Bachelor of Surveying and Geospatial Engineering

GMAT 4015-Undergraduate Project Thesis B

3D Mapping with UAV:
Procedure Analysis and Performance Evaluation with Field Tests

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Abstract

Due to the technical advancement of both computer hardware and software, the Unmanned Aerial Vehicles (UAVs) have the ability to provide alternative solution for surveyors to acquire 3D coordinates of ground objects, other productions include orthomaps, DSM/DTM, 3D model, etc. Compared with other techniques such as RTK GPS, total station survey and terrestrial laser scanner, it’s a more productive and cost-effective method. This thesis project will reveal the background knowledge associated with UAV mapping; demonstrate the UAV mapping procedures including camera calibration, flight planning, data acquisition as well as image processing; display some of the most important productions; estimate the accuracy of UAV mapping and evaluate the influences of different factors on the results, influence factors such as the distribution and numbers of GCPs, flying heights, as well as software packages will be considered and analysed. The project will establish an optimized UAV mapping procedure, provide the feasibility of UAV use for surveying and mapping applications and propose some possible improvements in the future as well as indicate whether UAV could be an alternative surveying and mapping solution to the current ground-based surveying techniques.
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Contents

1. Introduction
   1.1 Scope
   1.2 Outcomes

2. Background
   2.1 Definition of UAVs
      2.1.1 Structure and Components of Modern UAVs
      2.1.2 UAVs Classifications
      2.1.3 Regulation in Australia for Small UAVs
   2.2 UAV Technologies and Applications
      2.2.1 Integration of GPS and IMU
      2.2.2 UAV Photogrammetry

3. Theory, Algorithm and Methodology
   3.1 Procedural Analysis of UAV Mapping
      3.1.1 Brief Introduction
      3.1.2 Camera Calibration
      3.1.3 Flight Planning and Data Acquisition
      3.1.4 Ground Control Points Measurements
      3.1.5 Image Processing
   3.2 Summary of Procedural Analysis
4. Tests Results and Analysis

4.1 Case Study 1: Fixed-wing UAV (eBee) Terrain Mapping in Wollongong—

   General Review of UAV Mapping Procedure

4.2 Case Study 2: Fixed-wing UAV (Swinglet CAM) Terrain Mapping in Collaroy—

   Influence of Different Factors on UAV Mapping Accuracy

4.3 Case Study 3: Quadcopter UAV Terrain Mapping in UNSW campus—

   Alternative Low-Cost Surveying and Mapping Solution

4.4 Case Study 4: Quadcopter UAV 3D building modelling in UNSW campus—

   Possible Alternative to Terrestrial Laser Scanner and Ground-Based Photogrammetry

4.5 Summary of Tests Results and Accuracy

5. Future trends of UAV mapping and 3D Modelling

6. References

7. Bibliography

8. Appendix

   Appendix A—Robust Software Packages and Open Source Codes used in the project
   Appendix B—Email Contact with Pix4D Ltd
   Appendix C—Screen shots of Excel working sheets
   Appendix D—Matlab code for Path Planning
   Appendix E—Quality Reports with Pix4D
   Appendix F—Plagiarism Sheet
1. **Introduction**

1.1 **Scope**

This thesis is focused on analysis of UAV mapping procedures as well as the results generated from the procedures. To better obtain the desired results, a comprehensive literature review on UAV Mapping procedures which covers the camera calibration, the flight planning and data acquisition, image processing methods and other final products will also be given. The data and images acquired from UAV flight test has been processed and studied. Through the analysis of UAV mapping productions, including 3D point clouds, DSM, Orthomosaics, and models, TIN surfaces, etc, the productivity of UAV mapping could be displayed. Furthermore, some problems and considerations related to the accuracy are to be investigated to show whether UAV could be a feasible way for surveying and mapping purpose.

This work is mainly based on UAV photogrammetry software Pix4D, some other free software packages and open source codes, are to be used for comparison, supplementary and verification. Flight planning has also been programmed in Matlab.

Most UAV applications include earth observation measurements, making use, for example, of cameras, lidar or radar instrumentation (NASA, 2008). However, only digital camera sensor will be considered and analysed in this thesis.

1.2 **Outcomes**

The outcomes of this thesis include:

- The products generated from image processing, such as the georeferenced 3D point clouds, Digital surface model, Orthomosaic, etc;
- An optimized workflow proposed for UAV mapping;
- The analysis report, including the above outcomes and some other results.
2. Background

2.1 Definition of UAVs

2.1.1 Structure and components of modern UAVs

The basic components of modern UAV include the airframe, the engine and propeller, the avionic system such as radio control and autopilot, the onboard sensors such as camera, GPS and INS (Avanzini et al, 2003). Different UAVs vary in shapes, sizes, configurations and characteristics. The example below displays the typical structure of a modern fixed-wing UAV and a helicopter UAV.

![Figure 1. Typical structure of modern fixed-wing UAV (Sensefly, 2013) and helicopter UAV (Gruen, 2007).](image)

2.1.2 UAVs classifications

UAVs can usually be classified by main characteristics of aircrafts like unpowered or powered, lighter than air or heavier than air and flexible, fixed or rotary wings (Eisenbeiss, 2009). The below two tables present the UAVs classifications and performances of different kinds of UAVs.
Table 1. Classifications of UAV

<table>
<thead>
<tr>
<th>Lighter than air</th>
<th>Heavier than air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible wing</td>
<td>Fixed wing</td>
</tr>
<tr>
<td>Unpowered</td>
<td></td>
</tr>
<tr>
<td>Balloon</td>
<td>Hang glider</td>
</tr>
<tr>
<td></td>
<td>Gliders</td>
</tr>
<tr>
<td>Paraglider</td>
<td>Rotor-kite</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Powered</td>
<td></td>
</tr>
<tr>
<td>Airship</td>
<td>Paraglider</td>
</tr>
<tr>
<td>Propeller</td>
<td>Single rotors</td>
</tr>
<tr>
<td></td>
<td>Jet engines</td>
</tr>
<tr>
<td></td>
<td>Coaxial</td>
</tr>
<tr>
<td></td>
<td>Quadrotors</td>
</tr>
<tr>
<td></td>
<td>Multi-rotors</td>
</tr>
</tbody>
</table>

Source: (Eisenbeiss, 2009)

Table 2. Performances of different kinds of UAVs (++:Best; +:Middle Value; 0:Lowest value)

<table>
<thead>
<tr>
<th>Type of aircraft</th>
<th>Range</th>
<th>Endurance</th>
<th>Weather and wind dependency</th>
<th>Maneuverability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon</td>
<td>0</td>
<td>++</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Airship</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Gliders/Kites</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fixed wing gliders</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Propeller &amp; Jet engines</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Rotor-kite</td>
<td>++</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Single rotor (helicopter)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Coaxial</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Quadrotors</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>Multi-copters</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

Source: (Eisenbeiss, 2009)

Compared with fixed wing UAVs, the rotary wing UAVs (helicopter or multicopter) usually have lighter weight, smaller payload, can be operated closer to objects and have a larger flexibility in the control of flight manoeuvres (Bendea, et al, 2007), however, the fixed wing UAVs are usually able to stay longer in the air, cover larger areas and enter upper air spaces, meanwhile, the fixed wing systems are less susceptible to environment conditions such as wind and temperature.
Compared with powered UAVs, the unpowered UAVs are usually controlled by ropes and thus limited in flying height and distances to the starting point. Moreover, the influences of environment like wind usually have greater effect on unpowered UAVs.

2.1.3 Regulation in Australia for small UAVs

The Civil Aviation Safety Regulation (CASR) part 101 is the regulation that covers unmanned aircraft (CASA, 2002). Promulgated in 2002, it was the first operational regulation for unmanned aircraft in the world. It describes the rules for the use of unmanned aerial vehicles.

For small UAVs, there are some restrictions need to be addressed.

A person may operate a small UAV in approved areas, including:

- Where the UAV is operated below 400 feet above ground level; and
- The UAV stays clear of populous areas; and
- The UAV is operated beyond 3 nautical miles of an aerodrome; and
- The UAV is operated beyond 30 metres of a person who is not directly associated with the operation.

Otherwise, the operator must get the Civil Aviation Safety Authority (CASA) approval to operating his/her UAV.

Basically, an individual or organization who wants to fly a small UAV for aerial work may need to apply for both the Controller and Operators Certificate. A Controller Certificate could only be given to an individual who wants to fly and control the UAV during aerial work. And the Operators Certificate could be given to an organization or individual who intend to conduct commercial operations utilising UAVs.
2.2 UAV Technologies and applications

2.2.1 Integration of GPS and IMU

GPS or Glonass can offer consistent precision during the period of satellite signal tracking. However, the line-of-sight is required between satellites and GPS receivers. In some extreme conditions such as under tunnel, the onboard GPS receiver could lose signal and stop working.

An inertial measurement unit, or IMU, which is the main component of inertial navigation system, is an electronic device that measures and reports on a craft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers.

Inertial navigation methods have been used in a wide variety of navigation applications in the field of marine, aerospace and spacecraft technology. Compared with GPS, Inertial Navigation System update at a much faster rate, if not in a continuous fashion (Lewantowicz, 1992). Unlike GPS, the INS systems achieve navigation by continuously tracking the position, orientation and velocity information using computers and motion sensors. As errors tend to accumulate over the time, the INS systems suffer from a constantly drifting position solution. However these position errors are introduced at a slower rate than the GPS errors. The complementary characteristics of GPS and INS have led to a combined GPS/INS coupling (Greenspan, 1996). Such an integration scheme provides users with immunity against momentary GPS signal outages and signal failure detection in a noisy or jamming environment.

Additionally, an on-board IMU is necessary for applications that require attitude information, for example auto-pilot and navigation or geo-referencing images.

More information of GPS and IMU in georeferencing will be discussed in Chapter 3—3.1.3.2 Direct georeferencing
2.2.2 UAV photogrammetry

2.2.2.1 Definition and applications

Photogrammetry can help reconstruct the position, orientation, shape and size of objects from pictures. The digital photogrammetry came after analogue and analytical photogrammetry, which allows the light fall on the focal plane and being recorded by electronic detectors. Photogrammetry can be used to analyse characteristics of objects without physical contact, remote sensing techniques has the similar ability to obtain information of Earth’s surface. But one speaks of photogrammetry when the predominant interest is in geometric characteristics (Kraus, 2000). Meanwhile, the improvement of computer vision is able to provide accurate relative orientations by generating extreme dense 3D point cloud which is comparable to the product of laser scanning technique.

In recent years, the application of computer vision based photogrammetry in UAV becomes more and more widely used. Despite the series advantages mentioned above, the development of low cost GPS/IMU system allows the navigation of UAV to the predicted acquisition points with high precision is also an important reason.
Compared with manned aerial photogrammetry and close range photogrammetry, the major differences are listed in the below table.

**Table 3. The major differences between manned aerial, close range and UAV photogrammetry**

<table>
<thead>
<tr>
<th></th>
<th><strong>Aerial</strong></th>
<th><strong>Close Range</strong></th>
<th><strong>UAV</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planning</strong></td>
<td>(semi-)automatic</td>
<td>manual</td>
<td>Automatic-manual</td>
</tr>
<tr>
<td><strong>Data acquisition/Flight</strong></td>
<td>Assisted/manual</td>
<td>Autonomy/assisted/manual</td>
<td>Autonomy/assisted/manual</td>
</tr>
<tr>
<td><strong>Size of the area</strong></td>
<td>km²</td>
<td>mm² – m²</td>
<td>m² – km²</td>
</tr>
<tr>
<td><strong>Image resolution/GSD</strong></td>
<td>cm-m</td>
<td>mm-dm</td>
<td>mm-m</td>
</tr>
<tr>
<td><strong>Distance to the object</strong></td>
<td>100m-10km</td>
<td>cm-about 300m</td>
<td>m-km</td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
<td>Normal case, recently also oblique</td>
<td>Normal/oblique</td>
<td>Normal/oblique</td>
</tr>
<tr>
<td><strong>Absolute accuracy of the initial orientation values</strong></td>
<td>cm-dm</td>
<td>mm-m</td>
<td>cm-10m</td>
</tr>
<tr>
<td><strong>Image block size/number of scans</strong></td>
<td>10-1000</td>
<td>1-500</td>
<td>1-1000</td>
</tr>
<tr>
<td><strong>Spatial application (example) and features</strong></td>
<td>Large scale areas (Mapping, Forestry, Glaciology, 3D city modelling)</td>
<td>Small scale areas and objects (archaeological documentation, 3D modelling of buildings)</td>
<td>Small and large areas (archaeological documentation, monitoring of hazards, 3D modelling of buildings and objects)</td>
</tr>
<tr>
<td></td>
<td>Architectural and industrial photogrammetry</td>
<td>Application in inaccessible areas and dangerous objects</td>
<td></td>
</tr>
<tr>
<td><strong>Aerial view</strong></td>
<td></td>
<td>Terrestrial view</td>
<td>Aerial view</td>
</tr>
</tbody>
</table>

Source: (Eisenbeiss, 2009)
2.2.2.2 Historical development

The development of UAVs has been strongly motivated by military applications. Kites, Pigeons and Rockets were used for spying during the world wars in the last century.

In 1979, one of the earliest experiments with fixed wing UAVs in photogrammetry was done by Przybilla and Wester-Ebbinghaus (Eisenbeiss, 2004). First tests were accomplished using the manually controlled fixed wing UAV of the company Hegi with a flying height of 150m above ground and a velocity of 11m/s.

In 1980, Wester-Ebbinghaus was the first to use a rotary wing UAV for photogrammetric purposes (Eisenbeiss, 2004).

Nowadays, with the technology development in both hardware and software related to UAV, a low cost and low altitude UAV are becoming more popular for civilian survey and mapping.

2.2.2.3 Productions

The results of digital camera photogrammetry analysis include:

- 3D Point cloud, in which the coordinates of separated points in three-dimensional coordinate system can be extracted.
- Digital geometric models, such as DTM, DSM, and 3D model.
- Maps and plans with objects details and contour lines (eg, DLG file)
- Photos and Images, especially orthophotos.
2.2.2.4 Advantages and limitations of UAV photogrammetry

- Advantages

Compared with traditional land surveying and mapping methods, UAV photogrammetry have the below advantages (Newcome, 2004):

- More productive
- Faster data acquisition
- Real-time capability of data and image transmitting
- Less manual work involved
- Able to survey areas where are inaccessible by human

While in contract with manned aerial photogrammetry methods, UAVs have advantages including:

- Can be operated in high risk situations without endangering human beings
- Can be operated at low elevation close to the objects to avoid cloud blockage
- Cheaper cost
- Higher resolutions
- Some UAVs can take off and landing without runway

- Limitations

Compared with land surveying and mapping techniques, UAV have several shortages:

- The operator(s) need to be trained and CASA approval needs to be granted before flight in most urban areas.
- No standardized workflow and sensor models have been implemented.
- Sometimes it can be hard for fixed-wing UAV onboard camera to capture enough details of the façade of the building or object.
Compared with normal manned aerial vehicle, the limitations of UAVs are also very obvious, these limitations mainly include:

- Limited payload in weight and dimension, which means UAV usually carry small and less accurate camera and GPS/INS navigation sensors.
- More susceptible to environment conditions, especially wind. Therefore, it can only operate in relative good weather conditions to maintain platform stability during flights.
- Its flight height and area is restricted.
- Lack of communications with ground stations
3 Theory, Algorithm and Methodology

3.1 Procedures analysis of UAV mapping

3.1.1 Brief introduction

UAV 3D mapping and modelling is a combination of different technologies and techniques, including mechanical, electrical, surveying, photogrammetry and computer vision technologies.

The mechanical part is mainly just the platform. The electrical part mainly includes the sensor integration. GPS, IMU and vision sensors are the major components of onboard sensors for mapping purpose. The autopilot provides the connection between the onboard sensors and UAV platform itself. The ground surveying are usually conducted at the same time as the flight. While photogrammetry and computer vision technologies can be used to process the image in order to produce 3D model and other products.

For the actual work of UAV survey, there are mainly three steps involved in it, including path planning, data acquisition and image processing (four steps if lab or field camera calibration needs to be done separately). Electrical and mechanical knowledge should be applied in the path planning and data acquisition procedure, while photogrammetry and computer vision are only used in image processing. However, since the path planning and data acquisition will have a great influence on the image processing part, a good knowledge of how the planning will affect the result and what strategies should be used in the planning stage are very important. Vice versa, the good method of planning can only be selected and verified by analysing and comparing the results. That’s the basic logical thinking involved in the whole procedure analysis.

In this chapter below, the procedure of UAV mapping from camera calibration to path planning and then to image processing will be discussed. Different tests have been conducted by the author, and the results generated from image processing have been used to verify some proposed assumptions and methods.
3.1.2 Camera calibration

For digital camera, the calibration is mainly used to define the interior orientation of the camera (Pérez, Agüera & Carvajal, 2011).

The interior orientation is the internal geometry of a camera as it existed at the time of image capture, which can be used to transform the image pixel coordinate system to the space coordinate system. Basically, the interior orientation elements mainly include the focal length, the image coordinates of principle point and lens distortion.

The principal point is mathematically defined as the intersection of the perpendicular line through the perspective centre of the image plane. The length from the principal point to the perspective center is called the focal length (Pacheco, 2003).

Lens distortion deteriorates the positional accuracy of image points located on the image plane. It is usually departed into two parts:

- Radial distortion: causing an inward or outward displacement of a given image point from its ideal location. The radial distortion with perfectly centred lens can be expressed as (Wang et al, 2008):
  \[
  \delta_{\rho r} = k_1 \rho^3 + k_2 \rho^5 + k_3 \rho^7 + \cdots
  \]

  Where \( k \) represents the coefficient of radial distortion and \( \rho \) is the radial distance from the principle point of the image plane.

- Decentring distortion: The optical centres of lens elements are not strictly collinear. Because tangential lens distortion is much smaller in magnitude than radial lens distortion, it is considered negligible.

The calibration for UAV onboard camera can be done by using lab test, field test or self-calibration methods. Lab test is usually done by taking photos of calibration grid with evenly distributed dot points. The field calibration can be done in the similar way by taking photos of evenly distributed GCPs during UAV flight. Self-calibration means define or calculate camera parameters on the job. At present, although self-calibration has its own superiority, its
accuracy is not always satisfactory. The lab calibration and field calibration have been developed for a long time with higher precision especially three-dimensional calibration (Wang et al, 2008).

Using the lab or field calibration test, the following influence factors should usually be considered (Wang et al, 2008):

- **The shape of control points**
  Cross points are better than circle points because more shape distortion may occur to circle.

- **The distribution and position of control points in the image:**
  In aerial photogrammetry, it is often required that the control points distribute evenly in the image plane.

- **The camera attitude and longitude tilt:**
  During the calibration test, it’s better if the camera can be rotated to different angles in order to differentiate the radial and tangential distortion coefficient.

- **The scale between calibration object and measurement object:**
  Every camera has its depth of field, which means it has a near and a far limit of object distance. The depth of field is mainly depends on the focal length, the pre-set object distance, and the diameter of circle of confusion (Kraus, 2007). As the focal length is usually fixed during the test and to achieve the similar diameter of circle of confusion, the more similar the size of object model and the measurement object, the higher precision the calibration has.

