

**ACCURACY ANALYSIS AND EVALUATION OF UAS PHOTOGRAMMETRY
AND STRUCTURE FROM MOTION IN ENGINEERING SURVEYING**

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ABSTRACT

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Highly detailed topographic mapping at minimal cost and effort has always been one of the developing areas of scientific interest. Image-based remote sensing solutions using Unmanned Aerial Systems (UAS) and Structure from Motion (SfM) with Multi-View Stereo (MVS) photogrammetry are the latest automation and advancement in surveying engineering. The aim of this research was to evaluate the accuracy of UAS SfM-MVS as a rapid and low-cost alternative to conventional survey methods. For this purpose, two flights at 100 and 170 m heights Above Ground Level (AGL) for nadir and one flight at 16 m AGL for oblique image acquisition were conducted using fixed-wing and rotary-wing UAS equipped with non-metric cameras. For validating the UAS-SfM products, field measurements were performed using Real-Time Kinematic Global Navigation Satellite System (RTK GNSS), terrestrial laser scanner, and total station. The collected images were processed using three SfM software packages. By applying the SfM-MVS workflow, 22 photogrammetric projects were processed, and as a result, point clouds, triangulated 3D models, Digital Surface Models (DSMs), Digital Terrain Models (DTMs), and orthomosaics were generated. Finally, absolute and relative accuracy assessments were performed. The spatial resolution of orthomosaics and DSMs derived from the UAS images of 16, 100, and 170 m AGL, was 0.005, 0.025, and 0.04 m, respectively. The highest accuracy was obtained from the results derived from 16 m AGL oblique images, which the horizontal and vertical RMSE values were 0.025 and 0.02 m, respectively. From the nadir images of 100 and 170 m AGL, $RMSE_{XY}$ of 0.03 m and $RMSE_z$ of 0.04 and 0.06 m were achieved, respectively. The achieved accuracies of orthomosaics and DSMs reconstructed from 16, and 100 m AGL images are sufficient for most applications requiring terrain analysis, including civil engineering projects.

Keywords: UAS Photogrammetry, Structure from motion (SfM), Digital elevation model, UAV, Terrestrial laser scanning

ÖZET

MÜHENDİSLİK ÖLÇMELERİNDE İHA FOTOGRAMETRİSİ VE SfM'NİN DOĞRULUK ANALİZİ VE DEĞERLENDİRİLMESİ

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Daha az maliyet ve çaba ile detaylı topografik haritalama, her zaman bilimsel ilgilinin gelişmekte olan alanlarından biri olmuştur. İnsansız Hava Araçları (İHA) ve hareket ile nesne oluşturma (SfM) ile çok görüşlü stereo fotogrametri (MVS) kullanan görüntü tabanlı uzaktan algılama yöntemleri, harita mühendisliği alanındaki son otomasyon ve ilerlemelerdir. Bu araştırmanın amacı, konvansiyonel haritalama metodlarına hızlı ve düşük maliyetli bir alternatif olarak, İHA tabanlı SfM-MVS'nin doğruluğunu değerlendirilmesidir. Bu amaçla, dikey görüntüler elde etmek için, sabit kanatlı İHA kullanılarak 100 m ve 170 m yüksekliklerde iki uçuş yapılmıştır. Eğik görüntüler elde etmek için döner kanatlı İHA kullanılarak 16 m'de bir uçuş gerçekleştirilmiştir. İHA-SfM ürünlerini doğrulamak için Gerçek Zamanlı Kinematik Küresel Navigasyon Uydu Sistemi (RTK GNSS), yersel lazer tarayıcı, ve total station kullanılarak alan ölçümleri yapılmıştır. Toplanan görüntüler üç adet SfM yazılım paketi kullanılarak işlenmiştir. SfM-MVS iş akışı uygulanarak 22 fotogrametrik proje işlenmiştir. Sonuç olarak, nokta bulutları, üçgen 3B modeller, Sayısal Yüzey Modelleri (SYM), Sayısal Arazi Modelleri (SAM) ve ortogörüntüler oluşturulmuştur. Son olarak, mutlak ve bağıl doğruluk değerlendirmeleri yapılmıştır. 16 m, 100 m ve 170 m yükseklikteki İHA görüntülerinden elde edilen ortogörüntülerin ve SYM'lerin mekansal çözünürlüğü sırasıyla 0.005 m, 0.025 m ve 0.04 m'dir. En yüksek yatay ve dikey doğruluk değerleri (RMSE [Root Mean Square Error]) sırasıyla 0.025 m ve 0.02 m olan 16 m yüksekliğindeki eğik görüntülerden elde edilen sonuçlardan elde edilmiştir. 100 m ve 170 m yükseklikteki nadir görüntülerden, sırasıyla 0.03 m'lik $RMSE_{XY}$ ve 0.04 ve 0.06 m'lik $RMSE_Z$ elde edilmiştir. 16 m ve 100 m yükseklikteki görüntülerden oluşturulan ortogörüntülerin ve SYM'lerin elde edilen doğrulukları, inşaat mühendisliği projeleri de dahil olmak üzere, arazi analizi gerektiren pek çok uygulama için yeterlidir.

Anahtar Sözcükler: İHA Fotogrametrisi, Hareket ile nesne oluşturma (SfM), SfM-MVS, Dijital yükseklik modeli, Yersel lazer tarama

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Sayed Ishaq DELIRY

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Anadolu University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

.....
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TABLE OF CONTENTS

	<u>Page</u>
TITLE PAGE	i
FINAL APPROVAL FOR THESIS	ii
ABSTRACT.....	iii
ÖZET	iv
ACKNOWLEDGEMENTS	v
STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	x
LIST OF FIGURES	xii
ABBREVIATIONS.....	xx
1. INTRODUCTION.....	1
1.1. Background.....	1
1.2. Problem Statement.....	5
1.3. Research Objectives.....	7
1.3.1. Specific objectives	7
1.4. Thesis Structure	8
2. LITERATURE REVIEW.....	10
2.1. General Overview	10
2.2. Quantification of Error in Structure from Motion and Validation Methods.....	11
2.3. Previous Studies	19
2.3.1. Review articles.....	19
2.3.2. Influence of flight height, GCP number, image overlap, and terrain morphology on accuracy of UAS-SfM products	21
2.3.3. RTK-enabled UAS-based survey.....	23
2.3.4. Oblique photogrammetry and combination of photogrammetric blocks.....	25
2.3.5. Comparison of UAS-SfM and TLS 3D models.....	26

