowledge of influence of flight parameters on accuracy lets an operator conduct a mission that will provide desired results and UAV technology is still in rapid development so even higher quality of products can be expected.

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