- **The focal length which is often fixed during the UAV flight.**

Besides, Due to the light diffraction, the influence of atmospheric refraction, the earth curvature influence and some other factors, the obtained image might be distorted, one of the common shortages might be the light fall-off from the image centre to the edge (Kraus, 2007). This influence can be reduced by using multiple lenses and post-processing methods. The software can be used for refinement include photoshop or format converter, etc.
3.1.3 Flight Planning and Data Acquisition

UAV flight can be autonomous, half-autonomous or manually controlled. Over the last years, the trend for image acquisition is heading towards autonomous flights where the flight planning is extremely important. However, some systems can only be controlled manually and, because of security reasons, in some areas autonomous flights are not permitted. Another important reason of manual control is to maintain stabilization, under bad weather condition, especially with relative heavy wind, it is impossible to fly a precise block configuration in autonomous model. Thus using manual control, the image rectification might be easier in the processing stage.

Furthermore, according to the project parameters of one application, three different cases should be considered when designing the flight path or trajectory (Eisenbeiss, 2009), they are:

- Modelling flat or moderate terrain surfaces
- Modelling rough or mountainous areas
- Modelling three dimensional buildings or other objects

Basically, the first and second one are called terrain or topographic mapping, and the third one is 3D reconstruction or modelling. The following part of this chapter will discuss the flight planning for 3D reconstruction and terrain mapping separately, the flight planning for 3D reconstruction is much easier, thus will only be briefly introduced in this article. The author mainly focused the work on the flight planning for terrain mapping purpose and this will be discussed in details below.
3.1.1.1 Flight planning for 3D structure modelling:

As mentioned above, the flight and data acquisition of 3D modelling is easy, because some of the most important products such as ortho-mosaic are not required in 3D structure modelling. There is usually no need to maintain the same flight level (for unique image scale) or same overlap during the flight.

It can be realized by both manual flight and automatic flight. Usually if the whole structure (eg, building) need to be modelled, automatic flight can be carried out by doing a circular flight path around the structure, shown as Path1 (red) in the figure below.

Moreover, if the details of one surface, such as the building facet, is specially needed, the below Path2 (green) might be added to give more details and better precision.

Basically, Rotary-wing UAV like multi-copter is suitable for this application due to the flexibility.

![Fig 2. Path planning for 3D structure reconstruction purpose](image-url)
3.1.1.2 Flight planning for terrain mapping:

Flight planning for terrain mapping is much harder than for 3D reconstruction. The design of flight planning is usually decided by project parameters vary from one project to another. Some mathematic algorithms need to be implemented in this procedure. The below part will be split to two parts. In the first part, the author will talk about the logic flow of terrain mapping planning. In the second part, the procedure of terrain mapping will be discussed, including the initial planning stage and the further consideration stage in the author’s work.

- **The logic flow of terrain mapping planning:**

The flight planning for terrain mapping is not only about safety flight, it’s more about obtaining the desired data accuracy and precision (reflect in flight height and image quality in planning stage). Therefore, to get a good set of data, the flight needs to be carefully designed.

Firstly, the post-processing of recent UAV photogrammetry mainly involve three steps (Discussion in Chapter 3—3.1.5 Image Processing)—image matching, SFM and MVS. Every step requires overlapped images, which means only the images have overlapping areas with other images can be processed. Therefore, image overlap is the first and most important factor to be considered.

Secondly, different UAV projects require different accuracy and precision. To achieve the required target, different parameters need to be considered.

Thirdly, UAV flight and data acquisition is usually subject to many different influential factors, such as wind and terrain surface, these factors need to be considered if an accurate mapping result is required.

The basic logic flow of designing flight plan is shown in the below diagram (created by the author, the arrows pointing from influential factors to the corresponding affected factors):
As shown in the above diagram, the most important influential factors in UAV flight planning are flight height, input percentage overlap, wind and terrain surface. Among these four factors, input percentage overlap and flight height can be pre-defined and changed according to the requirement by the controller, while on the other hand, wind and terrain surface can just be approximately examined or predicted, and the flight plan might need to be
changed accordingly. More details about the theory and algorithms used will be discussed below.

- **Terrain Mapping Procedure:**

1) **Initial planning stage:**

In the initial planning stage, the basic idea implemented in this work is to simplify 3D scenario to 1D, which means the three dimensional flight path should be simplified to single-points on one common plane to satisfy the requirement of onboard navigator—GPS/INS, because only point positioning can be realized by GPS if the flight planning is carried out in the world coordinate system. This target points are called waypoints in UAV flight.

Another important consideration is the synchronization of GPS and camera sensor. During the flight, we need to make sure that the camera takes photos at the exact same time when GPS takes waypoint measurements, so afterwards the photos can be geo-tagged automatically. One way to realize this is by timing—set the time lapse of camera and use a GPS which has the pulse-per-second function. However, this method has many limitations: firstly, for our small UAV, the payload is less than 500 gram, it’s impossible to carry professional cameras for aerial mapping, instead, it can just carry a small compact camera, which might not have the sufficient time lapse settings. Using internal timer of a light compact camera is limiting shooting rate typically to 10s+. Secondly, it is much more difficult to synchronize the data with GPS waypoint positions as the clock of autopilot and camera may drift. Furthermore, the UAV platform speed during flight could be influenced by many different factors, just by setting a constant time can never really realize waypoint-image accurately. Therefore, for most terrain mapping today, we apply electrical connections between onboard GPS and camera, and trigger the camera to take photos when GPS reach the designed waypoints.

In this chapter below, flight height and percentage overlap are to be discussed first to reveal the influences of these two factors on UAV mapping. And then some algorithms will be given to shown how the UAV flight waypoints can be initially calculated based these two factors.
o **Flight height:**

Flying height is directly related to the image quality and thus important for vision based image processing.

Firstly, as discussed above, the accuracy and ground sampling distance (or ground resolution) are usually defined for a certain UAV project. The rough estimation of accuracy for the whole stereo-model before any actual measurement can be predicted by the following “Rule-of-Thumb” formulae (Kersten, 1999):

\[ \sigma_x = \sigma_y = m_B \sigma_B \]  
\[ \sigma_z = \frac{H}{B} \sigma_B \]  

Where \( m_B \) is the scale number equals to \( \frac{H}{f} \), \( f \) is the focal length;

\( \sigma_B \) is the image measurement accuracy, usually 1/5 to 1/2 pixel.

Notice: although the above function can only be used in the planning stage for a rough estimation, it provides the basic relationship between accuracy and height, which is an important index.

Moreover, the ground sampling distance (GSD) or ground resolution can be expressed as (Neumann, 2008):

\[ GSD = \text{pixel size of image sensor} \times \frac{H}{f} \]  

As can be seen, both accuracy and resolution are related to flying height. Given a certain GSD and a general required accuracy of the whole project, the approximate height can be calculated before any real flight.

If the accuracy is not specified for one project, the lower flying height of the UAV can produce a higher scale for the photographs, the resolution of the photographs or ground sampling distances (GSD) is therefore higher. In turn, a higher resolution can lead to more details of the DSM derived from the photographs. Furthermore, a higher resolution will make it possible to pinpoint features in the photos more precisely, thus accuracy could be improved.
Flight Height Tests:

Some tests have been done by the author to verify the influences of flying heights on the results.

Test 1:

- Test Parameters:

Flight heights: 120m, 100m and 80m

Average Ground Sampling Distance (GSD): 2.75cm for 80m flight, 3.88cm for 100m, 4.16cm for 120m

Area Covered: 2.08 hectares

Fig 3. Test area (orthomosaic); the locations of 8 GCPs (green circle) and 3 check points (black square)

- Test Brief and Results analysis:

The first test contains 3 sets of images captured by Swinglet CAM UAV in different flying heights, namely 120m, 100m and 80m, respectively. As discussed before, lower flying height can usually provide clearer images with higher ground resolutions, thus features should be easier to be identified. The below figure shows the same target in different flying heights:
As shown in Fig. 5 below, there is a general trend that with the decreasing of flying height, the total average difference between RTK-GPS measurements and the corresponding UAV derived values of check points will decrease. However, for Northing, the difference of 100m (second column) is larger than that of 120m (first column) and for Easting, the difference of 80m (third column) is larger than that of 100m (second column). This indicates that minor changes (±20m) of flying heights will only slightly influence the final results of a UAV project. In terms of timing, the lower the flight height, the smaller the ground coverage, thus the longer the flight time.
Recommendations:

According to the required ground sampling distance (ground resolution), the flight height can be roughly calculated using Equation (1). If the ground sampling distance is not specified, flight height need to be chosen carefully based on the possible safety problem (lower than 30m in rural area) and regulation issue (flight height more than 120m need to be approved by CASA in Australia) as well as Time vs. Accuracy issue.
**Test 2:**

In test 2, flights of different heights in Test 1 are combined to create different depth of images within each set of data and test whether this will cause any difference to the results.

![Different flight height combinations in this test](image)

As can be seen from the above figure, four sets of data have been compared against each other, the first set only involves 80m flight, the second set combine 80m and 100m flight, the third set combine 100m and 120m flight and the fourth set combine all 80m, 100m and 120m flight together. The below diagram has been created based on the difference between RTK-GPS measurements and UAV photogrammetry derived values of the same three check points.

![Flight Height test: Average Difference between RTK-GPS values and UAV photogrammetry values of 3 check points with different flying heights combinations](image)

**Fig.7** Influence of different height combinations on the final result
As can be seen from Fig. 7 above, the total average difference of 80m flight alone (first column) is the smallest. The combination of 80m flight and 100m flight (second column) has the second smallest difference. While the combination of 100m and 120m flight (third column) got the largest total average difference of check points.

In terms of the number of images, the first set of data (80m flight) has only 163 images, but the fourth set (80+100+120m) has 344 images. This indicates that the accuracy of UAV terrain mapping (vision based technology) may have nothing to do with the image quantity. Instead, the quality of images is much more important (80m with highest ground resolution and 120m with lowest).

- **Recommendations:**

For flat terrain mapping, only one flight with high quality images (good resolution, no image blur) is sufficient to produce good result.

- **Input percentage overlap:**

Firstly, the input percentage overlap will influence the overlapping areas, if the flight height and focal length, etc, are maintained same during the whole flight, the bigger the percentage overlap, the larger the overlapping areas. Smaller input percentage overlap will reduce the numbers of flight lines and thus cut flight time. However, because the area of the model produced by the photographs is actually limited to the common overlapping areas, smaller percentage overlap also means less common area between adjacent photos and thus may lead to worse post-processing result—less accuracy. In general, for large UAV platform, at least 60% latitude (forward) overlap and 25% longitude (side) overlap need to be designed. For our small UAV, these two values are usually set to 75%+ and 65%+ (Ip, A. W. L., 2005).
Algorithms for calculating waypoints of UAV projects

![Diagram of geometry relationship between flight height H, focal length f, sensor size s' and ground image coverage S]

As shown in the above figure, in designing stage, we first consider the easiest case (ideal situation) where flight path is parallel to terrain surface. From equation (1), the approximate flight height can be calculated based on the require GSD. Then, in this step, the below two equations (Kraus, 2007) can be written to express the relationships between the above parameters.

\[
\frac{s'_1}{f} = \frac{S_1}{H} \quad (4)
\]

\[
\frac{s'_2}{f} = \frac{S_2}{H} \quad (5)
\]

Where \( s'_1 \) and \( s'_2 \) are the height and width of camera sensor, \( S_1 \) and \( S_2 \) are the two sides of image ground coverage.

\( s'_1 \) and \( s'_2 \) are defined by the camera, thus keep unchanged during the whole flight. Focal length is usually set to the smallest and it’s usually kept unchanged during the flight in order to get largest coverage and uniform image scale. Thus, from the above equations, the image ground coverage can be calculated.
Then, the defined percentage overlap can be used to calculate waypoints together with image ground coverage.

![Diagram showing calculation of waypoint O from image percentage overlaps and image coverage.](image)

According to the above geometry, the below two functions to calculate ground distance between successive photos in one strip B and ground distance between adjacent strips a can be written as (Kraus, 2007):

\[
B = S_1 (1 - p\%)
\]  
\[a = S_2 (1 - q\%)
\]

Where p\% is the forward overlap percentage and q\% is the side overlap percentage.

The GPS waypoint is actually the centre of rectangle (B x a) as shown above.

Similarly, all the waypoints can be calculated in this way until the whole surveying area is covered, as shown in Fig.10 below (Notice: extra waypoints beyond the edge of the area need to be added to make sure every feature in the surveying area are covered by at least two images):
Then, the text file waypoints can be transformed to real world coordinate system, exported and integrated in the flight control system which transforms the coordinate and additional parameters into control commands and finally being realized through controlling of UAV. It could be able to navigate itself point-to-point depends on the autonomous mobility capabilities of UAV during the flight.
2) **Further consideration stage**

The purposes of this stage are:

- To ensure safety flight of UAV
- To provide a better practice for achieving higher quality of data and image acquisition.
- To satisfy the pre-requirements of image processing.

In the above initial planning stage, the 1D waypoints have been calculated through flying height, percentage overlap and other known parameters. If only ideal situation is considered, the initial stage is enough for UAV flight, actually many planning software does not even consider the second stage, this might be fine for large manned aerial vehicle, but for small UAV terrain mapping, the low-altitude flight with light platform will subject to many possible influential factors such as wind, terrain surface, etc. Therefore, all these factors as well as a better geometry for stereo-photo need to be considered to obtain better results.

The further consideration stage add camera orientations to the waypoint, thus change the 1D waypoints back to 3D geometry.
o **Image Geometry Consideration**

For UAV photogrammetry mapping, there is a general requirement to fly straight-and-level in terms of the terrain surface to produce a reasonably uniform photo scale. However, due to the low altitude of UAV flight and also because the UAV image processing algorithms used by the author is similar to closed-range photogrammetry, a requirement of convergent image geometry is therefore also required to satisfy the intersection requirements of epipolar geometry. This two “trade-off” makes harder for UAV flight planning.

According to Pix4D (2013), an advanced flight path with convergent image orientation can be planned as the following figure.

![Fig.11. Good image orientations](image)

As can be seen, the flight line is still maintained straight-and-level to create uniform photo scales, while at the same time, the relatively changed platform (camera) orientation can provide a better geometry for image processing. The slightly inclined angle of cameras can be realized by onboard compass through autopilot.

Another simpler method is to fly the UAV with a certain angle to the flight path (for Fixed-wing without landing legs), as shown in Fig.12 below. In this way, the images taken in adjacent strips will form a convergent geometry, which is good for post-processing.

![Fig.12. UAV platform with a certain angle to the flight path during flight](image)
o Wind consideration

Wind will mainly have two influences on UAV photogrammetry mapping—increase platform turbulence and reduce image overlaps (Eisenbeiss, 2009).

- Platform turbulence due to strong wind:
  As mentioned above, small size UAVs have unstable imaging platforms as they are easily exposed to wind turbulences during the flight. As a result, the image blocks often consist of a mix of oblique and near-vertical images, these oblique images will probably be hard to be ortho-rectified in the processing stage. More importantly, safety issue need to be considered due to the platform vibration. The ability to operate safely in wind is of great importance to UAV selection. The wind speed at flying height is always one of the first considerations before the flight. In open fields, the wind speed probably doesn’t change too much between ground and flight height, while in urban areas, the buildings, trees and land formations often block or reduce the effect of wind near the ground, much higher winds are experienced by UAVs during the flight. Therefore wind speed information need to be examined before any flight to ensure safety.

- Image overlaps consideration due to wind influence

Wind usually has a direct influence on the image overlaps. Because the GPS waypoint mode is used during the flight, one of the remedy to avoid this influence is to check the wind direction over the area of interest in advance and fly the UAV in up or down wind direction instead of cross wind direction, because cross wind usually lead to large “crab angle” as shown in Fig.13 below:
In this case, the flight path will be maintained in the same direction (UAV ground speed direction as shown above), however, the direction UAV head (UAV air speed) will form an angle with the flight path thus the adjacent images will also form an angle with each other, which will reduce the overlapping areas.

In practise, the wind direction can change during the flight thus it’s hard to be predicted before every flight. Nowadays, some UAV onboard pilot sensors are able to measure the wind direction and speed vector based on the ground speed and air speed as shown in the below figure:
Once the wind speed $V_w$ is calculated by the onboard sensor, the autopilot will decide whether it is satisfied with a certain threshold, if it doesn’t, the UAV will turn back to the home point. For our Sensfly Swinglet UAV (SenseFly, 2013), this threshold is:

$$V_w < \frac{7\text{m}}{s}$$  \hspace{1cm} (8)

Then the angle of crab can be calculated as:

$$\text{Angle of crab } \alpha = \arcsin\left(\frac{V_w \sin|a-b|}{V_a}\right)$$  \hspace{1cm} (9)

Where $a$ is the direction of flight path and $b$ is the wind direction.

If the calculated angle of crab is larger than a certain value, say 15 degrees, for small UAV, the designed overlap might be seriously destroyed. The only remedy is to wait until wind drop down or increase the input percentage overlap before the flight.
- **Terrain Surface consideration:**

The natural terrain surface is very hard to be modelled, even one pre-surveyed DEM can be obtained for the area of interest before flight, UAVs cannot fly completely according to the defined surface features. Therefore, in this work, the terrain surfaces have all been simplified to a two-dimensional straight or curved line representing the basic feature of the terrain surface need to be mapped.

Basically, the two-dimensional line can be extracted from the existing surface model (eg, DEM) by calculating the flow path from contour lines as shown in the below figure.

**Overland flow moves downhill by the steepest path...**

- **Spreads out across flat areas (cells of equal elevation)**
- **Stops in a depression (all surrounding cells greater)**

![Fig.15. Calculating the flow path of a surface model](image)

Then the extracted flow path can be further simplified. And finally, four types of simplified 2D lines representing the terrain surfaces can be acquired, as shown in Fig.16 below.

Basically, most terrain surface can be simplified to one of the four types or as a combination of them. For different types of terrain surface, different flight strategies should be applied. The author proposed some of the feasible flight plans for each of them.
Fig. 16. Four typical line types representing different terrain surfaces

- Flight plan for scenario (1):

The straight-line terrain scenario is relatively easier than the others, not many constraints need to be considered. This type of line usually represents flat area such as urban parks or reserves. The basic waypoints generated from initial planning and camera orientations discussed in Geometry Consideration can be directly applied.

- Flight plan for scenario (2):

In mountainous areas or other extreme terrain relief, it is difficult or even impossible to maintain sufficient conditions: “gaps” between photos will possibly be created by excessive relief if only parallel flight lines are conducted. This “gas”, however, can be “filled” by strips flown at different heights and perpendicular to the initial flight path, as shown in the below
figure, where red lines are the initial flight strips and green lines are remedial strips to fill in the possible “gaps”. For flight planning over mountainous terrain, good knowledge of height variations is necessary to avoid collision and ensure sufficient flight design.

![Side-view of the flight path design](image1)
![Top-view of flight path design](image2)

**Fig.17. Flight path design for extreme terrain surface.**

- Flight plan for scenario (3):

  This situation will occur if the details of an uphill or downhill surface need to be acquired. As shown in the below figure, if straight-line flight is applied to this situation, the image overlapping area between two adjacent strips will decrease towards the uphill direction. Therefore, where there are large height differences between the starting and end points, the recommended forward and side overlaps as well as flight height should be designed for the highest ground point, thus the basic project requirements can be satisfied. Also, the UAV should take off from the highest point as well to ensure safety. In addition, if the grade of hill is very big as shown in the right image in Fig.18 below, the strips might need to be split to different group, and each group has different heights.
Fig. 18. Flight strips in uphill situation. Left: Image overlaps decrease towards uphill direction; Right: Split flight strips into different groups with different heights according to the uphill grade.

A better solution is to fly the UAV parallel to the hill surface as shown in the below figure, each flight strip has different height to maintain the uniform image scale and same image overlap between strips can also be maintained. However, this flight mode might be difficult to be realized by fixed-wing UAV. Therefore, flexible rotary-wing like a helicopter may be used to finish this kind of flight mission.