	<u>Page</u>
2.3.6. Performance of structure from motion software	27
2.3.7. Earth work and volumetric measurements	29
2.3.8. Agriculture and forestry.....	29
2.3.9. Coastal and riverine.....	31
2.3.10. Snow and glacier	32
2.3.11. Landslide.....	33
2.3.12. UAS-SfM accuracy in challenging terrain.....	33
2.3.13. Miscellaneous studies.....	34
2.4. Summary.....	36
3. THEORETICAL BACKGROUND.....	38
3.1. Unmanned Aerial Systems	38
3.1.1. Definition and terminology	39
3.1.2. Platforms and components.....	40
3.1.3. Classification	42
3.1.4. Applications	44
3.1.5. Regulations	45
3.2. UAS Photogrammetry	47
3.2.1. Structure from motion.....	48
3.2.2. Camera.....	55
3.2.3. Photogrammetric project planning.....	56
3.2.4. Georeferencing and bundle adjustment.....	67
3.2.5. Photogrammetric mapping products	71
3.3. Terrain Modeling and Data Acquisition Techniques	74
4. METHODS	83
4.1. Project Planning and Data Acquisition.....	85
4.1.1. Study area	85
4.1.2. Equipment and software	86
4.1.3. Ground control points and checkpoints measurement.....	93
4.1.4. Terrestrial laser scanning and data processing.....	96
4.1.5. Flight planning and image acquisition	101

	<u>Page</u>
4.2. SfM Photogrammetry-Based Image Processing.....	104
4.3. Accuracy Assessment.....	111
5. RESULTS AND DISCUSSION	114
5.1. Absolute Accuracy Analysis and Evaluation of Results	114
5.1.1. Horizontal and vertical accuracy assessment based on 7 marked CPs	115
5.1.2. Vertical accuracy assessment based on 200 unmarked CPs	118
5.2. 3D modeling and volumetric accuracy assessment	136
5.3. Profile and cross-sectional analysis	142
5.4. Visual inspection and quality assessment	158
5.4.1. Comparison of Point clouds	158
5.4.2. Comparison of DSMs.....	160
5.4.3. Comparison of DTMs	162
5.4.4. Comparison of orthomosaics	164
6. CONCLUSIONS AND RECOMMENDATIONS.....	165
6.1. Summary of Findings.....	166
6.2. Advantages and Challenges of UAS Photogrammetry and Structure from Motion.....	168
6.3. Limitations of the Study and Recommendations for Future Research.....	170
REFERENCES.....	171
CURRICULUM VITAE	

LIST OF TABLES

	<u>Page</u>
Table 2.1. Summary of the literature contributed to the accuracy assessment of UAS-SfM-based mapping.	15
Table 4.1. Technical specifications of SenseFly eBee Plus unmanned aerial system. ..	88
Table 4.2. Technical specifications of DJI Phantom 4 Pro.	89
Table 4.3. JAVAD TRIUMPH-1 GNSS specifications.	91
Table 4.4. Technical specifications of Trimble M3.	92
Table 4.5. Software packages utilized for data processing and analysis.	92
Table 4.6. Coordinates and accuracy of measured GCPs.	95
Table 4.7. Flight and data acquisition parameters.	102
Table 5.1. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 100 m AGL nadir images, processed with 5 GCPs and assessed with 7 GNSS CPs. All values are in meters.	115
Table 5.2. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 100 m AGL nadir images, processed with 10 GCPs and assessed with 7 GNSS CPs. All values are in meters.	115
Table 5.3. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 170 m AGL nadir images, processed with 5 GCPs and assessed with 7 GNSS CPs. All values are in meters.	115
Table 5.4. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 170 m AGL nadir images, processed with 10 GCPs and assessed with 7 GNSS CPs. All values are in meters.	116
Table 5.5. Horizontal and vertical error statistics of orthomosaics and DSMs derived from the merged process of 100 and 170 m AGL nadir images and assessed with 7 GNSS CPs. All values are in meters.	116
Table 5.6. Vertical error statistics of DSMs derived from 100 m AGL nadir images, processed with 5 & 10 GCPs and assessed with 100 GNSS CPs. All values are in meters.	118
Table 5.7. Vertical error statistics of DSMs derived from 170 m AGL nadir images, processed with 5, 10, and without GCPs and assessed with 100 GNSS CPs. All values are in meters.	118

	<u>Page</u>
Table 5.8. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 16 m AGL oblique images, processed with 4 GCPs and assessed with 10 GNSS-TS CPs. All values are in meters.....	134
Table 5.9. Vertical error statistics of the building point clouds derived from oblique and nadir images of different flight heights using PhotoScan and assessed with 16 GNSS-TS CPs. All values are in meters.....	135
Table 5.10. Vertical error statistics of the building point clouds derived from oblique and nadir images of different flight heights using Pix4D and assessed with 16 GNSS-TS CPs. All values are in meters.....	135
Table 5.11. Vertical error statistics of the building point clouds derived from oblique and nadir images of different flight heights using 3Dsurvey and assessed with 16 GNSS-TS CPs. All values are in meters.....	135
Table 5.12. Building dimensions and volume measured from 3D point clouds of TLS and SfM (derived from oblique images of 16 m AGL taken using DJI Phantom 4 Pro).	139
Table 5.13. Building point cloud statistics and comparison of the building volumes calculated from PhotoScan point clouds.....	140
Table 5.14. Building point cloud statistics and comparison of the building volumes calculated from Pix4Dmapper point clouds.....	140
Table 5.15. Building point cloud statistics and comparison of the building volumes calculated from 3Dsurvey point clouds.	141
Table 5.16. Profile statistics of elevation difference between UAS-SfM (100m AGL) and TLS.....	151
Table 5.17. Profile statistics of elevation difference between UAS-SfM (170 m AGL) and TLS.....	151
Table 5.18. UAS-SfM point cloud statistics of the study area.....	158