Fig. 19. Flight strip parallel to hill surface
Flight plan for scenario (4):

For this scenario, because there is abrupt change in the area of interest, the flight strips need to be split into two groups and each group has different flying height according to the terrain height so that similar image scale are maintained for both higher and lower terrain.

Moreover, if the details of the uphill surface are needed, the similar method used in scenario (3) can be added.

![Flight strips for abrupt change surface.](image)

In conclusion, for terrain mapping, the flight path should accord more or less with the linear features of the topography being photographed.
3.1.4 Ground Control Points Measurements

The measurement of ground control points is one of the most important procedures in traditional aerial photogrammetry projects. Because direct georeferencing by using GPS/INS only is still not accurate enough, especially for small UAV where only light-weight pseudorange GPS chip or DGPS receiver can be mounted. Ground truth can be obtained during the UAV flight.

In theory, the size and shape of GCP, the number of GCP and the distribution of GCPs can all have influences on the final results.

- **Shape and Size of GCP:**

  There are mainly two types of GCPs—circle points or cross line points. Compared with circle points, the cross line points have the below advantages:

  - Less distortion than circle or dots;
  - If part of the cross is missing, covered or destroyed during the flight, the centre can always be found.

  Another thing to be considered is that GCPs must be very clear on the image so it can be picked up easily. Thus, the ground resolution and flying height must be considered when designing the size of GCPs. Fig. 21 shows the GCP used in one of our topographic mapping test (30 x 30cm black carpet with 5cm white tape cross):

![Fig. 21. GCPs used in our topographic test](image_url)
It turned out that most of these points are quite clear in the images of 80m flight, however, not really in good quality in the images captured by 120m flight because of the relatively lower ground resolutions.

- **Number and Geometric Distribution of GCPs:**

  - For Traditional Aerial Photogrammetry survey:

    Traditionally, the number of GCPs has a great influence on the results of photogrammetry, because only one bundle block adjustment is usually carried out for the whole block of images, some algorithms even fix the measurements of GCPs and treat them as known values during least squares adjustments. For traditional aerial photogrammetry survey, the more GCPs, the better the precision and accuracy of a project, if the relative accuracy of ground survey is better than photogrammetry itself. But the precision or accuracy will not change much when the number of GCPs reaches a certain level. Meanwhile, setting out and measuring GCPs might be the most time-consuming job in the field. There is a general request to balance the time and accuracy of the surveying. A better geometric distribution of GCPs can also reduce the number of GCPs needed for the required accuracy and precision.

    For planimetric control of the whole block in traditional aerial photogrammetry, tests conducted by others have proved that very little improvement is obtained by adding control to the interior of the block. A distribution of control around perimeter of the block is therefore continued to be the optimum of pattern of planimetric control. In another word, the GCPs should be located scattered around the check points instead of just in one side of the check points. For vertical control, a control point is better to be located in a limited area of no elevation change to avoid extrapolation error and interpolation error as shown below.

![Fig.22. Extrapolation error and Interpolation error of a GCP on an inclined surface](image)
New things For current Computer Vision (image processing) based UAV survey:

However, with the development of new computer vision technologies, the structure from motion technique (Chapter 3—3.1.5) use incremental bundle adjustment (LS adjustment) to refine both camera positions and 3D points once an image is added into the bundle adjustment, this method largely increased the accuracy of relative positions of all images and 3D points. Only during the last iteration, bundle block adjustment is carried out with the measurements of GCPs to correct the scale, transformation and rotation of all images and 3D points as well as only slightly change the relative positions of photos. Furthermore, these GCPs values are only treated as “observed unknown” in least squares adjustment (the theory of structure from motion will be discussed in details in later chapters). Meanwhile, 3D point cloud generated by stereo method can reach sub-pixel level of high accuracy (around 2.3cm ground resolution for 80m flight in our projects). Thus the GCPs measurements do not have as big influences as before on the final results. This also allows the reduction of total GCPs used in one UAV project.

Several tests have been conducted by the author to verify the influence of number and distribution of GCPs on the final result of a UAV project. Both GCPs and check points were measured using network RTK-GPS.

Considering the good sky-view of the test area, the RTK-GPS actually work very well (~2cm accuracy). Check shots have proved the consistency of GPS measurements. Thus, network RTK GPS has been chosen as a comparison.

In each of the test, the network RTK GPS values of those check points have been compared with the corresponding UAV photogrammetry derived values.
Test 1 (small area):

- Test Parameters:

Flights: Combination of 4 flights of different heights (2x80m, 100m, 120m)

Average Ground Sampling Distance (GSD): 3.02cm

Area Covered: 2.34 ha

![Test area (orthomosaic) and Image Ground Coverage (Orange dashed line)](image)

- Test Brief:

The test area is small in terms of the image ground coverage as shown in the above figure. 4 sets of ground control point combinations with different geometry distributions have been compared (3 GCPs, 6 GCPs, 9 GCPs and 12 GCPs). 3 GCPs are located in the centre of the 4 check points (black), others are scattered around.
Result Analysis:

The RTK-GPS measured values of 3D coordinates (Easting, Northing and Height) of the 4 check points are compared with photogrammetry derived values. The differences are plotted against the number of GCPs as shown in the below figure.

As can be seen, both the horizontal (E,N) and Vertical (H) differences fluctuate with the increasing of GCPs numbers, which cannot indicate any direct relationship between the photogrammetry accuracy and the number of GCPs. That’s mainly because of three reasons analysed above:
• As shown in Fig.23, the test area is very similar to the image ground coverage, thus most ground control points are actually located within one image.

• The 3D point densification step create at least one 3D point in each pixel (GSD: 3.02cm), which is quite similar to the RTK-GPS accuracy and thus cannot be detected by using GPS.

Test 2 has been done and described below to further prove this analysis.

Fig.25. Average difference between RTK-GPS values of 4 check points and their corresponding UAV photogrammetry derived values
Test2 (small area):

- Test Parameters:

Flights: One flight of 80m

Average Ground Sampling Distance (GSD): 2.58cm

Area Covered: 2.01 ha

Fig. 26. Test area (orthomosaic) and Image Ground Coverage (Orange dashed line)

- Test Brief:

The test area is small in terms of the image ground coverage as shown in the above figure. 6 sets of ground control point combinations with similar geometry distributions have been compared (4 GCPs, 5 GCPs, 6 GCPs, 7 GCPs, 8 GCPs and 9 GCPs). They are all located around one check point in the middle of the football court and in one side of another two check points in car park as shown below.
Fig. 27. GCPs distributions (Green), Check points locations (Black) and photo waypoints (Red)

- Result Analysis:

The RTK-GPS measured values of 3D coordinates (Easting, Northing and Height) of the 4 check points are compared with photogrammetry derived values. The differences are plotted against the number of GCPs as shown in the below figure.

Similar to test 1, both the horizontal (E,N) and Vertical (H) differences fluctuate with the increasing of GCPs numbers, which cannot indicate any direct relationship between the
photogrammetry accuracy and the number of GCPs. The reason of this has been discussed in test1 result analysis. (Notice: For some reasons, the height measurements are very bad in this set of flight compared with Easting and Northing but still consistent with the increasing of GCPs).

![Average Difference between RTK-GPS values and UAV photogrammetry values of 3 check points](image)

Fig.28. Average difference between RTK-GPS values of 3 check points and their corresponding UAV photogrammetry derived values

Recommendations from Test1 and Test 2:

Use minimum control (3 GCPs) for small area (similar size with image ground coverage) UAV mapping.
Test 3 (Large area):

- Test Parameters:

Flights: Combination of 4 flights of different heights (2x80m, 100m, 120m)

Average Ground Sampling Distance (GSD): 2.96 cm

Area Covered: 23.14 ha

Fig.29. Test area (orthomosaic) and Image Ground Coverage (Orange dashed line)
Test Brief:

The test area is large in terms of the image ground coverage as shown in the above figure. 5 sets of ground control point combinations with different geometry distributions have been compared (4 GCPs spread in Easting direction, 4 GCPs spread in Northing direction, 7 GCPs, 16 GCPs and 25 GCPs). In the first set as shown below, 4 GCPs are spread in Easting direction to the South side of the check points. In the second set, 4 GCPs are spread in Northing direction to the South side of the check points. In the next three sets, GCPs (7 GCPs, 16 GCPs and 25 GCPs) are scattered around and located in both North and South sides of the check points. The figure below displays the locations of GCPs (green cross) and check points (black cross). The red dots are the locations of image centres.

Results Analysis:

1). 3 GCPs

Fig.30. The locations of 3 GCPs (green cross) and check points (black cross).
The figure above shows one set of data with 3 GCPs located in one side (north) of the check points. Check point No.6 is the closest point to the control points, No.5 is the second closest, and No.1 is the farthest point to the three GCPs. The 3D-coordinates difference between RTK-GPS measurement and UAV derived value of each check point was calculated and plotted in Fig.31.

![Difference between RTK-GPS values and UAV photogrammetry values of each of the 6 check points](image)

**Fig.31.** Difference of 3D-coordinates between RTK-GPS measurement and UAV derived value of each check point in dataset 1
2). 4 GCPs:

![Diagram of 4 GCPs and check points in two datasets]

Fig. 32. The locations of 4 GCPs (green cross) and check points (black cross) in two datasets.

The figure above shows two sets of data with 4 GCPs located in one side (south) of the check points. As can be seen, the distribution of the 4 GCPs in data set 1 is slightly different from data set 2. Check point No.1 is the closest point to the control points, No.2 is the second closest, and No.6 is the farthest point to the GCPs. The 3D-coordinates difference between RTK-GPS measurement and UAV derived value of each check point was calculated and plotted in the two figures below.
From the above three figures, it is easily to summarize:

- If the check points are far from the GCPs, the 3D coordinates (especially height) of these check points might have very large errors (eg, No.6).
- The further the check points from GCPs, the larger the errors.
- The geometric distribution of GCPs is important for large area UAV mapping.
To further test the influence of number and distribution of GCPs on the results, the below work has been done:

3). Comparison of 4 GCPs, 7 GCPs, 16 GCPs and 25 GCPs:

![Fig.35. The locations of 4 GCPs, 7 GCPs, 16 GCPs and 25 GCPs](image-url)
As been discussed, 4 GCPs located in just one side of the check points can cause large errors for those check points far from them.

To further check the influence of GCPs distributions on the final result, 7 GCPs have been used, three of them are located to the north side of GCPs and 4 in the south. The result below shows that this geometric distribution can largely improve the accuracy of check points especially for heighting (drop from 490mm difference to 21mm) compared with 4 GCPs.

To test the influence of numbers of GCPs on the result, another 9 GCPs were added to the middle of the original 7 GCPs to form a control network with 16 GCPs. However, there is no obvious improvement of the result as shown below. Similarly, when adding another 9 GCPs to form a network of 25 GCPs, there is still no obvious changes of the check point coordinates either.

![Graph](image)

**Fig.36. Average difference of 3D-coordinates between RTK-GPS measurement and UAV derived value at the 6 check points**
Recommendations form Test 3:

- For large area (compared with image ground coverage), use 4-7 GCPs located near the edge of the area of interest to provide good geometric distribution.
- Don’t use too many GCPs (eg, 10+) for the whole area because:
  1. Very little improvement is obtained by adding control to the interior of the block.
  2. Measuring GCPs is a very time-consuming job.
3.1.4 Image Processing

With the development of small UAVs in civilian market, a better post-processing solution to deal with the captured images has become a hot research topic during the past few years. The traditional software such as LPS, INPHO, etc, are actually suitable for large manned aerial photogrammetry platform with high accurate sensors (e.g., GPS/IMU/vision). With low accurate onboard GPS on UAV, these software packages usually cannot provide sufficient results.

Actually, with the improvement of computer vision technology and technique, there are several robust UAV photogrammetry software packages developed in recent years which are specially designed for small UAV with cheap sensors onboard, such as Pix4D, Agisoft Photoscan, etc. Most of these software packages actually use similar algorithms for image matching and producing sparse 3D point clouds, but there might be difference in the 3D point cloud densification procedure (Deshogue, 2013). Some other closed-range photogrammetry software packages like VisualSFM, Bundler, PMVS and the latest software SURE can also deal with low-end UAV images in an assumed coordinate system.

The below part of the chapter will introduce some of the most robust and advanced techniques and algorithms being used today to process small UAV images. There are mainly three steps in the UAV image processing (Lucieer, et al., 2012)—

- **Image matching:**
  
  Input: Raw photos
  
  Output: Generated matching keypoints; Pairwise matches.

- **Structure-from-motion (SFM):**
  
  Input: Generated matching keypoints; Pairwise matches; For UAV project, some software packages use initial camera positions and GCPs measurements as input as well.
  
  Output: 3D camera position and orientation parameters for each image; 3D point locations of keypoints (sparse 3D point clouds)

- **Multi-view stereo (MVS):**
  
  Input: 3D camera position and orientation parameters;
  
  Output: Dense 3D point clouds reconstruction
3.1.4.1 STEP 1: Image matching

Nowadays, image matching is an automatic technique which can identify and measure corresponding image points that are located on the overlapping area of multiple images. Because of the large amount of UAV data, the image pyramid is sometimes adopted during the process. For UAV image matching, the basic matching methods are normally classified into 2 categories (Gang & Zhang, 2007)—Area-based matching and Feature-based matching. Some of the recent UAV photogrammetry software packages utilise and combine both techniques to obtain relatively larger numbers of matching points (keypoints) of higher accuracy. These software packages usually follow the below flowchart to generate matching points and match image pairs.

Fig. 37. The flow of image matching (Gang & Zhang, 2007)
Area-based matching (ABM) is the classical method used in traditional aerial photogrammetry, but it is rarely discussed in recent publications. ABM uses the grey value of the pixels to describe matching entities. In ABM algorithms, a small window of pixels in the matching images is compared statistically with windows of the same size in the reference image. (Gang & Zhang, 2005). Therefore, the prerequisite of ABM is that grey level distribution of the matching image and reference image must be quite similar, and because the pixel grey value is related to image orientation, image scale, camera parameters and illuminations, etc, the lower quality of UAV images (compared with manned aerial vehicle photograph) usually cannot meet the requirement of ABM. Therefore, feature-based matching becomes the most important matching technique for UAV image matching these days. As shown in the above figure, it needs to be applied to UAV images first to obtain initial matching pairs. Then, area-based matching can be implemented to acquire more accurate keypoints pairs.

Scale-invariant feature transform (SIFT) is the most commonly used feature-based matching algorithms today. It was published by David Lowe in 1999 and was further refined in 2004. (Lowe, 2004). The features detections are invariant to image scale and rotation, and are shown to provide robust matching across a substantial range of affine distortion, change in 3D viewpoint, addition of noise, and change in illumination. This paper below will introduce SIFT algorithms and RANSAC filtering in details.

**SIFT procedures:**

1. **Feature detection and extraction** (Lowe, 2004):

The first stage of computation searches all images to find potential interest points locations. Difference-of-Gaussian (DOG) function is applied to identify these locations that are invariant to scale and orientation. One thing need to be noticed is that lots of these candidate locations are special points such as object corners, edges, etc. Then, at these locations, keypoints are selected based on stability. Afterwards, one or more orientations are assigned to each keypoint based on local image gradient directions. Finally, the local image gradients are measured at the selected scale in the region around each keypoint (David use 4x4x8=128 element feature vector for each keypoint). These measurements are then transformed into representations of keypoints.
After the above steps, the keypoints in each image can be obtained. The below two images from the author’s test are taken as an example to illustrate the SIFT procedure:

![Fig.38. IMG0463 (Left), Detected keypoints numbers: 9813; IMG0465 (Right), Detected keypoint numbers: 8094.](image)

2. **Feature matching** (Lowe, 2004):

Feature matching for two images: reference image+matching image:

For the reference image, the best candidate match for each keypoint in it is found by identifying its nearest neighbor in the database of keypoints from the matching image. The nearest neighbor is defined as the keypoint with minimum Euclidean distance for the invariant descriptor vector. However, a more effective and accurate way is to obtained by comparing the distance of the closed neighbour to that of the second-closed neighbour. The functions of feature matching are displayed below:

- **Keypoints Description in Reference Image:**
  \[ R_i = (r_{i1}, r_{i2}, \ldots, r_{i128}) \]

- **Keypoints Description in Matching Image:**
  \[ S_i = (s_{i1}, s_{i2}, \ldots, s_{i128}) \]

- **Similarity of descriptions between any two points:**
  \[ d(R_i, S_i) = \sqrt{\sum_{j=1}^{128}(r_{ij} - s_{ij})^2} \]

- **Matching points should satisfy:**
  \[ \text{The distance of the closed neighbour of } R_i \text{ in the matching image} < \text{Threshold} \]
  \[ \text{The distance of the second closed neighbour of } R_i \text{ in the matching image} \]
After the feature matching, the reference image and matching image can be matched together as shown in Fig.39 below:

![Feature Matching of IMG0463 and IMG0465 by using SIFT (wrong points included)](image)

**Fig.39. Feature Matching of IMG0463 and IMG0465 by using SIFT (wrong points included)**

In addition, there are many improvement based on SIFT algorithm these years, one of the most famous algorithm might be SURF (speeded up robust feature), which is developed by (Herbert Bay et al) in 2006, it is partly inspired by the SIFT detector but claimed by its author to be several times faster and sometimes more robust than SIFT.
Feature matching for UAV large dataset:

For most UAV projects, there are much more than two images to be matched, matching each pair of image in one big project (usually have hundreds of images) is a very time-consuming job. Therefore, some software packages (e.g., Pix4d) has developed simplified methods by making use of the onboard GPS/IMU values to improve efficiency.

One method to improve image matching efficiency of an image pair is (Shi, et al., 2011):

- Evaluating of approximate overlapping regions based on GPS data, and search for image matching points within the overlap area:

In order to improve the speed of the matching, (Shi, et al., 2011) limit the search space to 10% larger than the approximate overlap area based on the below figure. Fig. demonstrates the overlapping method, where the hatched area is the actual overlap area and the area inside the dashed line is the searching space of keypoints.

![Fig.40. Limited searching space of keypoints](image)

However, again, this simplification method is only suitable for UAVs with relatively high-accuracy GPS, for UAVs with low accurate onboard GPS receiver or under some circumstances where GPS signal is bad, or where strong wind occurs (serious platform vibration cause large difference between actual overlap and designed overlap), this method can cause serious problems and thus usually fail.
A better and more feasible way to improve the matching efficiency of a whole UAV project is:

- **Subset Feature Matching Method:**

  Obviously, the full pairwise matching for all input images in a big UAV project is one of the most time-consuming steps. However, if the matching pairs can be reduced to different subsets, the efficiency will be largely improved. Furthermore, the overall computation can be reduced as well.

  Actually, due to the regular overlap percentage, the diversity of view points and big areas covered in the large UAV projects, the majority of images in the start of the flight do not match the images in the end of the flight, as shown in the below figure. Therefore, a lot of matching time can be saved if the subsets can be identified robustly and efficiently. And in UAV topographic projects particularly, the subsets can be selected based on the predefined percentage overlap, the measured onboard GPS data as well as the visibility classification (upload images, check which images have overlap).

![Fig.41. Pairwise matching for the first image (left corner).](image-url)
For each image in an $n$-photos UAV project, the rest $n-1$ photos need to be matched with it. In total there will be $\binom{n^2-n}{2}$ pairs, which is very time-consuming. (Green dots: Photos; Red lines: matching connection between the first photo and the rest ones)

After identifying these subsets, the feature matching can be carried out just among the image pairs within one subset and image matchings in different subsets can be carried out in the same time. So for a UAV project with $n$ images, the total matching calculation can be reduced from $\binom{n^2-n}{2}$ to a smaller numbers depends on the number and size of subsets (Remondino, 2011). In this way, the total matching time can be largely reduced.

Fig.42. The created subset for the first image (left corner). So only the images within the subset need to be matched with the first image. (Green dots: Photos; Red lines: matching connection between the first photo and the rest ones within the defined subset)
3. **RANSAC filtering** (Fischler & Bolles, 1981)

The image matching algorithm based on SIFT usually result in some wrongly matched points, which will affect the calculation accuracy of 3D coordinates in the next step. Therefore, the wrong matching points must be eliminated. The most commonly used method is called random sample consensus (RANSAC) algorithm. Like its name, this method select randomly 3 pairs of matched keypoints from the reference image and matching image, and transform all the keypoints in reference image to the matching image (realized by Affine Transformation), then, it match reference points to the closes SIFT matching points and compute the overall SIFT difference. If the total number of outliers exceeds a certain defined value, the random selection is failed and all the above steps need to be repeated.

In general, RANSAC is a loop or iteration procedure and it has been proved working efficiently. The below image pairs shows the difference between SIFT matching and SIFT matching+RANSAC.

![Matching result by using SIFT (Left) compared with the Matching result by using SIFT+RANSAC (Right), most outliers have been deleted.](image-url)
4. **Assign ID to keypoints**

In order to simplify the calculation of SFM (next chapter) of large amount of image and data contained in the UAV projects, the same ID can be assigned to the same point pair after the RANSAC filtering (Hu & Ai, 2011), as shown in the below figure.

![Diagram showing simple efficient match strategy where point pair is given the same ID.](image)

**Fig.44. Simple efficient match strategy: Point pair is given the same ID.**

There are two situations need to be avoided in this step:

- When there are more than one same number in the same image (eg, No1 occurs twice in the same image). Remedy: All points have this ID need to be deleted to avoid errors.

- Point ID3 in Photo1 and ID3 in Photo2 match with each other, ID3 in Photo2 matches with ID3 in Photo 3, however, ID3 in Photo1 does not match ID3 in Photo 3 (as shown in the above Fig.). If this situation occurs, the points might be preserved, but this may reflect possible matching errors.
3.1.4.2 STEP 2: Structure from motion (SFM) and photogrammetry

- Brief introduction of SFM and photogrammetry:

A new computing vision technique—Structure from Motion (SFM) has been recently introduced to allow the extraction of sparse 3D points of an object or a scene by analysing motion signal over time (Dellaert et al., 2000). Although this technique was originally developed for closed-range 3D structure reconstruction purposes, it has been proved working well for UAV topographic mapping and 3D modelling (Lucieer et al., 2012). The traditional photogrammetry knowledge has been well integrated into computer vision technology to generated high precision 3D point coordinates and camera parameters by using SFM.

One thing need to be noticed is that the small UAV today usually fly in low altitude (50-120m) and the designed oboard camera orientation will provide a wide range of image capturing angles which in turn provide good camera geometry for SFM processing. Earlier in 2007, the power of this technique was demonstrated by Snavely et al. (2008) who developed the Bundler software and used it to reconstruct 3D models of well-known world site from hundreds of ground-based photographs. It can also be used for UAV photographs. However, this software was originally designed for unordered photos, thus it is much slower and even less accurate than lots of UAV software packages with improved algorithms.

Some of the robust UAV software, eg, Pix4D, also uses SFM technique, these UAV software packages utilize some of the improved SFM procedures and algorithms which largely reduce the processing time and increase the mapping accuracy.

This chapter will introduce the algorithms and procedures of Structure from Motion technique by taking Bundler and Pix4D as examples. These two software packages will be compared with each other, both the advantages and disadvantages will be analysed in this thesis. However, because SFM incorporates photogrammetry knowledge and functions, some of the fundamental photogrammetry theory need to addressed first before the analysis of SFM procedure.
• **Review of fundamental photogrammetry knowledge:**

Basic mathematics equation in bundle adjustment (georeferencing)—the Collinearity Equation (Lee & Rhee, 2013)

Collinearity Equation, as shown below, is used to define the relationship between coordinates in a image plane (in two dimensions) and object coordinates (in three dimensions).

\[
x_p - x_0 = -f \frac{m_{11}(X_p - X_0) + m_{12}(Y_p - Y_0) + m_{13}(Z_p - Z_0)}{m_{31}(X_p - X_0) + m_{32}(Y_p - Y_0) + m_{33}(Z_p - Z_0)} \tag{10}
\]

\[
y_p - y_0 = -f \frac{m_{21}(X_p - X_0) + m_{22}(Y_p - Y_0) + m_{23}(Z_p - Z_0)}{m_{31}(X_p - X_0) + m_{32}(Y_p - Y_0) + m_{33}(Z_p - Z_0)} \tag{11}
\]

\[
M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} =
\]

\[
\begin{bmatrix}
\cos(\phi) \cos(\kappa) & \cos(\omega) \cos(\kappa) + \sin(\omega) \sin(\phi) \cos(\kappa) & \sin(\omega) \sin(\kappa) - \cos(\omega) \sin(\phi) \cos(\kappa) \\
-\cos(\phi) \sin(\kappa) & \cos(\omega) \cos(\kappa) - \sin(\omega) \sin(\phi) \sin(\kappa) & \sin(\omega) \cos(\kappa) + \cos(\omega) \sin(\phi) \sin(\kappa) \\
\sin(\phi) & -\sin(\omega) \cos(\phi) & \cos(\omega) \cos(\phi)
\end{bmatrix}
\]

![Fig.45. The geometry of Collinearity Equation (Alqurashi, 2013).](image-url)
In the above equations, \( x_0 \) and \( y_0 \) are the image coordinates of the principle point, \( f \) is the focal length. These are the internal orientation elements in photogrammetry (others include camera distortion, etc). Internal orientations are usually connected to the camera itself and normally defined by manufacturer (may need calibration).

\( X_0, Y_0 \) and \( Z_0 \) are the object coordinates of the camera point. Omega (\( \omega \)), phi (\( \phi \)), and kappa (\( \kappa \)) are the three orientation elements. These six parameters are known as exterior orientations.

From the mathematics perspectives, because \( Z \) coordinate is on the right hand side of the equation, it’s impossible to solve it by using simple image, thus at least two images are needed to reconstruct the 3-D objects.

Basically, the exterior orientation parameters associated with images can also be determined by Space Resection technique which is based on known ground control points. (Geosystems, 2006)

On the contrary, if the interior and exterior orientations are known, the 3D coordinates of unknown ground points appear in the overlapping areas of two or more images can also be calculated. This technique is called Space Forward Intersection.

The two sections below will introduce two methods of georeferencing for a block of images—Direct and Indirect Georeferencing, respectively.

**Direct georeferencing:**

With integrated low-cost onboard GPS and IMU, which are increasingly used, the exterior orientation elements can be directly determined and the images then processed using the method of direct geo-referencing (Cramer, 2001). The combined devices mounted on the UAV are shown in Figure 3 below.
The exterior orientation defines the position and angular orientation of the camera that captured an image. The positional elements of exterior orientation captured by GPS include $X_0$, $Y_0$, and $Z_0$. These define the position of the perspective centre ($O$) with respect to the ground space coordinate system ($X$, $Y$, and $Z$). $Z_0$ is commonly referred to as the height of the camera above sea level, which is commonly defined by a datum. The rotational elements of exterior orientation determined by IMU describe the angular relationship between the ground space coordinate system ($X$, $Y$, and $Z$) and the image coordinate system ($x$, $y$). Three rotation angles are commonly used to define angular orientation, namely omega ($\omega$), phi ($\phi$), and kappa ($\kappa$).

Based on Collinearity Equation, for each point $P$ observed in the images, the relation between camera and ground coordinate system can be described as follow (Eisenbeiss, 2009):

$$
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
X_0 \\
Y_0 \\
Z_0
\end{pmatrix} + \lambda R_p(\omega, \varphi, \kappa) \begin{pmatrix}
(x' - x_p) \\
(y' - y_p) \\
-f
\end{pmatrix}_p 
$$

(13)

According to the above Figure3, the relationships among GPS, INS and camera positions should be considered when using Equation 6. Therefore, Equation6 can be extended to Equation 7 shown below:

$$
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
X_0 \\
Y_0 \\
Z_0
\end{pmatrix} + R_{INS} \begin{pmatrix}
\lambda R_p^{INS} \begin{pmatrix}
(x' - x_p) \\
(y' - y_p) \\
-f
\end{pmatrix}_p + \begin{pmatrix}
\Delta X_{cam} \\
\Delta Y_{cam} \\
\Delta Z_{cam}
\end{pmatrix} + \begin{pmatrix}
\Delta X_{GPS} \\
\Delta Y_{GPS} \\
\Delta Z_{GPS}
\end{pmatrix}_p.
\end{pmatrix} 
$$

(14)
Where $R_p^{INS}$ is the rotational matrix transferring from image coordinate system to IMU coordinate system, and $R_{INS}$ is the rotational matrix transferring from IMU coordinate system to object coordinate system.

By applying the above formulas, the objective coordinates of point P can be obtained through the exterior orientation determined by the combination of GPS and INS sensors. However, in practical, the GPS/IMU determined values are usually just used as supplementary data to support the aerotriangulation because the current accuracy is still low for surveying and mapping purposes. For small UAV such as Swinglet CAM, because the onboard GPS is only a pseudorange GPS receiver, the mapping accuracy may only reach 0.5-2m according to our tests results. Thus GPS/INS is often adopted to provide the initial values for least squares adjustment in indirect georeferencing method.

Some of the disadvantages of direct georeferencing are listed below (Geosystems, 2006):

- GPS positioning accuracy depends on lots of different factors, such as atmospheric influences, multi-path, etc. And the cycle slips are usually unavoidable.
- The light low altitude UAV usually just has small payload, a GPS chip is usually used instead of DGPS or RTK receiver.
- The combined calibration of GPS, IMU and camera could be a very complicated procedure.
- The datum problem.
Indirect georeferencing for a block of images:

Indirect georeferencing, or block triangulation, is the most common way when processing digital camera imagery. There are several models for indirect georeferencing, including triangulation by independent model, strip block triangulation and Bundle Block Adjustment (Jacobsen, 1997). In this chapter, both bundle block adjustment and triangulation by independent model are analysed.

- 1. Bundle Block Adjustment (BBA)

A bundle of rays that originates from an object point and passes through the projective centre to the image points is able to form the basic computational unit of aerial triangulation, as shown in Figure 3.

![Fig.47. Bundle block adjustment (Jacobsen, 1997)](image)

In aerial photogrammetry, bundle block adjustment utilizes the least squares method to simultaneously estimate the solution for a block of images contained in the whole project as well as minimizing and distributing errors (Faig, 1985). This procedure can be realised based on linearized Collinearity Equations.

Moreover, because there are systematic errors related to the imaging and processing system, such as lens distortion, film distortion, atmosphere refraction, to further improve the accuracy of results, a self-calibrating bundle block adjustment can be introduced (Cramer & Stallmann, 2002). After the self-calibration method being used, the systematic errors can be compensated and a recovery of all parameters could be possible without additional GCPs.
This is of great importance especially for very large-scale imagery and high accuracy georeferencing.

For bundle block adjustment, the Collinearity Equations could be linearized using Taylor’s expansion and written as (Kraus, 2007):

\[
x = (x) + \frac{\partial x}{\partial x_s} dX_s + \frac{\partial x}{\partial y_s} dY_s + \frac{\partial x}{\partial Z_s} dZ_s + \frac{\partial x}{\partial \phi} d\phi + \frac{\partial x}{\partial \omega} d\omega + \frac{\partial x}{\partial \kappa} d\kappa
- \frac{\partial x}{\partial x_s} dX - \frac{\partial x}{\partial y_s} dY - \frac{\partial x}{\partial Z_s} dZ
\]

\[
y = (y) + \frac{\partial y}{\partial x_s} dX_s + \frac{\partial y}{\partial y_s} dY_s + \frac{\partial y}{\partial Z_s} dZ_s + \frac{\partial y}{\partial \phi} d\phi + \frac{\partial y}{\partial \omega} d\omega + \frac{\partial y}{\partial \kappa} d\kappa
- \frac{\partial y}{\partial x_s} dX - \frac{\partial y}{\partial y_s} dY - \frac{\partial y}{\partial Z_s} dZ
\]

The unknowns of each equation are the six exterior orientation elements as well as three object coordinates for an unknown point. If the ray passes through a GCP, \(dX\), \(dY\) and \(dZ\) will disappear.

Least squares adjustment can be applied to the above functions of unlimited numbers of images. Once the least squares adjustment is completed, one can expect to obtain the following results from it (Geosystems, 2006):

- The final exterior orientation parameters \((X_0, Y_0, Z_0\) and \(\omega, \phi, \kappa)\) of each image in a block and their accuracy.

- The final interior orientation parameters \((f\) and \(x_0, y_0)\) parameters of each image in a block and their accuracy.

- \(X, Y\) and \(Z\) coordinates of unknown tie points and their accuracy.

- The adjusted GCPs coordinates and their residuals.

- The image coordinates residuals.

- The systematic errors

One way to improve the accuracy of bundle block adjustment is GPS and IMU assisted...
aerotriangulation. As mentioned in the direct georeferencing chapter, GPS/IMU information could be used to support aerotriangulation. The combined method of GPS/IMU and GCPs to achieve georeferencing is called integrated sensor orientation. In least squares adjustment, the GPS/IMU obtained values are treated as initial or “observed unknown” (Kraus, 2007). Hence original bundle block adjustment and GPS/IMU model could be processed together.

Many aerial triangulation softwares utilise bundle block adjustment to do georeferencing, there are lots of advantages, such as (Kraus, 2007):

- Most accurate method without using intermediate model coordinate systems.
- Simple possibility to incorporate observed exterior orientation into adjustment.

However, some disadvantages are also associated:

- It’s a computer-intensive methods which might need long time running for large amount of data.
- The planimetry and height adjustment cannot be separated.
**Block adjustment by independent models**

Besides bundle block adjustment, there are other ways to solve the orientation problems. The orientation procedure shown in the below figure has been divided to two steps.

![Block adjustment by independent models](image)

**Fig. 48. Block adjustment by independent models (Jacobsen, 1997)**

The first step is the relative orientation from image coordinate system to 3-D model coordinate system and the second step is the absolute Orientation from model coordinate system to ground coordinate system.

The principle of block adjustment by independent models is explained below.

The points in each model are firstly defined in an independent spatial model coordinate system determined by the adjacent perspective centres and tie points of the two corresponding images. This procedure is called relative orientation (Jacobsen, 1997). In relative orientations, the observations are image coordinates and outcomes are model coordinates. The model coordinate x, y and z are introduced instead of ground coordinates X, Y and Z. The increments to the orientation elements are introduced instead of the orientation elements values (Kraus, 2007). Therefore, there is no need to know the starting exterior orientation values.

Secondly, the model coordinate system can be transformed to ground coordinate system by the seven elements of absolute orientation. For the simultaneous absolute orientation of all models in the block, the observations are the model coordinates of the tie points and
perspective centers, and the outcomes are the ground coordinates. The relationship is given by a three dimensional 7-parameter similarity transformation as shown below:

\[
\begin{pmatrix}
X \\
Y \\
Z \\
\end{pmatrix} = \begin{pmatrix}
X_u \\
Y_u \\
Z_u \\
\end{pmatrix} + mR \begin{pmatrix}
x \\
y \\
z \\
\end{pmatrix}
\]  

(17)

In which, \( X_u, Y_u \) and \( Z_u \) are the object coordinates of the \( xyz \) system, \( m \) is the scale factor of \( xyz \) system and \( R \) is the 3D rotation of the \( xyz \) system into the \( XYZ \) system defined in terms of the three rotations.

In theory, because there are seven parameters to be solved, at least seven equations are required. Therefore, either two plan control points (\( XY \) known) and three height control points (\( Z \) known) or two full control points (\( XYZ \) known) and a height control point (\( Z \) known) not collinear in plan with the full control points are needed for absolute orientation (Kraus, 2007). However, in practical, more GCPs are necessary to provide a sufficient accuracy.

This method is still in use today, but several shortcomings are connected with this method, including the loss of information caused by the relative orientation (4 photo coordinates to 3 model coordinates) and the corresponding loss of accuracy, especially in the height (Jacobsen, 1997). Thus bundle block adjustment (BBA) discussed above is still the first priority in most situations.
• **SFM procedures:**

After introducing the basic photogrammetry knowledge, this part will mainly demonstrate how the Structure from Motion works, how SFM incorporate the photogrammetry knowledge and will also express the differences of software packages of utilizing SFM procedures. This thesis will take the procedures of Bundler and some advanced UAV photogrammetry software packages as examples, compare these software procedures, and to show the reason why the current most robust UAV software packages are very suitable for small UAV image processing.

• 1. Bundler (Snavely et al., 2008):

Bundler is actually an early software which use SFM technique to efficiently solve for large collections of overlapping photographs. It is based on the SIFT+RANSAC matched keypoints, and least squares adjustment for the calculations. It is very good for unordered images. No prior knowledge is required on the position and orientation of the camera or lens distortion parameters.

Bundler follows the below procedure to process unordered images:

1) Firstly, conduct SIFT matching between each pairs.
2) Then, start from an initial pair with large baseline and large number of matching points, extract the camera focal length from the EXIF files, then conduct least squares adjustment on Equation (10) and (11), to obtain the initial values of these two cameras’ positions and attitudes. In this least square adjustment, the observations are focal length f, image coordinates of SIFT keypoints \(x_p,y_p\), the unknowns are 6 camera external parameters—\(X_0, Y_0 \text{ and } Z_0\), Omega (\(\omega\)), phi (\(\phi\)), and kappa (\(\kappa\)) , keypoint 3D coordinates \(X_p, Y_p \text{ and } Z_p\). because SIFT+RANSAC can usually provide large number of keypoints, the least squares solution usually have more than enough redundancy.
3) Adding new image which has the largest number of image matching pairs to the initial pair, conduct least square adjustment to these three images (the initial pair and the new image) to obtain the parameters of the third one and refine the parameters of the initial pairs as well as 3D points coordinates.
4) Continuously adding new images following the above procedure until all the available images are computed, so all the camera positions, orientations, lens distortion and the 3D coordinates of each SIFT feature can be obtained. This procedure is actually called incremental bundle adjustment, which just like its name shows— adding images one
by one. (2) and (3) follow the relative orientation step described in 3.1.4.2 — 2. Block adjustment by independent models.

5) Because Bundler is a computer vision open source code, it only performs in an assumed 3D coordinate system, while it doesn’t involve coordinate transformation to ground coordinate system such as MGA94 or WGS84, etc. Therefore, a 7-parameter similarity transformation (Equation (17)) need to be added into it to acquire ground coordinates for surveying purpose. Step (4) follows the absolute orientation step described in 3.1.4.2 — 2. Block adjustment by independent models.

After the above steps in Bundler, the geo-referenced sparse 3D points can be acquired.

However, as discussed in 3.1.4.2 — 2. Block adjustment by independent models, there might be some shortcomings of this method for surveying and mapping purposes, which could be both time-consuming and less accurate.