LIST OF FIGURES

	<u>Page</u>
Figure 2.1. Potential of UAS photogrammetry accuracy in surveying.....	11
Figure 2.2. Scatter plot of SfM RMSEz versus flight height, plotted from the synthesis of previous studies given in Table 2.1.	13
Figure 2.3. Relative frequency histogram of vertical error plotted from the synthesis of previous studies given in Table 2.1.....	13
Figure 2.4. Plot of SfM RMSEz against GCP number.	14
Figure 3.1. Examples of small UAVs: (a) fixed-wing senseFly eBee+; (b) multirotor DJI Mavic 2 Pro; (c) VTOL FireFly 6.....	43
Figure 3.2. Tracks between two images in PhotoScan (right); valid matches are shown in blue, while invalid matches are given in red. The left screenshot shows the identification of the same feature in multiple images in Pix4D.	51
Figure 3.3. Vertical and oblique photography	58
Figure 3.4. Geometry of a vertical photograph.....	58
Figure 3.5. Side view of a vertical photograph over flat terrain	59
Figure 3.6. Side view of a vertical photograph over variable terrain	60
Figure 3.7. Ground coordinates of a vertical photo	62
Figure 3.8. Forward lap of successive photos along a flight line	62
Figure 3.9. Side overlap of adjacent flight strips: (a) top view (b) side view.....	63
Figure 3.10. Regular grid image acquisition plan.....	67
Figure 3.11. An example of pre-marked ground control point.	68
Figure 3.12. Rotational angles in fixed-wing and rotary-wing aircraft	70
Figure 3.13. (a) collinearity condition, and (b) rotated image coordinate system	70
Figure 3.14. Collinearity relationship for the point P on image and its corresponding point on a DEM	73
Figure 3.15. Schematic illustration of digital orthophoto production process.....	73
Figure 3.16. (a) raw aerial image and (b) rectified orthoimage.	74
Figure 3.17. DSM and DTM.....	75
Figure 3.18. An example of digital contour map and ground-based surveying instruments	77
Figure 3.19. SAR image acquisition by two satellites at different times.....	80

	<u>Page</u>
Figure 3.20. Examples of laser scanning point cloud and elevation models	81
Figure 4.1. Workflow of the methods used in this research	84
Figure 4.2. Study area	86
Figure 4.3. SenseFly eBee Plus with its ground control system during fieldwork.	87
Figure 4.4. DJI Phantom 4 Pro with its control system during fieldwork.	89
Figure 4.5. SenseFly eBee Plus (left) and DJI Phantom 4 Pro (left) UAS cameras.	89
Figure 4.6. RIEGL VZ-2000 TLS during scanning.	90
Figure 4.7. JAVAD TRIUMPH-1 GNSS (right) and Trimble M3 total station (left). ..	92
Figure 4.8. Ground control points, checkpoints, and specific assessment areas.....	94
Figure 4.9. RTK DGNSS and TS measurements of ground control points.....	95
Figure 4.10. Scan positions for building and road survey.	96
Figure 4.11. Scan positions in single color before registration.....	97
Figure 4.12. Automatic registration failure.....	98
Figure 4.13. Polydata created using plain patch filter.	98
Figure 4.14. Histograms of multi-station adjustment residues, four iterations from top to bottom.....	99
Figure 4.15. TLS point cloud after multi-station adjustment (2D and 3D reflectance view).	100
Figure 4.16. Colored and filtered point clouds of the building, filtered using two octree increment values.	101
Figure 4.17. Flight mission planned in eMotion 3.....	102
Figure 4.18. Building GCPs and CPs (left), and oblique image acquisition (right). ...	104
Figure 4.19. Sparse point cloud generated using PhotoScan.	106
Figure 4.20. 3D view of dense point cloud generated using PhotoScan.....	107
Figure 4.21. 3D view of the solid mesh model generated using PhotoScan.....	107
Figure 4.22. 3D view of the textured mesh model generated using PhotoScan.	108
Figure 4.23. DSM generated from the point cloud in PhotoScan.	108
Figure 4.24. DTM generated using semi-automatic algorithm in PhotoScan.....	109
Figure 4.25. Orthomosaic generated using PhotoScan.	110

Figure 5.1. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 100 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	120
Figure 5.2. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 100 m AGL nadir images, processed with 5 GCPs.....	120
Figure 5.3. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 100 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	121
Figure 5.4. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 100 m AGL nadir images, processed with 10 GCPs.....	121
Figure 5.5. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 170 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	122
Figure 5.6. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 170 m AGL nadir images, processed with 5 GCPs.....	122
Figure 5.7. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 170 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	123
Figure 5.8. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 170 m AGL nadir images, processed with 10 GCPs.....	123
Figure 5.9. Relative frequency histogram of vertical errors and scatter plot of correlation between UAS-SfM and DGNSS non-vegetated elevations. UAS-SfM DSM derived from merged process of 100 and 170 m AGL nadir images, processed with 10 GCPs using.....	126

	<u>Page</u>
Figure 5.10. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from merged process of 170 m (Flight 1) and 100 m (Flight 2) AGL nadir images, processed with 10 GCPs using PhotoScan.	126
Figure 5.11. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 170 m AGL nadir images, processed using the three software without GCP.	127
Figure 5.12. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 100 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	128
Figure 5.13. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 100 m AGL nadir images, processed with 5 GCPs.	128
Figure 5.14. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 100 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	129
Figure 5.15. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 100 m AGL nadir images, processed with 10 GCPs.	129
Figure 5.16. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 170 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	130
Figure 5.17. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 170 m AGL nadir images, processed with 5 GCPs.	130
Figure 5.18. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 170 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	131

	<u>Page</u>
Figure 5.19. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 170 m AGL nadir images, processed with 10 GCPs.	131
Figure 5.20. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 100 m AGL nadir images, georeferenced with 5 GCPs using PhotoScan.	132
Figure 5.21. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 170 m AGL nadir images, georeferenced with 5 GCPs using PhotoScan.	133
Figure 5.22. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 100 m AGL nadir images, georeferenced with 10 GCPs using PhotoScan.	133
Figure 5.23. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 170 m AGL nadir images, georeferenced with 10 GCPs using PhotoScan.	133
Figure 5.24. 3D dense point cloud of the building generated using PhotoScan from oblique image of DJI Phantom 4 Pro UAS at 16 m AGL.	136
Figure 5.25. 3D solid mesh of the building generated using PhotoScan.	137
Figure 5.26. 3D textured mesh of the building generated using PhotoScan.	137
Figure 5.27. Comparison of TLS (left) and SfM-PhotoScan (right) building point clouds.	137
Figure 5.28. Comparison of oblique and nadir point clouds derived from images of DJI oblique 16 m AGL (a), senseFly 100 m (b), 170 m (c), and merged of 100 and 170 m (d) processed using PhotoScan (left), Pix4D (middle), and 3Dsurvey (right) SfM-MVS software packages.	138
Figure 5.29. Comparison of the 3D point cloud (a) and 2.5D DSM (b) of the building with the overhanging element.	142
Figure 5.30. Location of the selected road profile and cross-section on the DSM (a) and point cloud (b) of the study area.	142
Figure 5.31. Road longitudinal profiles created from TS (a) and TLS (b) data.	143
Figure 5.32. Vertical differences between TLS point cloud profile and PhotoScan DSM extracted profile (flight 1; 5 GCP).	143

	<u>Page</u>
Figure 5.33. Vertical differences between TLS point cloud profile and Pix4D DSM extracted profile (flight 1; 5 GCP).....	144
Figure 5.34. Vertical differences between TLS point cloud profile and Pix4D DSM extracted profile (flight 1; 5 GCP).....	144
Figure 5.35. Comparison of vertical profiles extracted from TLS point cloud and UAS-SfM based DSMs (flight 1; 5 GCP).	145
Figure 5.36. Comparison of UAS-SfM based profiles processed with and without GCPs (flight 1; 5 GCP).....	145
Figure 5.37. Cross-section of the road extracted from the TLS point cloud.	146
Figure 5.38. Vertical differences between TLS point cloud and PhotoScan DSM cross-sections (flight 1; 5 GCP).	146
Figure 5.39. Vertical differences between TLS point cloud and Pix4D DSM cross- sections (flight 1; 5 GCP).	146
Figure 5.40. Vertical differences between TLS point cloud and 3Dsurvey DSM cross-sections (flight 1; 5 GCP).	147
Figure 5.41. Comparison of road cross-sections extracted from TLS point cloud and UAS-SfM DSMs (flight 1; 5 GCP).	147
Figure 5.42. Comparison of UAS-SfM based road cross sections processed with and without GCPs.....	147
Figure 5.43. Vertical differences between TLS point cloud profile and PhotoScan DSM extracted profile (flight 2; 5 GCP).	148
Figure 5.44. Vertical differences between TLS point cloud profile and Pix4D DSM extracted profile (flight 2; 5 GCP).....	148
Figure 5.45. Vertical differences between TLS point cloud profile and 3Dsurvey DSM extracted profile (flight 2; 5 GCP).	149
Figure 5.46. Comparison of vertical profiles extracted from TLS point cloud and UAS-SfM based DSMs (flight 2; 5 GCP).	149
Figure 5.47. Vertical differences between TLS point cloud and PhotoScan DSM cross-sections (flight 2; 5 GCP).	150
Figure 5.48. Vertical differences between TLS point cloud and Pix4D DSM cross- sections (flight 2; 5 GCP).	150

	<u>Page</u>
Figure 5.49. Vertical differences between TLS point cloud and 3Dsurvey DSM cross-sections (flight 2; 5 GCP).	150
Figure 5.50. Comparison of road cross-sections extracted from TLS point cloud and UAS-SfM DSMs (flight 2; 5 GCP).	151
Figure 5.51. Comparison of road profiles extracted from TLS point cloud and SfM DSMs of flight 1 and 2.	152
Figure 5.52. Comparison of road cross-sections extracted from TLS point cloud and SfM DSMs of flight 1 and 2.	153
Figure 5.53. Comparison of profiles of flight 1 (a) and 2 (b) processed using 10 GCPs.....	154
Figure 5.54. Comparison of cross-sections of flight 1(a) and 2 (b) processed using 10 GCPs.....	154
Figure 5.55. Comparison of DSM surface quality generated by PhotoScan, Pix4D, and 3Dsurvey from images of two flights.	155
Figure 5.56. Comparison of point clouds in road profiles extracted from SfM point clouds generated by PhotoScan, Pix4D, and 3Dsurvey.....	156
Figure 5.57. Comparison of point clouds in road cross-sections extracted from SfM point clouds generated by PhotoScan, Pix4D, and 3Dsurvey.	157
Figure 5.58. Comparison of building cross-sections extracted from point clouds of TLS (a), oblique images of 16 m AGL (b), nadir images of 100 m AGL (c), and nadir images of 170 m AGL (d). SfM point clouds was processed using PhotoScan.....	157
Figure 5.59. Comparison of TLS and UAS-SfM point cloud density. SfM point cloud derived from 16 m AGL oblique images of DJI UAS, processed using PhotoScan.	158
Figure 5.60. Comparison of point cloud density derived using different software packages from UAS images of different flight heights.	159
Figure 5.61. Comparison of point clouds produced by PhotoScan (a), Pix4D (b), and 3Dsurvey (c) from images of UAS at 170 m height AGL.	159
Figure 5.62. Comparison of point clouds produced by PhotoScan (a), Pix4D (b), and 3Dsurvey (c) from images of UAS at 100 m height AGL.	160

	<u>Page</u>
Figure 5.63. Comparison of DSMs produced by different software packages from images of different flight height AGL.....	161
Figure 5.64. Camera locations of flight 2.	161
Figure 5.65. DSM of the entire campus derived from 170 m AGL, processed using PhotoScan.	162
Figure 5.66. Comparison of DTMs generated from UAS images of 170 m AG, (a) PhotoScan, (b) Pix4Dmapper, (c) 3Dsurvey	163
Figure 5.67. 3D comparison of DSM (left) and DTM (right) created using automatic algorithms of PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).	163
Figure 5.68. Comparison of contours produced using DTMs of PhotoScan (a), Pix4D (b), and 3Dsurvey (c).....	163
Figure 5.69. Comparison of orthomosaics generated using PhotoScan (left), Pix4D (middle), and 3Dsurvey (right).....	164