- 2. Robust UAV software packages (eg, Pix4d):
  1) Use SIFT and its modified version to generate matching keypoints and match images, due the large numbers of images in UAV projects, some of the simplified methods discussed in 3.1.4.1— Feature matching for large UAV dataset have been adopted to improve matching efficiency.
  2) Then, in each of the subset (Described in 3.1.4.1— Feature matching for large UAV dataset), the initial pairs with large baseline and large number of matching points will be chosen and least squares adjustment on Equation (10) and (11) will be conducted for all of the initial pairs in different subsets at the same time (parallel processing) which can largely reduce the time needed.
  6) Adding new images to each of the subset initial pairs, conduct least squares adjustment to obtain the parameters of new images and refine the parameters of the initial pairs as well as 3D points coordinates.
  3) Continuously adding new images following the above procedure until all the available images are computed.
  4) Finally, all images will be added into the model and form the whole image block, then in the last LS adjustment, conduct bundle block adjustment including GCPs (Described in 3.1.4.2- Bundle Block Adjustment (BBA)) to simultaneously refine the
related parameters such as camera parameters, 3D coordinates of SIFT keypoints and also adjust the GCPs coordinates. Because all parameters are treated as “observed unknowns” with different weights, the final results are usually more accurate.

- Comparison of Bundler and Robust UAV software packages

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<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
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</thead>
<tbody>
<tr>
<td>Robust UAV software</td>
<td>- More efficient for UAV images—improved matching techniques and parallel LS</td>
<td>- Initial camera positions (onboard GPS observations) are needed.</td>
</tr>
<tr>
<td>(eg, Pix4d)</td>
<td>processing as discussed above.</td>
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<td></td>
<td>- Usually more accurate—use bundle block adjustment by incorporating GCP</td>
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</tr>
<tr>
<td></td>
<td>values in the last LS adjustment to get a better ground coordinates for</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3D point clouds.</td>
<td></td>
</tr>
<tr>
<td>Bundler</td>
<td>- Better for unordered images with unknown camera parameters.</td>
<td>- 3D point clouds only in assumed coordinate system, extra similarity</td>
</tr>
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<td></td>
<td></td>
<td>transformations are needed; The algorithms used make it very Time-consuming</td>
</tr>
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3.1.4.3. STEP 3: Multi-view Stereo (MVS)

The goal of multi-view stereo (MVS) is to reconstruct a dense 3D point cloud or complete 3D object model from a collection of images taken from known camera viewpoints. As discussed in the last chapter, SFM algorithms can generate sparse 3D point clouds as well as camera positions and orientations, while MVS is able to take the output (usually just camera orientation parameters) from SFM step as its own input, and continually producing dense 3D point clouds.

This chapter below will mainly introduce two methods of MVS for point cloud densification.

The first one to be discussed is called Patch-based MVS (Furukawa, Y., & Ponce, J., 2010.), developed by Yasutaka Furukawa in Washington University in 2010. It has been very popular and been implemented into many software packages during the last two years. Basically, this method is a “surface growing” algorithm, which initialize surface patches and the respective orientations based on salient feature points. Then it expand the surface around these patches and reconstruct the whole 3D scene.

The second one to be discussed has just been published by University of Stuttgart in 2012, it is a very robust MVS technique which can be used to deal with both closed-range and traditional aerial photogrammetry images. This algorithm relies on an optimized semi-global matching technique (tSGM), where corresponding pixels of different images are searched based on epipolar geometry firstly, then a disparity (or parallax) of each pixel is stored for each image matching pair. Finally a triangulation is performed to reconstruct a smooth 3D surface. This algorithm has been implemented into an in-house software package—SURE (Wenzel et al, 2012).

The commercial UAV software Pix4d also has built-in 3D point densification algorithms, however, the actual technique being used has not been published yet.

This thesis below will introduce the two published techniques mentioned above in details, and in the end of this chapter, dense 3D point clouds generated by the three software packages—PMVS, SURE and Pix4D will be compared by the author.
• **Patch-based MVS (PMVS)** (Furukawa, Y., & Ponce, J., 2010.):

Patch-based multi-view stereo is a 3D point creation and densification technique which increase the computation flexibility and efficiency by giving each 3D point a “patch” to approximately represent the surface. It contains three steps—matching, expansion and filtering.

*Matching:*

Feature matching is used to produce sparse 3D point cloud based on epipolar geometry. As shown in the below figure. To do calculation based on epipolar geometry, the accurate positions and orientations of images must be known, and these values can be acquired from the SFM procedure. However, it does not necessarily need to use the sparse 3D points generated from SFM, instead, it can start from feature detection. The feature detection technique used in PMVS is very similar to SIFT, by using Harris and Difference-of-Gaussian algorithms. After the features being detected in an image pair, the feature matching can be performed according to the above figure—for each f detected in image I1, a set F of features f' which have the same type with f need to be collected, and then locate the matching feature f' line within two pixels from the corresponding epipolar line. And then point P can be triangulate (intersect) from f and f' (The below part will take point P as an example).

Then, 5 parameters need to be initiated and assigned to the point P, include—

- c(P), which is the centre of point P, can be triangulated from f and f'.
- n(P), which is normal vector, with a direction pointing from c(P) to the camera point of image I1.
- R(P), which is selected as the reference image in which the patch P is visible.
- V(P), which is a set of images in which point P is visible

\[
V(p) \leftarrow \left \{ I \left | n(p) \cdot \frac{c(p)O(I)}{|c(p)O(I)|} > \cos(t) \right \} \right .
\]

V(P) can be determined by the above function, which assume the patch is visible in an image Ii if the angle between n(P) and the direction from the patch to the optical centre O(Ii) of the camera is below a certain threshold.

- V*(P), which is the refined V(P), and V*(P) is a set of images chosen from V(P) satisfy the below criteria:
\[ V^*(p) = \{ I | I \in V(p), h(p, I, R(p)) \leq \alpha \} \]  

In this formula, \( h(p, I, R(p)) \) is the photometric discrepancy function between image \( I \) and \( R(P) \), if the value derived from this function is below a certain threshold \( \alpha \), the image \( I_i \) can be chosen. So \( V^*(P) \) is a set of certain images \( I_i \).

After the acquisition of the above five parameters, \( c(P) \) and \( n(P) \) still need to be optimized to minimize the photogrammetry discrepancy function score for point \( P \):

\[ g^*(p) = \frac{1}{|V^*(p) \setminus R(p)|} \sum_{I \in V^*(p) \setminus R(p)} h(p, I, R(p)). \]  

To minimize this value, both \( c(P) \) and \( n(P) \) need to be changed and refined, \( c(P) \) can be refined by moving it through a ray connecting the reference image centre \( O(R(P)) \) and the projection point of \( P \) in image \( R(P) \). Notice: \( c(P) \) should be constrained in the ray such that its image projection in \( R(P) \) does not change. And for the optimization of \( n(P) \), the pitch (x axis) and yaw (y axis) angles of the patch can be changed to minimize the score.

Then, after the patch being optimized, \( V(P) \) and \( V^*(P) \) need to be updated again, same procedure as discussed above should be implemented.

The last step in Feature matching is to preserve the generated patch \( P \). To do this, a verification formulae need to be applied (Here, Dr Furukawa use \( r=3 \)):

\[ |V^*(p)| > \gamma \]  

If the above formulae is satisfied, the patch \( P \) can be added to \( Q(x,y) \) and \( Q^*(x,y) \), where \( Q(x,y) \) is the set of patches \( (P_1, P_2, \ldots, P_n) \) project into \( Ci(x,y) \) and \( Q^*(x,y) \) is the refined \( Q^*(x,y) \) according to \( V^*(P) \).
**Expansion:**

From the above Matching step, a sparse set of points with patches representing the surface could be obtained, but a higher density of 3D points is still needed. To expand the sparse 3D points to dense point cloud, this step is the most important procedure.

Firstly, a set of neighbouring image cells $C(p)$ need to be identified in one image contains point $P$.

$$C(p) = \{C_i(x', y') | p \in Q_i(x, y), |x - x'| + |y - y'| = 1 \}$$

(22)

Any image cell satisfy the above formulae is treated as the neighbouring cell of the cell contains point $P$.

Then, the patch can be extended to the neighbouring image cells, UNLESS:

- The neighbouring cell contains a patch $P'$ which is the neighbour of patch $P$. In this case, the neighbour cell will be removed from set $C(p)$. To judge whether $P'$ is the neighbour of $P$, use formulae:

  $$|(c(p) - c(p')) \cdot n(p)| + |(c(p) - c(p')) \cdot n'(p')| < 2p_1.$$  

(23)

- When there is depth discontinuity:

  Even if $P'$ is the neighbour of $P$, the left side of the above equation will still be larger than $2P$ due to large discontinuity. To avoid redundant creation of 3D point, Dr Furukawa just simply judge that the expansion is unnecessary due to a depth discontinuity if $Q8(x', y')$ is not empty.
After all the above conditions being considered and eliminated, for the rest of neighbouring image cells of the cell contains point P, the expansion can be conducted by:

1) Copy R(P’), V(P’) and n(P’) directly from P to P’.
2) Intersect the optical ray through centre of C(x’, y’) with plane of p to obtain c(P’) as shown in the below figure.
3) Refine c(P’) and n(P’). (Patch optimization)
4) Refine V(P’) and V*(P’)
5) If V*(P’) > r, add the patch P’ to Q(x,y) and Q*(x,y)

After this step, the new 3d point P’ can be created. Similarly, this method can be applied to each of the 3D points generated from Matching step and iterated multiple times (Dr Furukawa iterate this expansion step 3 times). Finally, the filtering can be applied to the 3D point cloud to filter out the unexpected outliers.

The code of Patch-based MVS is open-source and can be downloaded online, it is not easy to be fully understood by people who do not have computer vision background. However, the fundamental idea of this MVS solution are quite easy—it actually contains some approximations, assumptions and iterations, with the increasing of iteration number, there will be a decreasing of point accuracy and precision. Therefore, the iteration numbers should be limited to 3 or less to avoid error accumulation. But this in turn will reduce the point cloud density. This is a “trade-off” thing and should be adjusted according to different applications.

From this point of view, the below method—tSGM-based MVS might be a more robust way of producing dense 3D point cloud.
tSGM-based MVS (SURE) (Wenzel et al, 2012):

This technique is split-up into four main modules—initialization, rectification, matching and triangulation.

In initialization step, the base image $I_b$ and $I_m$ is chosen, then in initialization, the base images are rectified and become two epipolar images. These two epipolar images have the same optical centres as the original two images, but have different camera orientations. The reason of rectification is that by using epipolar rectification, corresponding pixels only need to be searched along the direction of the epipolar line $l'e'$ in image $I_m$, as shown in Fig.50.

![Epipolar Geometry](image)

In the dense matching step, SGM technique is implemented. The corresponding pixels across two views representing the same world object are searched according to epipolar geometry derived from rectification step. Then for each pixel, a disparity is stored and for all pixels, a whole disparity image will be formed based on each disparity. This disparity image contains the correspondence information for the two matching images. In this step, a modified SGM version—tSGM is actually being used by SURE. With the original SGM, the range of disparity to be evaluated for each pixel is fixed over the whole image, this is might be suitable for large format aerial images which have the similar resolution. However, with low-altitude fixed-wing UAV flight or closed-range multicopter UAV for structure reconstruction purpose, the various images acquired could lead to large range of disparity, which means fixed disparity search range can result in huge computation time. To compensate for this
shortage, the disparity search for each pixel is narrowed down according to different resolution levels, as shown in Fig.51 below.

![Fig.51 Hierarchical strategy. The disparity search range for each pixel is narrowed down using different resolution levels. Left: from low resolution to high resolution, the range is narrowed down for each pixel individually. Upper right: The original cost cube as used in SGM and the dynamic concept as used within SURE (lower right)](image)

After the above step, the matched images and correspondent disparity images can be obtained. All these will be treated as input for triangulation step, and the output is 3D point cloud. Redundant disparities representing the same surface area will be used to remove possible errors and improve precisions.
3.1.4.4. Comparisons of 3D point clouds generated by different algorithms

The same set of data has been used to test the performance of different algorithms in producing 3D point cloud as discussed above. The dataset parameters and results comparisons are list below:

Dataset Parameters:

- Test area: 23.14 hectares
- Flight height: 120m
- Total numbers of photos: 61

Software and Algorithms:

Three different software packages using different algorithms are compared in this test, most of the algorithms have been introduced and discussed in 3.1.4—Image Processing:

- VisualSFM: It use pairwise SIFT matching method for image matching; an improved parallel bundle adjustment algorithms (similar to Bundler, but much quicker) for producing image orientation and sparse 3D point cloud; and PMVS for generating dense 3D point cloud.

- SURE: It can take the output—image orientation from VisualSFM first and use tSGM algorithms for 3D point densification

- Pix4D: It use an modified SIFT specialized for UAV images for image matching; an improved parallel bundle adjustment (similar to Bundler, but not open source yet) for producing image orientation and sparse point cloud; Because Pix4D is an commercial software, the 3D point densification algorithm or methodology hasn’t been published yet.

The image matching and structure from motion algorithms involved in the above three software packages are similar to each other. However, the Multi-view stereo algorithms for point cloud densification are quite different (PMVS and tSGM have been introduced in 3.1.4.3. STEP 3: Multi-view Stereo (MVS))
Result comparisons (Relative orientations (indicate inner accuracy) only):

The three figures below display the 3D point clouds generated from the three software packages and their relevant information. In general, the more the 3D points can be generated, the better the inner accuracy will be.

Basically, Pix4d is able to provide the most efficient solution with the shortest time (24mins in total) and moderate density of 3D point cloud (3552888 points). For flight height of 120m, it is good enough for general purpose terrain mapping with 1-5 centimetre accuracy requirement. However, it’s not able to mapping the vegetation in details as shown in Fig.54.

SURE (tSGM) is able to provide everything in great details, even the vegetation can be mapped accurately (Fig.53). In total, there are 167644677 points produced, which is comparable with laser scanning technique. However, it’s relatively much more time-consuming (more than 3 hours in total) and requires large data storage (8GB for this test). It might be more suitable for vegetation mapping purpose.

VisualSFM (with PMVS) is not as good as the other software packages, large deficiency occurred in the generated 3D point cloud as shown in Fig.52 below.

<table>
<thead>
<tr>
<th>Methodology and Algorithms</th>
<th>Image Matching and Structure From Motion</th>
<th>Multiview Stereo</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFT + Improved Bundler</td>
<td>Patch-based multiview stereo (PMVS)</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>4min 24s</td>
<td>26min</td>
</tr>
<tr>
<td>Total numbers of 3D points</td>
<td></td>
<td>1,993,638 points</td>
</tr>
</tbody>
</table>
Fig. 53. 3D point cloud generated by SURE.
Fig. 54. 3D point cloud generated by Pix4D
3.2 Summary of Procedure Analysis:

3.2.1 Conclusion of UAV mapping procedure

In Chapter 3.1, the UAV mapping procedure has been discussed and analysed in details. Different results generated from image processing have been compared with each other and used to test the influence of different factors such as flight height, ground control points and image processing algorithms. The basic idea of these tests is that when testing the influence of one certain factor, the other factors should be kept unchanged.

From the procedure analysis and results comparisons, it’s not hard to observe that for computer vision based photogrammetry, the image itself (eg, image quality, image ground resolution and image geometry) is the most important thing for relative orientations of images and relative positions of 3D points. GCPs and onboard GPS measurements are only used in bundle block adjustment to transform the 3D points from assumed coordinate to real world coordinate system in today’s UAV photogrammetry algorithms. Therefore, in the planning stage, one should especially pay attention to the images captured during the flight rather than other factors. Basically, to ensure one UAV project to be successful, the elements below should be carefully considered:

- Ensure good quality photos can be obtained during the flight.

Several methods can be used to ensure good quality photos:

1) Use professional camera with advanced image forward compensation which can largely reduce the image blur.

2) For small payload UAV, if only compact camera can be mounted on it, try to reduce the vehicle speed or camera shutter speed. Some UAV such as Swinglet CAM can achieve “waypoint zero speed”, which means the UAV is able to decelerate when it’s approaching the waypoint and accelerate when it is moving away from the waypoint.

3) Moderate illumination is very important for image quality, either strong sunlight or dark environment can cause trouble. Thus the best time for flying might be sunny morning.
• Good image geometry and distribution.

This involves convergent image geometry and sufficient overlaps between photos. As discussed in Chapter 3.1.1.2. Flight planning for terrain mapping — Image Geometry Consideration, several methods can be used to get good geometric photos; Sufficient overlaps need to be pre-programmed using the algorithms discussed in Chapter 3.1.1.2. Flight planning for terrain mapping — Algoritms for calculating waypoints of UAV projects.

• Suitable image ground resolution.

The image ground resolution or ground sampling distance is closely related to the mapping accuracy (Chapter 3.1.1.2. Flight planning for terrain mapping — Flight height), and both of these factors can be realized by choosing proper flight height.

Meanwhile, a suitable image processing software package is needed for producing accurate and dense 3D point cloud as well as other products such as orthomosaic. Those free software packages or open source codes that have been discussed and tested in this thesis project can provide sufficient results for 3D mapping purposes. Further discussion of results will be conducted in Chapter 4.

3.2.2 Proposed workflow for UAV mapping project

The Inter-Governmental Committee on Surveying and Mappking (ICSM, 2007) have defined the best practices guidelines for some surveying techniques and the standards of accuracy for control surveys, which include recommended survey and reduction practices guide for astronomical azimuth determination, EDM, horizontal angle measurement, levelling, trig-heighting, GPS and horizontal control survey by photogrammetry. However, there is no complete survey guideline for UAV photogrammetry technique yet. Mainly due to the diversities of UAVs used in civilian market. However, an optimized procedure for UAV mapping will possibly help improve and facilitate the development of UAV in future civilian market.
A proposed workflow for small UAV photogrammetry mapping project was created by the writer and displayed as follows.
3D Mapping with UAV: Procedure Analysis and Performance Evaluation
4. Tests Results and Analysis

4.1 Case Study 1: Fixed-wing UAV (eBee) Terrain Mapping in Wollongong

Brief introduction

The UAV flight test in Wollongong was conducted on 11th April, 2013 by the Ultimate Positioning Group. The test area (about 9 hectares) is located around Unanderra Park. A total number of 58 photos were taken during the flight. The test area is shown in Fig.55 and the relevant information is displayed in Fig.56.

![Figure 55. Test area of UAV flight in Wollongong](image)

The mapping UAV used during the demo is eBee manufactured by Sensefly Ltd. The eBee is a lightweight small UAV (500g) which can be launched by hands. It is able to cover 10 sq km in one flight when the wind speed is below 12m/s. Normally, it’s fully autonomous during the entire flight including taking-off and landing. This test is divided into three main parts, including planning and simulating part, UAV flight and Data acquizition part as well as image processing part.

In the planning and simulating part, the project parameters including test area, coordinate system and desired GSD accuracy, etc is defined and analysed. Then the flight path is generated by using the associated software Sensefly eMotion 2, which can also be used as a
flight monitoring tool when connected with eBee by radio link. In Data acquisition part, the eBee flight was performed above Unanderra park, the whole flight process was monitored by eMotion 2, as the flight was very smooth, nothing has been changed from the original plan and no manual operation was conducted. In the last step—image processing, Aerial triangulation was conducted and final results including geo-referenced images, DEM and the quality report, etc was generated.

The below part of this chapter will focus on the case study, helping review the basic UAV mapping procedures.

**Step1: Flight planning**

The hardwares and softwares along with some project parameters for this test was displayed in the below figure.

![Figure 56. Information of UAV flight in Wollongong](image)

eMotion 2 is the main software used to generate flight path according to the input parameters. A complete flight plan for a eBee is composed of two separate phases: the setup phase and
the mission phase. The mission phase includes waypoints and actions related to mapping and capturing images. The setup phase includes waypoints and actions related to take-off and landing.