ABBREVIATIONS

2D	: Two-dimensional
3D	: Three-dimensional
AGL	: Above Ground Level
ALS	: Airborne Laser Scanner
ASPRS	: American Society for Photogrammetry and Remote Sensing
ATO	: Above Takeoff Altitude
CAD	: Computer-Aided Design
CCD	: Charge-Coupled Device
CP	: Checkpoint
DEM	: Digital Elevation Model
DGNSS	: Differential Global Navigation Satellite System
DGPS	: Differential Global Positioning System
DSM	: Digital Surface Model
DTM	: Digital Terrain Model
EXIF	: Exchangeable Image File Format
GCP	: Ground Control Point
GCS	: Ground Control System
GIS	: Geographic Information Systems
GNSS	: Global Navigation Satellite System
GPS	: Global Positioning System
GSD	: Ground Sampling Distance
IMU	: Inertial Measuring Unit
LiDAR	: Light Detection and Ranging
MP	: Megapixel
MSL	: Mean Sea Level
MVS	: Multi-View Stereo
PPK	: Post-Processing Kinematic
RADAR	: Radio Detection and Ranging
RMSE	: Root Mean Square Error
RPA	: Remotely Piloted Aircraft
RPV	: Remotely Piloted Vehicle
RTK	: Real-Time Kinematic

SfM	: Structure from Motion
SIFT	: Scale Invariant Feature Transform
TIN	: Triangulated Irregular Network
TLS	: Terrestrial Laser Scanner
TS	: Total Station
UAS	: Unmanned Aircraft/Aerial System(s)
UAV	: Unmanned Aerial Vehicle
UTM	: Universal Transverse Mercator
WGS84	: World Geodetic System 1984



1. INTRODUCTION

1.1. Background

Highly detailed topographic mapping at minimal cost and effort has always been one of the developing areas of scientific interest. Unmanned aerial systems, also commonly termed Unmanned Aerial Vehicles (UAVs) or drones, are aircraft systems that operate without a pilot on board. With the advancement of technology, the use of UAS as a remote sensing platform and SfM-MVS as a photogrammetric technique to produce high-resolution topographic maps is increasing (Agüera-Vega et al., 2018; Greenwood, Lynch, & Zekkos, 2019; Nex & Remondino, 2014). The application of UAS and SfM-MVS is gaining increasing interest in most disciplines, particularly in engineering and earth sciences. Using the UAS images and SfM technique, valuable information can be obtained, such as 3D point clouds, digital elevation models, and orthoimages, which are the source of information in many engineering tasks. SfM-MVS enables rapid reconstruction of surface geometry from images of a non-metric camera with sufficient overlaps without the need for camera position or orientation data (Carrivick, Smith, & Quincey, 2016; Lowe, 1999, 2004; Snavely, Seitz, & Szeliski, 2008; T. Tonkin & Midgley, 2016). An increase in the use of UAS for image acquisition has coincided with the development of automated computer vision algorithms, commonly referred to as SfM and MVS. The integration of photogrammetry and computer vision has led to advances in automation; as a result, photogrammetric data collection has become more flexible with the possibility of collecting images from different directions and heights (Agüera-Vega, Carvajal-Ramírez, & Martínez-Carricondo, 2016; Carrivick et al., 2016; Martínez-Carricondo et al., 2018). Structure from motion technique is widely used to extract 3D information from such data.

Surveying is a rapidly developing engineering field that over the past decades, has benefited from a wide range of technological advances such as ground-based, water-based, airborne, and spaceborne. Engineering surveying involves planning, designing, and execution of surveys of different accuracy classes for the purposes of development, designing, construction, quality control, inspection, and operation and maintenance of civil and other engineering projects (ASCE, 2018; Kreisle, 1988; Wolf, 2002). Surveying has a broad professional practice of engineering, which one of the major activities is

providing high-accuracy topographic maps. Topographic surveys can be conducted using different techniques from the ground, air, and space that require various instruments. Method selection depends on the desired scale and accuracy of the project. Technological advancements in land surveying started with the advent of electromagnetic distance measurement (EDM) instruments. Subsequently, total station (TS) and Global Positioning System (GPS) improved the efficiency and accuracy of measurements. The TS, which combines distance and angular measurement in a single instrument, introduced in the early 1970s. This combination provides the capability of retrieving coordinates of the measured point in the device. Total stations have been productive instruments in topographic surveying and construction; robotic TSs allow remote operations with one operator resulting in higher productivity. Later on, RTK GNSS enhanced the speed and precision of satellite-based surveying.

Over the past decades, there have been rapid technological advances related to surveying and mapping, especially in digital terrain modeling. Along with technological developments, a large number of topographic surveys have been conducted using theodolites (Wolf, 2002), aerial photogrammetry (Dai & Lu, 2010), robotic and image-assisted total stations (Ehrhart & Lienhart, 2016; Roberts & Boorer, 2016), differential GNSS (Awange, 2012; Kizil & Tisor, 2011; Yiming, Jinning, & Zhizhou, 2003), satellite remote sensing and digital photogrammetry (Holland, Boyd, & Marshall, 2006; Honkavaara et al., 2009; Patino & Duque, 2013), airborne laser scanning (Li, Zhu, & Gold, 2004; Pirotti, Guarnieri, & Vettore, 2013), terrestrial laser scanning (Slattery & Slattery, 2013; Telling et al., 2017), and most recently UAS-SfM (Agüera-Vega et al., 2018; Nex & Remondino, 2014). However, cost and time-consumption are common limitations in most of the above methods. In physical surveying using the conventional methods, each individual point is surveyed in a subjective manner in which professional engineering surveyors with sufficient geomorphological knowledge, determine where to be measured to get accurate interpolation. The decision on the number and location of points for an accurate representation of topography using traditional methods highly depends on the surveyor's skill. Although highly detailed topographical surveys using physical surveying techniques are possible, this method is costly and extremely time-consuming.