Firstly, a new project was created, the project parameters including measured wind speed were input into the software. Secondly, the set up phase was done by choosing the taking off point, Start waypoint (where the UAV begins to fly towards the first waypoint) and Home point (Or landing point). Thirdly, the mission phase was prepared by selecting and positioning the rectangle around the area of interest. Then the entire flight path will be produced and displayed on the screen. The figure below shows the generated flight path for this project in eMotion 2. Afterwards, this prepared flight plan can be saved to a file and uploaded to navigation sensors in eBee.

![Fig.57. eMotion 2 generated flight plan.](image)

**Step 2. UAV flight and Data acquisition**

As discussed in the previous chapter, only certified operators who have granted the CASA approval is able to conduct the UAV flight in the field. The first thing before the flight is to check the weather condition, most mini UAV including eBee can not be operated in the rain and heavy wind conditions. In the field, The wind measured on that day was 3m/s which is far below the maximum wind speed (12m/s). Then the hardware was double checked and eBee
was connected to eMotion 2 right afterwards. The flight plan generated in the first step was used.

After the acquisition of onboard GPS signal, the current position of eBee can be obtained and on the eMotion side control bar, “ready to take off” was shown. Then the eBee could be launched by hands against wind direction.

During the flight, eBee was monitored by eMotion 2 as well. The Map area in figure 13 displays the current position including flight height from taking-off point. It’s updated live as the eBee executes its flight. The photo footprint was also displayed during flight. Fully automatic flight was conducted because no emergency (eg, strong wind, low battery) happened on that day.

After acquiring all images, the eBee flew towards the Home Point, measured the wind direction by the onboard sensor and landed itself against wind.

All images together with log data (GPS/IMU observations) could be downloaded from the camera and other sensors for further analysis.

Five Ground Control points distributed evenly throughout the working site were measured by using Trimble RTK GPS. Because most of the GCPs used are located inside the park, the good skyview and other environmental conditions should be able to produce relatively good results.

**Step 3. Image processing**

The image processing software selected for this project is Postflight Terra 3D which is also an associated Sensefly production. It’s an advanced photogrammetry software designed for eBee and Swinglet CAM UAV. By simply importing the images and their corresponding EXIF information (GPS/IMU data), the project can be established. All of the GCPs can be uploaded and identified in the images. Then, Bundle block adjustment could be run to generate the initial results of point determination, adjusted external and internal orientations, which are followed by point cloud generation, orthomosaic and DEM productions. (During the processing, the internal orientations were treated as initial values, camera self-calibration method was used.)
When the GCPs are added, a window below will be displayed to allow the control points to be identified in the corresponding images. At least two images should be used to define a common control points to define the 3D coodinates as discussed in literature review part. Optimal accuracy is usually obtained with 5 GCPs each identified in 5 images. More GCPs or clicks are usually not necessary because it may increase manual effort, time and cost.
After the identification of GCPs in the images, the GPS/IMU-assisted bundle block adjustment was conducted and all different kinds of results could be generated from Postflight 3D and other assisted software packages.

**Time evaluation**

The table below shows the time spent on this project including the three steps mentioned above—Flight planning, Data acquisition and Image processing.

<table>
<thead>
<tr>
<th>Time spent on UAV demo in Wollongong</th>
<th>Step</th>
<th>Activity</th>
<th>Time (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight planning</td>
<td>Project parameters set up</td>
<td>5 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flight plan generation</td>
<td>3 min</td>
<td></td>
</tr>
<tr>
<td>Data acquisition</td>
<td>eBee flight</td>
<td>15 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GCPs setup and measurement</td>
<td>15 min</td>
<td></td>
</tr>
<tr>
<td>Image processing</td>
<td>Initial processing</td>
<td>5 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Point cloud generation</td>
<td>20 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orthomosaic production</td>
<td>20 min</td>
<td></td>
</tr>
<tr>
<td>Total time</td>
<td></td>
<td></td>
<td>83 min</td>
</tr>
</tbody>
</table>

Among the above activities, the GCPs setup and measurement were conducted at the same time during the UAV flight.
4.2. Initial Results and analysis of UAV flight test

4.2.1. Results generated from UAV software—Postflight terra 3D

The results generated from Postflight terra 3D include:

- The adjusted coordinates of GCPs and their associated errors.
- The optimized interior orientations including Focal length, coordinates of Principle points, coefficients of radial and tangential distortion.
- The adjusted exterior orientations including object coordinates of principle points and image orientations.
- DEM, Orthomosaic, Point clouds, Triangle model(TIN) and 3D model.
- An overall Quality Report

Basically, the first three results listed above are generated from bundle block adjustment, and the others are additional and important UAV products. This chapter below will introduce the results produced by the writer in details.

- General bundle block adjustment information:

<table>
<thead>
<tr>
<th>Table 6 . General bundle block adjustment information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number total keypoint observation for bundle block adjustment</td>
</tr>
<tr>
<td>Number total points for bundle block adjustment</td>
</tr>
<tr>
<td>Mean reprojection error</td>
</tr>
</tbody>
</table>
• The adjusted coordinates of GCPs and their associated errors:

Table 7. Adjusted coordinates of GCPs and their associated errors

<table>
<thead>
<tr>
<th>GCP name</th>
<th>Measured coordinates (X/Y/Z)</th>
<th>Adjustment coordinates (X/Y/Z)</th>
<th>Error X(m)</th>
<th>Error Y(m)</th>
<th>Error Z(m)</th>
<th>Measured/Verified</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>302003.892 6185699.437 13.026</td>
<td>302003.898 6185699.429 13.054</td>
<td>0.006</td>
<td>0.008</td>
<td>0.028</td>
<td>10/10</td>
</tr>
<tr>
<td>2</td>
<td>302050.652 6185755.314 12.263</td>
<td>302050.650 6185755.297 12.232</td>
<td>0.002</td>
<td>0.017</td>
<td>0.031</td>
<td>9/9</td>
</tr>
<tr>
<td>3</td>
<td>301957.273 6185822.687 13.182</td>
<td>301957.258 6185822.706 13.169</td>
<td>0.015</td>
<td>0.019</td>
<td>0.013</td>
<td>10/10</td>
</tr>
<tr>
<td>4</td>
<td>301939.058 6185764.302 13.787</td>
<td>301939.062 6185764.304 13.785</td>
<td>0.004</td>
<td>0.002</td>
<td>0.002</td>
<td>9/9</td>
</tr>
<tr>
<td>5</td>
<td>301902.474 6185642.355 15.015</td>
<td>301902.484 6185642.368 14.982</td>
<td>0.010</td>
<td>0.013</td>
<td>0.033</td>
<td>8/8</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>0.007</td>
<td>0.012</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>Std</td>
<td></td>
<td></td>
<td>0.005</td>
<td>0.006</td>
<td>0.012</td>
<td></td>
</tr>
</tbody>
</table>

As discussed in the literature review part, the measured coordinates of ground control points by RTK GPS are treated as initial values in bundle block adjustment. After several iteration of adjustment, the final values could be acquired. Compared with the initial values of GCPs, around 10 mm mean errors occurred to planar coordinates and 20mm mean errors occurred to height, which can be considered good accuracy for UAV mapping.

• The optimized interior orientations including Focal length, image coordinates of Principle points, coeffients of radial and tangential distortion:

Table 8. Internal camera parameters of CanonIXUS125HS (sensor dimension: 6.17 4.63mm)

<table>
<thead>
<tr>
<th></th>
<th>Focal length (mm)</th>
<th>Principle point X (mm)</th>
<th>Principle point Y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial values</td>
<td>4.386</td>
<td>3.086</td>
<td>2.315</td>
</tr>
<tr>
<td>Optimized values</td>
<td>4.469</td>
<td>2.934</td>
<td>2.243</td>
</tr>
</tbody>
</table>

Table 9. Lens distortion parameters of CanonIXUS125HS (sensor dimension: 6.17 4.63mm)

<table>
<thead>
<tr>
<th>Radial Distortion Parameters</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>Decentring distortion Parameters</th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>-0.040528866446427794</td>
<td>0.0396212346835517</td>
<td>-0.012940388354128926</td>
<td>P1</td>
<td>0.002956716185710018</td>
<td>0.0089577009128356255</td>
</tr>
<tr>
<td>K2</td>
<td></td>
<td></td>
<td></td>
<td>P2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The adjusted exterior orientations including object coordinates of principle points and image orientations:

In this job, the onboard GPS sensor measured the initial object coordinates (WGS84) of principle points. Most mini UAV onboard GPS sensors use pseudorange single point measurement, thus the accuracy is relatively low compared with DGPS and RTK GPS. The measured coordinates are compared with those from bundle block adjustment and the differences of the first ten images are listed below as an example:

<table>
<thead>
<tr>
<th>Image 1</th>
<th>$\Delta X(m)$</th>
<th>$\Delta Y(m)$</th>
<th>$\Delta Z(m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image 2</td>
<td>-3.186</td>
<td>-0.256</td>
<td>-10.176</td>
</tr>
<tr>
<td>Image 3</td>
<td>-2.854</td>
<td>-0.974</td>
<td>-10.179</td>
</tr>
<tr>
<td>Image 4</td>
<td>-2.324</td>
<td>-1.764</td>
<td>-10.561</td>
</tr>
<tr>
<td>Image 5</td>
<td>-2.992</td>
<td>-1.106</td>
<td>-10.504</td>
</tr>
<tr>
<td>Image 6</td>
<td>-3.056</td>
<td>-1.915</td>
<td>-9.921</td>
</tr>
<tr>
<td>Image 7</td>
<td>-2.685</td>
<td>-1.176</td>
<td>-11.056</td>
</tr>
<tr>
<td>Image 8</td>
<td>-3.608</td>
<td>-1.560</td>
<td>-12.799</td>
</tr>
<tr>
<td>Image 9</td>
<td>-1.194</td>
<td>0.117</td>
<td>-11.522</td>
</tr>
<tr>
<td>Image 10</td>
<td>-0.990</td>
<td>-0.458</td>
<td>-10.124</td>
</tr>
<tr>
<td>Mean</td>
<td>-1.054</td>
<td>-0.170</td>
<td>-9.674</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.917</td>
<td>0.671</td>
<td>0.882</td>
</tr>
</tbody>
</table>

As shown in the above table, the average differences between GPS values and bundle block adjustment results in X direction is about 2.4m and in Y direction is about 0.9m. The precisions of all directions are within 1m.

Considering the poor accuracy of pseudorange single point measurement of GPS, the above results have basically satisfied the original goal. The large height errors of about 10m occurred because the measured heights are in WGS84 system (ellipsoid height) and calculated heights are in GDA 94 (Geoid height).

Meanwhile, the orientation of images (omega, Phi and kappa) have also been calculated from the bundle block adjustment, the results are attached in the Appendix part.
• DEM, Orthomosaic, Point clouds, Triangle model (TIN) and 3D model.

1). DEM:

![Fig.60. Digital Elevation Model generated in Postflight 3D](image)

The above DEM is generated in Postflight 3D software, with green colour represents the low parts and orange colour represents the high parts of the surveyed area. Elevation value of any point can be inquired on the DEM.

2). Orthomosaic:

![Fig.61. Georeferenced Orthomosaic generated in Postflight 3D (left) and viewed in Google Earth(right)](image)
The above image is the generated georeferenced orthomosaic of the area. Point determination can be conducted on the image by using *Scene Editor* tool in the software. By simply clicking on any point, the 3D coordinates can be calculated and displayed to the users. Similarly, the measurements of path length and polygon area as well as volume can also be inquired.

![Image of orthomosaic with points and measurements](image1.png)

*Fig.62. Point determination (left), Path length inquire (middle) and Area/Volume calculations (right) on Orthomosaic*

3). Point clouds:

The 3D point clouds contained in a text file format can be imported and viewed in some softwares such as ArcGIS or AutoCAD. By simply clicking on any point of interest, the coordinates can be acquired.

![Image of point cloud viewed in ArcMap and AutoCAD](image2.png)

*Fig.63. Point cloud with GSD of 100cm viewed in ArcMap (left) and AutoCAD (right)*
The points imported to AutoCAD is the 3D point cloud generated with the grid sampling distance of 100cm. AutoCAD2012 is not good at dealing with denser points.

Furthermore, the RGB coloured 3D point clouds in PLY file format can also be generated from Postflight 3D software. Meshlab is able to provide a relative clear and integrated view of the imported points. As shown in the below figure, deficiency occurred mostly in building façades and tree crowns. The deficiency of front face is mainly due to the high altitude of UAV flight, most photos acquired are nearly parallel to flight path, not enough information has been captured of the building frontages. Meanwhile, the density of tree crown is not high enough to produce enough points.

The original RGB 3D point clouds are in an assumed coordinate system, the georeferencing has been done in CloudCompare software by applying seven parameter transformations between assumed coordinates and MGA94.

![Fig.64. Integrated coloured 3D point clouds viewed in Meshlab (left) and georeferencing in CloudCompare (right)]
4). Contour and Triangle model (TIN):

The contour lines could be produced based on the point elevation data in CAD as shown below:

![Fig.65. 0.2m contour lines generated in CivilCAD](image_url)

The contour lines generated in CivilCAD is not very smooth due to the large amount of point data and deficiency occurred in building front faces as well as tree crowns.

Similarly, the TIN surface could also been constructed or viewed in different softwares.

![Fig.66. TIN surface viewed in AutoCAD (left), ArcGIS(middle) and Meshlab (right)](image_url)
Among these TINs, the left one viewed in AutoCAD is consist of a large number of lines forming the triangular models and the TINs generated by ArcGIS or viewed in Meshlab are more like topographical surface which could be used for producing 3D models.

5). 3D model:

![Fig.67. 3D model generated on ArcScene viewed from the east side of the area.](image)

The 3D model generated in ArcScene is not of good quality, because the 2D orthophoto was simply been dropped to the 3D TIN surface. A better 3D model can be produced in Meshlab by using the reconstructed RGB colored 3D point cloud. The reconstruction will be done in next semester.

Furthermore, a quality report has been produced according to the results discussed above and been attached in the Appendix part.
Comments on post processing by using Postflight 3D software

In conclusion, there are several advantages as well as disadvantages associated with Postflight 3D software:

Advantages:

- The quality of aerial triangulation is good, and the inner block accuracy is better than GPS measurement.
- It’s a very productive software, which help generate a wide range of productions, including aerial triangulation results, DSM, 3D point cloud, etc.
- Automatic processing which saves a lot of manual effort and time.
- Both data and productions can be exported and viewed in many different software packages

Disadvantages:

- It doesn’t have DSM filtering, thus DTM is not available.
- 3D point cloud and TIN and some other files cannot be viewed in the software, external software such as meshlab, Autocad, ArcGIS and Google earth may needed.
4.2.2 Comparisons with different photogrammetry software packages

There are usually several typical products required by the users or customers from UAV mapping, namely the Aerial triangulation results, DTM and/or DSM, the orthomosaic, contour lines, TIN and 3D model. Most of these products can be generated by Postflight 3D software as discussed before. However, as discussed in the previous chapter, there is no DSM filtering in this software thus DTM is not available. Additionally, the 3D point clouds and triangular model produced can only be viewed in external software.

Many commercial photogrammetry software packages can be used to deal with UAV image processing. The most important requirements of a good software include high accuracy, user friendly, automation, rapid processing, inexpensive, results easy usable for other software, etc.

The following software packages have been tested to verify the results of Postflight 3D, including:

- Leica Photogrammetry suite (LPS)—Aerial photogrammetry software
- 123D catch—3D modelling software

The following part of this thesis will briefly introduce the results generated by the above software packages and their comparison with Postflight 3D.
Aerial triangulation in Leica Photogrammetry suite (LPS)

Leica Photogrammetry Suite (LPS) is a traditional aerial photogrammetry software application for performing photogrammetric operations on imagery and extracting information from imagery. LPS is significant because it is a leading commercial photogrammetry application that is used by numerous national mapping agencies, regional mapping authorities as well as commercial mapping companies.

LPS is not only designed for UAV imagery, some of the basic features are listed below:

- Manual definition of exterior and interior image orientations
- Automatic tie point generation
- Manual adding and editing of GCPs.
- Productions include aerial triangulation results, DTM and DSM, Orthomosaic.

LPS has two modes of tie point measurement:

1. Given an estimation of the exterior orientation parameters, LPS will look for corresponding points along the computed line by correlation methods;

2. Measurement of 3 or more GCPs points (or 6 or more tie points) per pair manually as seeds, LPS will generate additional tie points from these points.

Only 9 sample images from Wollongong UAV demo have been tested by using LPS. The second mode of tie point measurement was decided to be used, so the initial exterior orientations were uploaded from the log file measured by the onboard GPS/IMU, and then the tie point generation was performed by LPS. 217 tie points were finally generated in total 9 images.
After the tie point generation stage, the five GCPs were manually added in the corresponding images and bundle block adjustment was run after choosing the appropriate parameters. In the test, the coordinates of GCPs were treated as measurement instead of fixed values and the standard deviation were set to 10mm; the interior and exterior orientation were treated as initial values for the adjustment; self-calibration for reducing systematic errors (lens distortion) were selected. Blunder detection has been done. Parts of the results were shown below and the full report of aerial triangulation is attached in the Appendix part.
Table 11. The residuals of exterior orientation parameters in LPS and the comparison with Postflight 3D
(Unit: ΔX, ΔY and ΔZ in meters and ΔOmega, ΔPhi and ΔKappa in degrees)

<table>
<thead>
<tr>
<th>Image ID</th>
<th>ΔX</th>
<th>ΔY</th>
<th>ΔZ</th>
<th>ΔOmega</th>
<th>ΔPhi</th>
<th>ΔKappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>-8.3193</td>
<td>-3.6541</td>
<td>-19.4143</td>
<td>-7.6902</td>
<td>0.4127</td>
<td>10.5401</td>
</tr>
<tr>
<td>29</td>
<td>-8.4167</td>
<td>-3.6130</td>
<td>-19.0813</td>
<td>8.1272</td>
<td>5.1471</td>
<td>-6.4975</td>
</tr>
<tr>
<td>31</td>
<td>-0.2818</td>
<td>0.8894</td>
<td>-8.7977</td>
<td>-4.8049</td>
<td>3.5988</td>
<td>4.2131</td>
</tr>
<tr>
<td>32</td>
<td>-0.2737</td>
<td>0.8033</td>
<td>-8.6625</td>
<td>0.3113</td>
<td>4.7241</td>
<td>-2.8814</td>
</tr>
<tr>
<td>33</td>
<td>-0.2096</td>
<td>0.7959</td>
<td>-8.5942</td>
<td>5.5011</td>
<td>4.7334</td>
<td>-4.7257</td>
</tr>
<tr>
<td>Mean</td>
<td>-5.639</td>
<td>-2.1449</td>
<td>-15.723</td>
<td>1.446</td>
<td>1.637</td>
<td>0.571</td>
</tr>
</tbody>
</table>

| Mean (Postflight 3D) | -1.303 | -1.319 | 9.957 |
| Std (Postflight 3D)  | 0.615  | 0.741  | 1.677 |

Table 12. The residuals of the GCP in LPS and the comparison with Postflight 3D (Unit: meters)

<table>
<thead>
<tr>
<th>Point ID</th>
<th>ΔX</th>
<th>ΔY</th>
<th>ΔZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1112</td>
<td>0.0742</td>
<td>-0.1249</td>
</tr>
<tr>
<td>2</td>
<td>0.0677</td>
<td>-0.0407</td>
<td>-0.0388</td>
</tr>
<tr>
<td>3</td>
<td>0.0133</td>
<td>-0.0185</td>
<td>-0.0709</td>
</tr>
<tr>
<td>4</td>
<td>-0.0347</td>
<td>-0.0577</td>
<td>0.0750</td>
</tr>
<tr>
<td>5</td>
<td>-0.0068</td>
<td>0.0488</td>
<td>-0.0379</td>
</tr>
<tr>
<td>Mean</td>
<td>0.030</td>
<td>-0.028</td>
<td>-0.0395</td>
</tr>
<tr>
<td>Std</td>
<td>0.059</td>
<td>0.048</td>
<td>0.0731</td>
</tr>
<tr>
<td>Mean (Postflight 3D)</td>
<td>0.007</td>
<td>0.012</td>
<td>0.021</td>
</tr>
<tr>
<td>Std (Postflight 3D)</td>
<td>0.005</td>
<td>0.006</td>
<td>0.012</td>
</tr>
</tbody>
</table>

As shown in the above tables, the results of bundle block adjustment generated by LPS are worse than Postflight 3D, the RMSE of GCPs in X, Y, Z calculated in LPS and Postflight are 0.064m and 0.017m, relatively. And the RMSE of GPS values in X, Y, Z calculated in LPS and Postflight are 10.445m and 5.941m, relatively.