Remote digital surveying, which includes digital photogrammetry and laser scanning, is the latest automation and advancement in surveying engineering that both

experienced their evolution at about the same time. Active and passive remote sensing technologies have made a significant change in modern surveying. The emergence of 3D terrestrial and airborne laser scanners has been one of the most significant technological revolutions in surveying and mapping. Laser scanning enabled a transition from a set of discrete points to a set of very high-density points. The laser scanning technique using the pulse of laser light yields a digital dataset of very high-density 3D points, which are known as point clouds (Mark W. Smith, 2016). Using a laser scanner, large amounts of data can be acquired in a short time. Remote surveying enables objective data collection with high accuracy and density in a short time. In this way, the terrestrial laser scanner (TLS) and airborne laser scanner (ALS) have gradually become an essential surveying tool for highly detailed mapping.

Structure from motion is one of the most recent and important developments in digital surveying (Carrivick et al., 2016; Greenwood et al., 2019; Micheletti, Chandler, & Lane, 2015). With the advances in computer vision, the combination of digital technology and structure from motion has revolutionized the photogrammetry field. Motion-based reconstruction or structure from motion was first introduced by Ullman (Ullman, 1979) in the late 1970s. It came to popularity with the development of computer vision algorithms and after further efforts of other researchers (e.g., Furukawa & Ponce, 2009; Lowe, 1999, 2004; Snavely, Seitz, & Szeliski, 2006; Snavely et al., 2008) in the 2000s. These techniques are used to reconstruct high-quality 3D structures from a range of 2D photogrammetric images. The SfM-MVS algorithms produce true color 3D dense point clouds, which are quite comparable to those of laser scanning surveys. Unlike classic aerial stereophotogrammetry, which requires careful flight planning and camera pre-calibration (Wolf, Dewitt, & Wilkinson, 2014), UAS-based SfM (UAS-SfM) provides simplicity in data acquisition and image processing, without the need for comprehensive planning or camera calibration (Martínez-Carricondo et al., 2018). Today, photogrammetric software packages with high computational power are available that can process hundreds of images simultaneously and extract 3D surface information using feature detection and matching algorithms. With these developments, using a lightweight UAV and a digital non-metric camera, unprecedented high-resolution 3D elevation models can be generated, which are comparable in scale and accuracy to that of TLS, ALS, and conventional photogrammetric approaches. In addition to achieving higher

resolution than traditional photogrammetry methods, SfM-MVS can reduce processing efforts by about 3-6 times (Mölg & Bolch, 2017).

Digital elevation models (DEMs) are the primary database for topography-related analysis such as engineering planning, infrastructure design, risk assessment, hazard monitoring, agricultural management, and natural resources exploration (Li et al., 2004; Martínez-Carricondo et al., 2018). Very high-resolution 3D models and associated orthoimages derived from UAS images are of great importance in scientific fields involving mapping subtle topographic variations and surface analysis, for instance, in structural monitoring and studies of earth surface dynamics (Carrivick et al., 2016). To overcome the limitation of traditional surveying techniques, and to obtain rapid and cost-effective data, the application of UAS-SfM has been the subject of many studies in recent years (Agüera-Vega et al., 2016; Coveney & Roberts, 2017; Fernández et al., 2016; Gerke & Przybilla, 2016; Gindraux, Boesch, & Farinotti, 2017; Jaud et al., 2016; Long et al., 2016; Lucieer, Jong, & Turner, 2014; Pajares, 2015; Sanz-Ablanedo et al., 2018). Very high spatial and temporal resolution images can be provided by combining UAS data and remote sensing techniques. UAVs have distinguished advantages over satellites and human-crewed aircraft, such as higher spatial and temporal resolution, lower cost, availability, rapid data acquisition, and operational flexibility (Agüera-Vega et al., 2018, p. 20; Colomina & Molina, 2014; Gonçalves & Henriques, 2015; Nex & Remondino, 2014; Stöcker et al., 2017). Furthermore, accessibility is a challenging issue in terrestrial surveys, where neither TLS nor ground photogrammetry is a practical option. In many situations, terrestrial surveys for generating 3D models are quite challenging, for example, in hazardous areas, steep and narrow valleys, and buildings with slanted roofs. UAS photogrammetry is the solution for such problems; therefore, UAS photogrammetry can be considered as an effective alternative to traditional photogrammetry.

Although recent developments have led to the extensive use of UAS-SfM in mapping applications, the only concern that remains is the UAS-based survey accuracy; is this method accurate enough to be used in engineering surveying applications as an alternative to conventional methods? Evaluation of accuracy and validation of products before they are applied to a real-world problem is a prerequisite for any emerging technology. In engineering works, data accuracy is the main concern that must be within acceptable limits; therefore, accuracy evaluation is crucial. Recently, many studies have been conducted to assess the ability of UAS-SfM as an alternative to conventional

surveying methods. However, each quantitative validation study is different from another due to variations in method, platform, camera, survey scale, terrain, comparison method, and software used for processing.

This research was motivated by the lack of comprehensive research on the recent developments in UAS photogrammetry and SfM in the field of surveying engineering. This thesis overviews the application of UAS and structure from motion in geomatics engineering, analyzes and highlights the most recent achieved accuracies based on a comprehensive literature review, and evaluates the accuracy of UAS-based surveying by conducting field surveys using fixed-wing and rotary-wing UAVs, RTK GNSS, TS, and TLS. In addition, the research presents a comparison of the accuracy and performance of three commercial photogrammetric software packages, namely Agisoft PhotoScan, Pix4Dmapper, and 3Dsurvey in the image processing and modeling of eight photogrammetric projects.

1.2. Problem Statement

For computer-based modeling of 3D structures and quantifying terrain variability, topographic information is usually needed in digital format. Digital elevation models have a variety of applications in the fields which require terrain analysis. The conventional terrestrial surveying methods are total station and differential GNSS (DGNSS) techniques, which are point-based survey methods. Both methods can be used separately or in combination. Using TS and DGNSS methods, in each hour of measurement, hundreds to thousands of high-accuracy points can be acquired (Bangen et al., 2014). These methods can provide excellent accuracy, but for large areas, they can be costly and time-consuming. On the other hand, since in terrestrial surveying, each point of interest is determined by the surveyor, survey design is influenced by subjectivity.

Remote sensing methods for obtaining digital elevation data are LiDAR, RADAR, stereophotogrammetry, and UAS-based and ground-based structure from motion. Providing more detail, speed, objectivity, and data collection from inaccessible areas are the advantages of remote sensing-based surveying. The airborne laser scanning method can provide terrain data with high density and vertical accuracy between 0.1 and 0.15 m (Gallay, 2013; Li et al., 2004). Terrestrial laser scanning offers high-resolution and high-accuracy full 3D data at an unprecedented speed that cannot be achieved by any of the above methods (Mark W. Smith, 2016). Although the TLS method is currently being used

as the most reliable method in highly detailed topographic surveys, this method is not the perfect solution because limitations such as cost, weight, line of sight, and logistics remain a problem. In addition, the amount of data collected with TLS or ALS for a specific area can be excessive for processing with a conventional computer, particularly with full waveform scanning, data volume may increase tens of times compared to the single return technique (Carrivick et al., 2016; Galloway, 2013). Conventional photogrammetry is based on photographs obtained by survey-grade metric cameras, usually mounted on manned aircraft. This method can provide high-resolution planimetric data and DEMs; however, in addition to higher flight height, cost, and availability problems, the workflow of this method is often lengthy and needs a large amount of work (Carrivick et al., 2016; Wolf et al., 2014).

Given the importance of planimetric maps and 3D terrain models in earth observations and engineering tasks, producing accurate and highly detailed maps at the lowest cost and in the shortest possible time is of paramount importance. Structure from motion can produce very high-resolution orthoimages and terrain models from images of non-metric cameras taken by low-cost UAS. UAS photogrammetry has many advantages over conventional digital photogrammetry. In recent years, due to advances in technology, image-based approaches have been significantly reduced in cost and increased in ease of use. SfM-MVS is a rapid and efficient method for producing terrain models and is the only method that can produce full 3D point clouds that can compete with that of TLS.

The application of UAS-SfM is gaining increasing interest in most disciplines, particularly in engineering and geosciences. Recently, SfM is widely used in earth sciences applications as a low-cost topographic survey technique to produce dense 3D point clouds, digital elevation models, and topographic maps (Agüera-Vega et al., 2018; Carrivick et al., 2016; Coveney & Roberts, 2017, 2017; Cryderman, Mah, & Shufletoski, 2014; Gabrlik et al., 2018; Gerke & Przybilla, 2016; Gindraux et al., 2017; Martínez-Carricondo et al., 2018; Salach et al., 2018). However, in view of the literature review, achieved accuracies significantly vary by study characteristics. Hence, further studies are needed to evaluate the accuracy of UAS-SfM in surveying applications. For evaluating the accuracy and quality of SfM-MVS survey design in surface reconstruction, rigorous accuracy assessment is required, which entails practical comparative studies.

Even though there are a large number of studies comparing the accuracy of SfM derived point clouds, DSMs, and orthoimages, there is still a lack of comprehensive studies regarding the influence of flight height above ground level and distribution of ground control points on the accuracy of UAS-SfM surveys. Validation of the volumetric accuracy of UAS-SfM is also a significant gap in the literature. In the literature, for volumetric accuracy assessment, digital surface models (DSMs) have been used by most studies to calculate the volume of objects such as stockpiles or opencast mines (Cryderman et al., 2014; C. H. Hugenholtz et al., 2014; Slattery, Slattery, & Peterson, 2011; Wang et al., 2014). However, since DSMs are generated by interpolating 3D points of point clouds, and they represent a 2.5D surface, the volume of objects with more vertical details such as buildings with overhanging elements cannot be accurately computed using DSMs. In such cases, triangulated surfaces should be created from point clouds to preserve the 3D geometry of the object. Few studies have addressed the problem; therefore, it is necessary to evaluate the accuracy of the UAS-SfM point cloud in calculating the volume of objects that cannot be achieved using DSM.

1.3. Research Objectives

The main purpose of this research is to analyze and evaluate the accuracy of UAS-based structure from motion in engineering surveying activities.

1.3.1. Specific objectives

In order to achieve the aim of this research, the following specific objectives were set:

- To conduct UAS-based photogrammetric surveys and field measurements to produce dense point clouds, high-resolution 3D models, digital elevation models, and orthomosaics using SfM-MVS techniques.
- To perform accuracy analysis and quantify the uncertainty of the products, and to evaluate the accuracy of the results based on the American Society for Photogrammetry and Remote Sensing (ASPRS) 2014 positional accuracy standards for digital geospatial data.
- To assess the influence of flight height and image overlaps on the accuracy of point cloud, DSM, and orthomosaic.

- To assess the influence of the number and distribution of ground control points on the absolute accuracy of point cloud, DSM, and orthomosaic.
- To analyze and evaluate the absolute positional accuracy of UAS-SfM.
- To reconstruct 3D terrain models and orthomosaics by combining two vertical photogrammetric blocks of different flight heights, and to evaluate the contribution of block merging to the accuracy and quality of the final products.
- To examine the significance of processing software on the accuracy and quality of products by comparing three software packages.
- To compare automatic and semi-automatic DTM generation using three SfM software packages.
- To compare and evaluate the quality and accuracy of close-range oblique UAS photogrammetry versus terrestrial laser scanning in 3D modeling.
- To analyze and evaluate the accuracy of UAS-SfM compared to TLS in volumetric calculations.
- To perform profile and cross-sectional accuracy analysis.
- To assess point cloud density and surface quality of different flight heights.

1.4. Thesis Structure

This thesis is divided into six chapters:

Chapter 1 is an introduction, states the general topic, and gives some background on topographic surveying methods and their evolution, including UAS, SfM, and their potential capabilities. This chapter also evaluates the current situation and identifies the gap and the importance of the research. This leads to the statement of the problem and formulation of the objectives of the study.

Chapter 2 presents a comprehensive overview of the current literature relating to the UAS-SfM accuracy assessment and validation methods and identifies the potential of UAS photogrammetry accuracy based on the literature. This chapter first summarizes the fifty most related recent case studies. Then determines the parameters that have the most significant impact on the accuracy. Subsequently, extracts the achieved vertical accuracy and influential parameters, and combines the results of the previous quantitative analyses in a table. After that, analyzes the vertical accuracy achieved by previous studies and

provides an error histogram and scatter plots from the synthesis of the previous studies. Finally, achievable accuracy is evaluated and compared to the ASPRS 2014 standard.