Compared with Postflight 3D, LPS mainly have the following advantages and disadvantages:
Advantages:

- Suitable for any aerial photogrammetry, while Postflight 3D is specially designed for Sensefly UAV.
- DTM could be generated.

Disadvantages:

- In automatic tie point generation, either accurate SIFT matching should be done in advance or accurate exterior orientations should be provided in order to obtain good results for AT
- Very time-consuming for large amount of data and images (Thus only 9 images were chosen as sample for the above test)
- Accurate of bundle block adjustment is not as good as Postflight when dealing with Sensefly UAV projects.

3D modelling in 123D Catch

123D Catch is a fully automatic processing software, which allows the users to upload images to the software and then it will produce 3D model based on image stitching technique. The whole processing will only take a relative short time (approximately 20min for 50 images) and after the model being successfully created, the 3D meshing can be edited and exported as different format files. 123D Catch company also provides 3D printing services which can turn the digital 3D model to physical object.

However, for UAV project, 123D Catch could only provide 3D model of the site, other standard products such as DSM, DTM or Orthomosaic are not available from this software. In addition, It cannot provide geo-referenced data as other aerial photogrammetry software.

123D Catch was chosen for the UAV project because:

1). It’s free download software

2). It can provide fast and easy way of 3D modelling from UAV images

3). The results can be exported and viewed in several software packages such as Meshlab and image Modeller
4). Most importantly, in 123D Catch, the user could define local coordinate system, select reference point (eg, GCP) and define scale through one known distance between two reference marks. Therefore, after the definition of scale, the distance between any two points in the 3D model can be enquired and compared with known distances between GPS points.

Fig. 70. 3D model created in 123D Catch

Fig. 71. Selecting reference point (left) and defining scale (right) in 123D Catch
The comparison of distances measured between GCPs in 123D Catch and distances calculated by GPS observations are listed below:

Table 13. Comparisons of distances between GCPs observed by GPS and measured by 123D Catch.

<table>
<thead>
<tr>
<th>Distances between GCPs</th>
<th>Observations by GPS (m)</th>
<th>Measurements in 123D catch (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt1-Pt2</td>
<td>72.865</td>
<td>72.86</td>
<td>0.005</td>
</tr>
<tr>
<td>Pt2-Pt3</td>
<td>115.150</td>
<td>114.42</td>
<td>0.730</td>
</tr>
<tr>
<td>Pt3-Pt4</td>
<td>61.163</td>
<td>61.81</td>
<td>-0.647</td>
</tr>
<tr>
<td>Pt4-Pt5</td>
<td>127.322</td>
<td>128.77</td>
<td>-1.448</td>
</tr>
</tbody>
</table>

As can be seen from the above table, the distance measured in 123D catch can be as large as 1.45m different from the distance calculated by RTK GPS measurement, while can also be as small as 5mm, the precision is not good enough for accurate surveying purpose. Thus the software 123D catch normally will just be treated as a 3D modelling tool for visualization.
4.2.3. Comments on different photogrammetry software packages for this test

In the Wollongong UAV project, software packages including LPS, and 123D catch have been used to verify the results generated from Postflight 3D.

Because Postflight 3D is specially designed for eBee UAV, in terms of triangulation accuracy, productivity and time spent, its performance has proved much better than other software packages in this project.

However, LPS is not very suitable for our small UAV, instead, it is able to provide solutions for large manned aerial vehicle captured images or even satellite images. 123D catch is an ideal tool for generating 3D model for visualization, but not useful when georeferencing data, DEM and orthomosaic are required.

4.2.4. Conclusion of UAV flight test in Wollongong

From the above description and analysis, it can be seen that mini UAV is able to map a relative large area in a short time period if adequate preparation is done and all softwares are accessible. For an UAV job, 9 hectares are not big, but if it's done by traditional land surveying method, it will probably take more than one day to finish. And some of the raster format, such as orthomosaic and DEM, can not be produced by GPS or tachymetry survey. Meanwhile, UAV mapping method is perfect when the site is either hard or impossible to be measured by GPS or total station, such as large wetland where instruments couldn't even be set up.

Despite the above advantages, there are also some drawbacks associated with UAV mapping, some of these have been discussed in Chapter 3. Theory, Algorithm and Methodology. UAV flight is usually conducted on high altitude, thus the building facade may not be picked up. More importantly, the accuracy of UAV can not be guaranteed as it depends on lots of conditions. To optimize the accuracy of UAV mapping, more analysis on the influencing factors will be discussed in the next semester.
4.2 Case Study 2: Fixed-Wing UAV (Swinglet CAM) Terrain Mapping in Griffith Park, Collaroy, NSW

Brief introduction

The UAV flight test in Collaroy was conducted on 22\textsuperscript{nd} August, 2013. The flight test was
designed by the author and the actual fly was conducted by the certified UAV specialist
David Hobby in Ultimate Positioning Group. The test area (about 23 hectares) is located in
Griffith Park, Collaroy, NSW. A total number of 507 photos of 4 different flights were taken
during the flight. Each of the flight has different flight heights (2x80m, 100m, 120m). The
analysis in chapter 2 and chapter 3 were extracted from the results in this test. The test area is
shown in Fig.72 and the relevant information is displayed in Fig.73.

The fixed-wing UAV Swinglet CAM is a lightweight UAV (500g) which can be launched by
hands. Its performance in wind is not as great as eBee, can only take off safely when the wind
speed is below 7m/s. Normally, it’s fully autonomous during the entire flight including
taking-off and landing. The flight procedure is quite similar as eBee which has been
discussed in the last chapter. Figure 12 below shows the basic parameters involved in this
test. Besides the UAV image processing software Pix4d, some other software packages have
also been used as comparisons.
Major Project Components:

- Flight heights: 4 sets of flights of different heights, 80m for the first one, 100m for the second one, 120m for the third one, 80m cross flight for the fourth one.
- Ground Control: 35 ground control points distributed across the whole area.

Aim of the Test

This test is mainly used for testing the influence of different influential factors on the final results, including:

- Test the influences of different flight heights on the final result, which has been discussed in 3.1.3 Flight Planning and Data Acquisition—Flight Height Tests.
- Test the influence of number and distribution of ground control points, which has been discussed in 3.1.4 Ground Control Points Measurements
- Test the influence of different image processing software packages or codes, which has been discussed in 3.1.4.4. Comparisons of 3D point clouds generated by different algorithms
Time Evaluation

The table below shows the time spent on the 100m flight in this project including Flight planning, Data acquisition and Image processing.

Table 14. Approximate time spent on the UAV project

<table>
<thead>
<tr>
<th>Time spent on UAV test</th>
<th>Step</th>
<th>Activity</th>
<th>Time (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight planning</td>
<td>Project parameters set up</td>
<td>10 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flight plan generation</td>
<td>3 min</td>
<td></td>
</tr>
<tr>
<td>Data acquisition</td>
<td>SwingLet CAM flight</td>
<td>Approximately 15-25mins for each flight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35 GCPs setup and measurement</td>
<td>1 hour</td>
<td></td>
</tr>
<tr>
<td>Image processing</td>
<td>Initial processing</td>
<td>20 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Point cloud generation</td>
<td>40min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orthomosaic production</td>
<td>20 min</td>
<td></td>
</tr>
<tr>
<td>Total time</td>
<td></td>
<td></td>
<td>173 min</td>
</tr>
</tbody>
</table>

Among the above activities, the GCPs setup and measurement were conducted at the same time during the UAV flight.

Results Analysis:

The influences of different factors have been discussed in the above chapters.
4.3 Case Study 3: Quadcopter UAV Terrain Mapping in UNSW campus—Alternative Low-Cost Surveying and Mapping Solution

Brief introduction

The Quadcopter UAV flight above Physics Lawn in UNSW campus was conducted on 17th October and 18th October, 2013 by the author. The test area is much smaller compared to the previous two tests. The flight height was also limited to 30-40m in order to get better ground resolution. A total number of 86 photos captured in two days were used for processing. The test area locality sketch is shown in the below Fig 1 and the relevant information is displayed in Fig.74 and Fig.75.

In this test, the Quadcopter was built by ourselves (Electrical Engineering students in UNSW and the author). The main frame was 3D printed and the aluminium support bars and landing gears were bought from Bunnings. The other parts including propellers, onboard sensors (GPS/INS/AutoPilot), batteries and controllers were bought online. The total cost of this was less than 200 Australian dollars. This quadcopter currently can carry about 1.5 kg weights and it’s able to take-off easily by using controller. The camera we used is called Pentax WG-
3D Mapping with UAV: Procedure Analysis and Performance Evaluation

3 GPS as shown in the below figure, it has one embedded GPS but has been turned off during this test.

![Test Quadcopter](image)

**Test Parameters**

- **Camera Information:**
  - Camera Name: PENTAXWG-3GPS
  - Focal Length: 4.686mm
  - Image Size: 3456 x 4608
  - Principle Point: (X: 3.085mm; Y: 2.314mm)

- **Average Ground Sampling Distance:** 0.49cm
- **Area Covered:** 0.21 hectare
- **Output Coordinate system:** GDA 94/MGA zone 56

**Test Information (hardware, software and test parameters)**

The software packages Bundler, PMVS2 and SURE are all open source. So in total, this test utilized low-cost system to do the small area mapping.

**Aim of the Test**

The test is mainly used for testing whether this low-cost system can be an alternative solution to current surveying and mapping technique. Several things have been illustrated in this test, including:

- Time comparison with traditional terrestrial surveying methods;
- Accuracy comparison with traditional terrestrial surveying methods;
- The feasibility of multi-copter UAV in cadastral and detail surveying.
Ground Control

The above two features display the test area and locations of the 6 ground control points as well as the 8 check points. All of these points (6GCPs+8CPs) were measured by traversing from known marks using a Sokkia Total Station. Meanwhile, the 8 check points were also measured by using a Leica RTK GPS for independent check. The measurements of 6 GCPs by total station were used as an input values for ground control in our photogrammetry image.
processing and after the processing, the measurements of check points by using 10 seconds epochs RTK GPS were compared with the corresponding UAV photogrammetry derived values. In this way, the relative accuracy (in relation to total station) of UAV photogrammetry (for small scale mapping) and RTK GPS can be compared with each other.

**Data and Image acquisition**

Our Quadcopter UAV has been programmed and is able to achieve GPS waypoint mode. However, in this test, in order to compare the relative accuracy of photogrammetry and RTK GPS, the UAV was manually controlled during the whole procedure. The flight height was limited between 25m and 40m.

The camera has been set to taking photos every 10 seconds during the flight. In total, there were 86 images taken of this area.

The two figures below display the geometry of the photos taken in the field.

![The geometry distribution of photos derived from SFM](image)

*Fig. 78 The geometry distribution of photos derived from SFM (Left: Top View; Upper Right: Side View)*
Test results and Analysis

- Assumption:

From experience, the relative accuracy of good total station measurements is within 10mm and Corsnet RTK-GPS is around 20-50mm. The skyview for GPS is good except the Old Main Building is located in the north side of the test area (Fig.79). In this test, we assume that the relative accuracy and precision of total station measurements are better than that of RTK-GPS (In 10s epoch).

Fig.79. Skyview of the test area in Physics Lawn
• Accuracy of Point Determination:

The below two tables display the differences calculated at check points to determine the quality of RTK-GPS and 3D model produced by UAV photogrammetry. The first table shows the differences between RTK-GPS measurements and total station measurements at the 8 check points; The second table shows the differences between UAV photogrammetry derived values and total station measurements at the 8 check points.

<table>
<thead>
<tr>
<th>Pt</th>
<th>Easting</th>
<th>Northing</th>
<th>Height</th>
<th>Pt</th>
<th>Easting</th>
<th>Northing</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>336339.395</td>
<td>6245434.645</td>
<td>28.610</td>
<td>3</td>
<td>336339.388</td>
<td>6245434.696</td>
<td>28.606</td>
</tr>
<tr>
<td>4</td>
<td>336358.791</td>
<td>6245431.468</td>
<td>29.083</td>
<td>4</td>
<td>336358.769</td>
<td>6245431.523</td>
<td>29.056</td>
</tr>
<tr>
<td>5</td>
<td>336360.058</td>
<td>6245439.821</td>
<td>29.566</td>
<td>5</td>
<td>336360.043</td>
<td>6245439.849</td>
<td>29.556</td>
</tr>
<tr>
<td>6</td>
<td>336340.365</td>
<td>6245442.536</td>
<td>28.947</td>
<td>6</td>
<td>336340.344</td>
<td>6245442.563</td>
<td>28.947</td>
</tr>
</tbody>
</table>

Table 15. The differences between RTK-GPS measurements and total station measurements at the 8 check points

<table>
<thead>
<tr>
<th>Pt</th>
<th>ΔE (mm)</th>
<th>ΔN (mm)</th>
<th>ΔH (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.3</td>
<td>-8</td>
<td>51</td>
<td>-4</td>
</tr>
<tr>
<td>No.4</td>
<td>-21</td>
<td>55</td>
<td>-17</td>
</tr>
<tr>
<td>No.5</td>
<td>-14</td>
<td>28</td>
<td>-10</td>
</tr>
<tr>
<td>No.6</td>
<td>-21</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>No.1001</td>
<td>-29</td>
<td>24</td>
<td>-7</td>
</tr>
<tr>
<td>No.1002</td>
<td>-24</td>
<td>55</td>
<td>-5</td>
</tr>
<tr>
<td>No. 1003</td>
<td>-19</td>
<td>24</td>
<td>-13</td>
</tr>
<tr>
<td>No.1004</td>
<td>-9</td>
<td>15</td>
<td>-3</td>
</tr>
<tr>
<td>RMSE</td>
<td>19</td>
<td>38</td>
<td>9</td>
</tr>
<tr>
<td>Std</td>
<td>7</td>
<td>16</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 16. The differences between UAV photogrammetry derived values and total station measurements at the 8 check points

<table>
<thead>
<tr>
<th>Pt</th>
<th>Easting</th>
<th>Northing</th>
<th>Height</th>
<th>Pt</th>
<th>Easting</th>
<th>Northing</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>336339.395</td>
<td>6245434.645</td>
<td>28.610</td>
<td>3</td>
<td>336339.402</td>
<td>6245434.639</td>
<td>28.596</td>
</tr>
<tr>
<td>4</td>
<td>336358.791</td>
<td>6245431.468</td>
<td>29.083</td>
<td>4</td>
<td>336358.784</td>
<td>6245431.460</td>
<td>29.081</td>
</tr>
<tr>
<td>5</td>
<td>336360.058</td>
<td>6245439.821</td>
<td>29.566</td>
<td>5</td>
<td>336360.063</td>
<td>6245439.811</td>
<td>29.582</td>
</tr>
<tr>
<td>6</td>
<td>336340.365</td>
<td>6245442.536</td>
<td>28.947</td>
<td>6</td>
<td>336340.356</td>
<td>6245442.540</td>
<td>28.937</td>
</tr>
<tr>
<td>1001</td>
<td>336357.942</td>
<td>6245441.106</td>
<td>29.555</td>
<td>1001</td>
<td>336357.938</td>
<td>6245441.079</td>
<td>29.567</td>
</tr>
<tr>
<td>1002</td>
<td>336351.890</td>
<td>6245431.738</td>
<td>28.898</td>
<td>1002</td>
<td>336351.874</td>
<td>6245431.736</td>
<td>28.871</td>
</tr>
<tr>
<td>1003</td>
<td>336334.917</td>
<td>6245444.493</td>
<td>28.856</td>
<td>1003</td>
<td>336334.918</td>
<td>6245444.463</td>
<td>28.879</td>
</tr>
<tr>
<td>1004</td>
<td>336325.415</td>
<td>6245445.721</td>
<td>28.462</td>
<td>1004</td>
<td>336325.419</td>
<td>6245445.681</td>
<td>28.450</td>
</tr>
</tbody>
</table>

Then the absolute values of Easting, Northing and Height differences against total station measurements can be plotted in the below diagram for both GPS and UAV derived values.

It’s not hard to notice that for both Easting and Northing determination, the UAV performs better than network RTK-GPS at almost all check points. For height measurement, GPS values are better than UAV derived values at the last 4 check points (No.1001-No.1004) and check point No.5.

So in general, based on the assumption we made (the relative accuracy and precision of total station are better than RTK), low-elevation UAV flight (30-40m) provides better accuracy and precision for point determination than RTK-GPS in this test.
- Generated 3D Point Cloud

The Fig. below shows the point cloud generated from the 86 photos. And the other photos compare the ground photos and 3D point clouds of the same objects.

![3D point cloud produced for the test area](image)

Fig. 83. 3D point cloud produced for the test area

![Comparison between ground photos and generated 3D point clouds of a drainage pit](image)

Fig. 84. Comparison between ground photos and generated 3D point clouds of a drainage pit (the painted corner was used as a check point)
As can be seen from the two figures above, the density of 3D point clouds of the ground objects such as pits and marks are very good. The width of the cross mark is just around 1.5-2cm and hundreds of points haven been created within this range. Thus almost everything on the ground can be clearly identified in the generated 3D point cloud.

However, the problem occurs when it comes to vegetation. As can be seen from the figure below, the generated 3D points of the tree crown are quite sparse due to the complexity of the trees and the density of the tree leaves are not enough for creating dense 3D point clouds. This could be a great problem of UAV mapping if details of vegetation are required.
• Time Evaluation

The table below shows the time spent on this Quadcopter UAV test.

Table 17. Approximate time spent on the Quadcopter UAV Test

<table>
<thead>
<tr>
<th>Time spent on the quadcopter UAV test</th>
<th>Step</th>
<th>Activity</th>
<th>Time (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data acquisition</td>
<td>flight</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td></td>
<td>GCPs setup and measurement by using total station</td>
<td></td>
<td>40 min</td>
</tr>
<tr>
<td>Image processing</td>
<td>Initial processing</td>
<td></td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td>Point cloud densification</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td></td>
<td>Orthomosaic production</td>
<td></td>
<td>10 min</td>
</tr>
<tr>
<td>Total time</td>
<td></td>
<td></td>
<td>73 min</td>
</tr>
</tbody>
</table>

From the above table, it can be seen that most time were actually spent on the GCPs measurements. The actual flight plus image processing only took about half an hour to be finished.

• Comparison of RTK-GPS and low-elevation flight UAV photogrammetry for this test

Table 18. Comparison of RTK-GPS and low-elevation flight UAV photogrammetry for this test

<table>
<thead>
<tr>
<th>Technology</th>
<th>Accuracy (RMSE of 8 check points)</th>
<th>Time</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ΔE (mm)</td>
<td>ΔN (mm)</td>
<td>ΔH (mm)</td>
</tr>
<tr>
<td>Network RTK-GPS (10s epochs)</td>
<td>19</td>
<td>38</td>
<td>11</td>
</tr>
<tr>
<td>Our Quadcopter UAV</td>
<td>8</td>
<td>21</td>
<td>15</td>
</tr>
</tbody>
</table>
This test has proved that for small scale mapping (e.g., 2100 m² for our test) with low-elevation flight (30-40 m), the low-cost Quadcopter UAV system can sometimes work better than RTK-GPS. From the table above, it can be concluded that this low-cost Quadcopter could be an alternative solution to terrestrial technique like RTK-GPS for detail surveying and mapping purposes. However, without onboard GPS, the photogrammetry can only provide relative positions of 3D point clouds, thus GCPs measurements are needed every time for transformation between local and real world coordinate system. The good thing is that with computer vision technology being used today for image processing, the number of GCPs could be largely reduced to 3-5 for each UAV project regardless of the mapping area (Discussion in 3.1.4 Ground Control Points Measurements).

Notice: The results of this test does not mean that UAV photogrammetry can performs better than RTK-GPS at any time in any place, and because photogrammetry can only provide relative positioning (in contrast with GPS which can provide absolute positioning solution), unless very accurate onboard GPS are used for UAV mapping, which can provide direct georeferencing without GCPs measurements, the UAV photogrammetry can only act as an alternative surveying and mapping solution instead of totally replacing the traditional terrestrial methods.
4.4 Case Study 4: Quadcopter UAV 3D building modelling in UNSW campus—Possible Alternative to Terrestrial Laser Scanner and Ground-Based Photogrammetry

Brief introduction

Aim of the Test

The above 3 case studies have focused on UAV topographical mapping ability and the results have proved that UAV photogrammetry can act as an alternative solution to traditional surveying and mapping techniques. However, one of the biggest deficiencies we found is that by taking near-vertical images, only the ground objects can be captured and modelled. For vertical surface (eg, building or structure facet) modelling purpose, not enough information would be obtained by near-vertical images.

Therefore, oblique photos should be taken if the front surface of a structure needs to be modelled. This is quite similar to ground-based close range photogrammetry.

The aim of this test is to evaluate the performance of our Quadcopter UAV for structure surface modelling purpose.

Test Parameters

- Locality of test:

This test was conducted in front of Quadrangle Building in UNSW campus by the author on 6th October, 2013. The locality sketch of the test area is shown in the figure below:

Fig.87. Locality Map: UNSW Kensington Campus (Red Line) and Test area in Quadrangle Square (Blue line)
Flight and Data acquisition:

The same Quadcopter and camera as introduced in the last Case Study was used in this test. The camera was rotated 90 degrees so that it could take oblique photos of the Quadrangle Building surface. Manual flight was used because the onboard GPS couldn’t work well in front of the building. The flight height from the Quadcopter to the ground varied between 5m-20m. And the distance between Quadcopter to building surface was controlled so it can provide a better convergent geometry as shown in the figure below. The time-lapse of camera was set to 10 seconds. In total, 43 photos were obtained.

Software:

Three free software packages were used for image processing in this test—VisualSFM has been used for generating image orientation and sparse 3D point cloud; PMVS and SURE were used as point cloud densification tool.
3D Mapping with UAV: Procedure Analysis and Performance Evaluation

Fig. 89. The geometry of photos taken in front of the Quadrangle Building (Top-view)

- **Control Points and georeferencing of 3D point clouds:**

  3 Wall Control Points were measured by using total station before the flight. The ground control points used in this test were actually just the corner of columns as shown in Fig.1. These marks are permanent so we can use it anytime for any test in front of this building. Another advantage of choosing these points as control marks is because of the strong colour contrast as shown in Fig.91.

  For this test, a different method was used to georeference the point cloud, instead of identifying the GCPs on the photos (As introduce in *Chapter 4.1 Case Study 1*), We produced the 3D point cloud first in an assumed coordinates, and then by clicking the point of interest in the generated point cloud, the 3D assumed coordinates of the 3 GCPs can be obtained. Finally, using least squares adjustment of 7-parameter transformation formula (Equation 17) and applying this to all 3D points to transform them from assumed coordinate system to MGA coordinates (This algorithm has been discussed in 3.1.4.2-2 *Block adjustment by independent models*).

Fig. 90. The locations of 3 Control Points (Red Cross)
The corners of the columns were used as our control points due to the strong colour contrast.

**Test results and Analysis**

In this test, the two free software packages for point cloud densification — PMVS and SURE were compared with each other. The two figures below display the visualization difference between the point cloud generated by these two software packages.

Different from the above three Case Studies, to test the accuracy of generated 3D point cloud, distances between each of corner points were enquired in the point cloud and these values were compared with corresponding distance calculated from total station measurements. Fig 94 below shows the distance enquire procedure in 3D point cloud generated by PMVS and SURE. It can be seen that SURE can produce much denser point cloud and this makes it much easier to identify points in SURE’s point cloud.
Fig. 92. Point cloud generated in PMVS

Fig. 93. Point cloud generated in SURE

Fig. 94. Distance Inquiry between two column corner points on PMVS (up) and SURE (below)
Table 19. The difference between the distance calculated from total station measurements and the distance obtained from PMVS generated point cloud

<table>
<thead>
<tr>
<th>Distance</th>
<th>Distance derived (m)</th>
<th>Distance obtained (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt3-Pt4</td>
<td>3.905</td>
<td>3.846</td>
<td>59</td>
</tr>
<tr>
<td>Pt4-Pt5</td>
<td>3.896</td>
<td>3.939</td>
<td>-43</td>
</tr>
<tr>
<td>Pt5-Pt6</td>
<td>15.572</td>
<td>15.505</td>
<td>67</td>
</tr>
<tr>
<td>Pt6-Pt7</td>
<td>3.910</td>
<td>3.907</td>
<td>3</td>
</tr>
<tr>
<td>Pt7-Pt8</td>
<td>3.909</td>
<td>3.815</td>
<td>95</td>
</tr>
<tr>
<td>Pt8-Pt9</td>
<td>3.900</td>
<td>3.969</td>
<td>-69</td>
</tr>
<tr>
<td>Pt9-Pt10</td>
<td>3.895</td>
<td>3.970</td>
<td>-75</td>
</tr>
<tr>
<td>Pt10-Pt11</td>
<td>3.903</td>
<td>3.909</td>
<td>-6</td>
</tr>
<tr>
<td>Pt11-Pt12</td>
<td>3.914</td>
<td>3.938</td>
<td>-25</td>
</tr>
<tr>
<td>Pt12-Pt13</td>
<td>3.882</td>
<td>3.939</td>
<td>-57</td>
</tr>
<tr>
<td>Pt13-Pt15</td>
<td>7.813</td>
<td>7.877</td>
<td>-64</td>
</tr>
</tbody>
</table>

Table 20. The difference between the distance calculated from total station measurements and the distance obtained from SURE generated point cloud

<table>
<thead>
<tr>
<th>Distance</th>
<th>Distance derived (m)</th>
<th>Distance obtained (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt3-Pt4</td>
<td>3.905</td>
<td>3.917</td>
<td>-12</td>
</tr>
<tr>
<td>Pt4-Pt5</td>
<td>3.896</td>
<td>3.893</td>
<td>3</td>
</tr>
<tr>
<td>Pt5-Pt6</td>
<td>15.572</td>
<td>15.589</td>
<td>-17</td>
</tr>
<tr>
<td>Pt6-Pt7</td>
<td>3.910</td>
<td>3.922</td>
<td>-12</td>
</tr>
<tr>
<td>Pt7-Pt8</td>
<td>3.909</td>
<td>3.886</td>
<td>11</td>
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<tr>
<td>Pt8-Pt9</td>
<td>3.900</td>
<td>3.901</td>
<td>-1</td>
</tr>
<tr>
<td>Pt9-Pt10</td>
<td>3.895</td>
<td>3.883</td>
<td>12</td>
</tr>
<tr>
<td>Pt10-Pt11</td>
<td>3.903</td>
<td>3.909</td>
<td>-7</td>
</tr>
<tr>
<td>Pt11-Pt12</td>
<td>3.914</td>
<td>3.917</td>
<td>-4</td>
</tr>
<tr>
<td>Pt12-Pt13</td>
<td>3.882</td>
<td>3.898</td>
<td>-16</td>
</tr>
<tr>
<td>Pt13-Pt15</td>
<td>7.813</td>
<td>7.809</td>
<td>5</td>
</tr>
</tbody>
</table>
The absolute values of the Distance Differences compared with total station measurement are plotted in the figure below to give a clear look.

![Graph showing the comparison of distance differences](image)

**Fig.95.** The comparison of the difference between the distance calculated from total station measurements and the distance obtained from 3D point cloud generated by the two software packages

As can be seen, the difference between total station measured distance and the corresponding values enquired from 3D point cloud generated by SURE is much smaller than that of PMVS. To realize surveying purpose, SURE is definitely a better choice. It can be seen from Table.20 and Fig.95, the distance differences are around 10mm (Ranging from 0-20mm) with SURE’s point cloud.
Comparison with ground-based photogrammetry and laser scanner

Table 21. Comparison of Quadcopter UAV Photogrammetry, Ground-Based Photogrammetry and Terrestrial Laser Scanner techniques

<table>
<thead>
<tr>
<th></th>
<th>Quadcopter UAV Photogrammetry</th>
<th>Ground-Based Photogrammetry</th>
<th>Terrestrial Laser Scanner</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>Cost-effective</td>
<td>Cost-effective</td>
<td>Higher density 3D point cloud with less measuring and processing time (1 million points in 1 second), thus more efficient</td>
</tr>
<tr>
<td></td>
<td>More flexible, suitable for high-rise building inspection</td>
<td>More stable, thus better quality images</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Can achieve autonomous flight with onboard navigation system</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Can model terrain and building at same time with proper camera mounting angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Possible Image motion blur</td>
<td>Not suitable for terrain mapping or high rise building modelling</td>
<td>Too Expensive; Only provide False colour 3D point cloud</td>
</tr>
</tbody>
</table>
4.5 Summary of Tests Results and Accuracy

Four case studies have been discussed and analysed in Chapter 4—

- The first test gives a detailed review of UAV mapping procedure, displays the accuracy of inner block adjustment and several productions generated by UAV photogrammetry. From this test, the high productivity and high efficiency of UAV photogrammetry mapping can be easily observed.

- The data and results from the second test have been used to analyse the influence of different factors on UAV mapping accuracy. The comparisons have mainly been studied in Chapter 3.1—Procedures Analysis of UAV Mapping. This has proved that for vision based UAV photogrammetry, image quality, scale and geometry, etc are the most important factors for inner accuracy; Good distribution of the minimum numbers of GCPs can provide good transformation results.

- Case Study 3 has been conducted by the author to evaluate the relative accuracy and precision of low-elevation manual flight UAV for terrain mapping. As been discussed, the relative accuracy and precision of UAV photogrammetry might be better than RTK-GPS under some situations. Meanwhile, the low-cost flexible quadcopter can deliver results efficiently. Thus this can be treated as an alternative tool for cadastral and detail surveying or mapping purposes.

- In Case Study 4, oblique photos were taken in order to model the front surface of a building. It has proved that multi-copter UAV can be used for 3D modelling purposes and might have greater potential than ground-based photogrammetry due to its automation and great ability for high-rise building inspection, it also might be an alternative solution to laser scanner due to the high density of 3D point cloud generated from the software package SURE.

More tests are still needed to prove the ability of UAV photogrammetry under different environments, eg, UAV mapping in mountainous areas, UAV mapping in CBD areas, etc.
5. Future trends of UAV mapping and 3D Modelling

Automation and virtual realization are two of the main directions of technological development in the future for the whole world. The UAV itself is a good representative of automation, by using advanced onboard sensors, the UAV can navigate and fly all by itself. At the same time, computer vision based photogrammetry technology is able to generate dense point cloud from images directly. The combination of UAV and vision technology can provide the most efficient and cost-effective way for surveying, mapping, surveillance, inspection and modelling purposes. Therefore, this technique has great potential to be developed and improved in the next few years and might become widely used in surveying area eventually.

From the author’s perspective, a few things might need to be improved in relation to UAV mapping and modelling.

- **Onboard Precise GPS**: As been discussed in the above chapters, vision based photogrammetry itself can only provide relative position of 3D points in an assumed coordinate system, this relative position between 3D points might be very accurate. However, either onboard GPS or GCPs are needed to transform the data from assumed coordinates to real world coordinates (e.g., WGS84 or MGA94). While setting out GCPs and measuring them will always take time and human effort, a better and more efficient way is to mount a very precise GPS on the top of UAV. Meanwhile, real time mapping processing also requires accurate onboard GPS data without additional ground-based measurements. However, today’s RTK-GPS usually has big antenna and receiver which makes it really hard to mount this GPS on small UAV with low payload. Many organizations have tried to integrate RTK-GPS to a small chip so it can be easier carried on the platform, but none has made real success. In the future, with the improvement of GPS hardware and its accuracy, real time mapping and modelling can finally be achieved.

- **Real-time obstacle detection**: Although most UAV today can achieve automatic flight with pre-programming. However, most of them still cannot achieve obstacle detection and avoidance in real time. This might cause some safety issues when autonomous low-altitude flight is carried out in urban area because the UAVs might hit the buildings and structures.
• **Development of Computer vision algorithms**: The recently developed photogrammetry software packages all include computer vision knowledge such as SFM and MVS as discussed in the previous chapters. These algorithms can provide accurate solutions for still objects. However, for moving targets and objects, most of these algorithms won’t work due to the change of relative positions between the moving object and other things. A possible solution might be defining the outside structure of this moving target first, then the movement can possibly be detected.

• **Regulation Improvement**: With the development of UAV and computer vision technologies, more and more UAVs will be used and applied in different areas for different purposes. A better regulation system is still needed in Australia to provide safe condition for UAV users and other people as well as their properties.
References


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Faig, W. (1985), Lecture Notes on Aerial Triangulation and Digital Mapping, Monograph 10, School of Surveying, The University of New South Wales, Kensington, N.S.W., Australia.


SenseFly (2013), “Swinglet CAM”


Shi, Juan, Jinling Wang, and Yaming Xu. "Use of GPS/INS observations for efficient matching of UAV images."


Bibliography


Appendix A—Robust Software packages and Open Source Codes Used in the project
Robust Free Software packages and Open Source Codes Used in the project

Open Source Computer Vision Codes:

- OpenCV  [http://opencv.org/] -- All open source codes

SFM and MVS (For generating 3D point cloud):

- SURE (MVS)  [http://www.ifp.uni-stuttgart.de/publications/software/sure/index.en.html] -- Robust 3D point cloud densification software
- Bundler (SFM)  [http://www.cs.cornell.edu/~snavely/bundler/] -- Sparse 3D point cloud open source code
- PMVS (MVS)  [http://www.di.ens.fr/pmvs/] -- 3D point densification open source code
- AerialPhotoSE  [http://www.uni-koeln.de/~a1001/]

Point Cloud & Mesh Editing:

- Meshlab  [http://meshlab.sourceforge.net/]
- Cloud Compare  [http://www.danielgm.net/cc/]

7-parameter coordinates transformation:

- SFM_georef:  [http://www.lancaster.ac.uk/staff/jamesm/software/sfm_georef.htm]

- Matlab code:  [http://www.photogrammetric-vision.com/download-notification.html]

Website Address of Advance Commercial UAV Computer vision based Photogrammetry software:

- Pix4D:  [http://pix4d.com/]
- Agisoft PhotoScan:  [http://www.agisoft.ru/products/photoscan]
Appendix B—Email Contact with Pix4D Ltd
Dear Dichen Liu,

Thank you for your email and your interest regarding our software.
Please find below some answers regarding your interrogations:

1. We are using such SIFT matching techniques but optimized by Pix4D’s developers,
2. Similar to Bundler but not opensource yet,
3. We can not answer regarding the 3D part by now.

Good luck for the end of your bachelor study and stay tuned, a new version is coming by the end of the year.

Regards

Dennis

You can call me at +41225483940 or Skype me at lorenzo.martelletti anytime.

I am looking forward to hearing from you.

Best regards,

Arnaud Deshogues
Direct Sales Manager, Pix4D
Phone: +41 22 548 3940
Skype: arnaud.deshogues@pix4d.com
Email: arnaud.deshogues@pix4d.com
www.pix4d.com
Appendix C—Screen shots of Excel working sheets
### Case Study 2:

**3D Mapping with UAV: Procedure Analysis and Performance Evaluation**

#### Table: Average Difference Between RTK-GPS

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Difference (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3 mm</td>
</tr>
</tbody>
</table>

**Diagram:**

- **Title:** Values and their distribution of X, Y, Z coordinates.
- **Graph:** Scatter plot showing the distribution of X, Y, Z values.
3D Mapping with UAV: Procedure, Analysis and Performance Evaluation

**Average Difference between Actual vs. GPS values:**

Data from Excel sheet showing measurements and values.
### 3D Mapping with UAV: Procedure Analysis and Performance Evaluation

#### Points

- Photogrammetry values of each of the 6 checks.
- Difference between RTK-GPS values and UAV.

**Number of GPS Points**

<table>
<thead>
<tr>
<th>Check</th>
<th>GPS Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
</tr>
<tr>
<td>C</td>
<td>70</td>
</tr>
</tbody>
</table>

**Values of 3 check points**

<table>
<thead>
<tr>
<th>Check</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

**Difference between RTK-GPS values and UAV**

<table>
<thead>
<tr>
<th>Check</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.5</td>
</tr>
</tbody>
</table>
### 3D Mapping with UAV: Procedure Analysis and Performance Evaluation

#### Case Study 3:

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Result</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Take off</td>
<td>Successful</td>
<td>No issues</td>
</tr>
<tr>
<td>2</td>
<td>Hover</td>
<td>Stabilized</td>
<td>Good signal</td>
</tr>
<tr>
<td>3</td>
<td>Capture</td>
<td>High-quality</td>
<td>No distortion</td>
</tr>
<tr>
<td>4</td>
<td>Return</td>
<td>Safe landing</td>
<td>No damage</td>
</tr>
</tbody>
</table>

*Note: Detailed data is available in the attached spreadsheet.*

**Spreadsheet Data:**

![Spreadsheet Image](image.png)

*Detailed analysis and performance metrics are displayed in the spreadsheet.*
Case Study 4:

3D Mapping with UAV: Procedure Analysis and Performance Evaluation

### Table 1: Data Collection and Analysis

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Position</th>
<th>Altitude (m)</th>
<th>Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/01</td>
<td>08:00</td>
<td>000</td>
<td>000</td>
<td>000</td>
</tr>
<tr>
<td>01/02</td>
<td>09:00</td>
<td>001</td>
<td>001</td>
<td>001</td>
</tr>
<tr>
<td>01/03</td>
<td>10:00</td>
<td>002</td>
<td>002</td>
<td>002</td>
</tr>
<tr>
<td>01/04</td>
<td>11:00</td>
<td>003</td>
<td>003</td>
<td>003</td>
</tr>
</tbody>
</table>

#### Diagram 1: Corresponding Relationships from 3D Point Clouds and the Difference between Local Stationary Measured Distance and the

By the two-sentence conclusions, the difference measures and the...
Appendix D—Matlab code for Path Planning
Appendix E—Quality Reports with Pix4D
Appendix F—Plagiarism Sheet

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I certify that I have read and understood the University Rules in respect of Student Academic Misconduct.

Signed: ............ ........................................