Chapter 3 contains a summary of all theories related to the topic. The first section provides information about unmanned aerial systems, its definition and terminology, platforms, classification, applications, and regulations. The section UAS photogrammetry presents a theoretical background about photogrammetric methods and data production, including cameras, SfM, georeferencing, and photogrammetric products. The last section describes terrain modeling and data acquisition techniques. This section briefly reviews the available ground-based, aerial, and satellite-based methods for terrain modeling and highlights their advantages and limitations.

Chapter 4 describes the methods that are the fundamental part of the thesis that presents a practical approach to achieve the objectives. The chapter starts with describing project planning and data acquisition, which includes subsections providing information about the study area, instrumentation and software, ground control points, field measurements, and flight planning and image acquisition. The next section focuses on SfM-based photogrammetric image processing. This section presents a step by step description of the image processing and data production. The last section in this chapter discusses the methods adopted for the accuracy assessment of the generated point clouds, elevation models, and orthoimages.

Chapter 5 presents the results and interprets and discusses the results of this research in terms of obtained accuracy and quality. The first section analyzes the absolute and relative accuracy of the results and evaluates the achieved horizontal and vertical accuracies. The second section presents the results of 3D modeling and volumetric assessments using TLS and UAS-SfM, and then compares and discusses the results. In the third section, profiles and cross-sectional analyses are presented. The last section investigates the quality of the products, including point clouds, DSMs, DTMs, and orthomosaics.

Chapter 6 summarizes the main findings related to the objectives identified in this thesis. Based on the findings of the thesis, advantages and disadvantages are presented. The last chapter also contains challenges and recommendations for possible future studies.

2. LITERATURE REVIEW

This chapter presents a comprehensive literature review on the application and accuracy assessment of UAS-SfM in surveying and mapping. This chapter overviews the application of UAS and structure from motion in geomatics engineering, highlights the most recent achieved accuracies, and evaluates the accuracy of UAS-based mapping compared to the terrestrial methods.

2.1. General Overview

With the advancement of technology, the use of UAS and SfM in photogrammetry to produce high-resolution topographic maps is increasing. The application of UAS and SfM is gaining increasing interest in most disciplines, particularly in engineering and earth sciences. Some application examples include remotely sensed 3D surveying and mapping, 3D city modeling, urban planning, environmental monitoring and management, hazard monitoring, archaeological documentation, geological mapping, precision agriculture, etc.

Since 2009, a significant number of studies have been conducted on the application of UAVs in mapping and 3D modeling. A filtered literature search on Scopus found over 1400 publications from the year 2009 to 2019. Recently, there has been a proliferation of accuracy assessment and validation studies of UAS-SfM-based surveying, focusing on the assessment of the ability of SfM as an alternative to conventional surveying methods. However, quantitative validation studies are slightly different and achieved accuracies significantly vary from study to study due to variations in method, platform, camera, survey scale (flight height), comparison method, study area (terrain), and software used for processing.

After laser scanners, the advent of UAS photogrammetry and its application in the geomatics field is another revolution in surveying and mapping. The cost-effectiveness, rapid mapping capabilities, and providing highly detailed planimetric maps and terrain models using aerial photos, attract the attention of professionals and commercial sectors in this domain. Many studies showing promising results have been carried out to evaluate the reliability of UAS-based mapping; however, considering the sensitivity of the information obtained from UAS-based mapping and the variation in accuracy reported in the literature, further studies are needed to evaluate and determine the accuracy of UAV-

based mapping as an alternative to conventional terrestrial surveying techniques. Figure 2.1 compares UAV-based photogrammetry with other survey methods in terms of total coverage and survey error. Potential sources of error in UAV-based surveying are discussed in detail by Siebert and Teizer (2014).

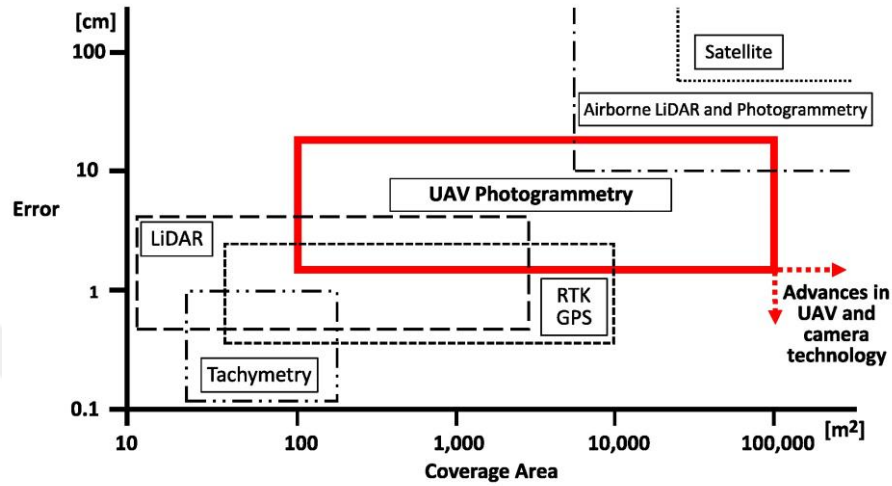


Figure 2.1. Potential of UAS photogrammetry accuracy in surveying (Greenwood et al., 2019; Siebert & Teizer, 2014).

2.2. Quantification of Error in Structure from Motion and Validation Methods

Several studies have quantified the accuracy of 3D models generated using SfM, by comparing them to ground-based surveying data, such as those from the TS, DGNSS, and TLS surveys. This section presents a synthesis of the results of recent studies conducted quantitative assessments of UAS-SfM-derived digital elevation data sets, and thus demonstrates the accuracy and limitation of UAS-SfM-based surveying and mapping.

SfM-MVS produces full 3D dense point clouds of the survey area in a non-selective nature. TLS also produces point clouds non-selectively; therefore, TLS data would be the most appropriate validation data for the SfM-MVS dataset. However, for validation of DSMs, DGNSS has been prevalently used. Three methods are commonly used in the literature to compare SfM-derived data with the conventional terrestrial surveying methods (Carrivick et al., 2016): (1) point to surface (raster) comparison, (2) raster to raster comparison, and (3) point to point comparison. The first validation method is more common because precise validation data can be provided by TS and DGNSS surveys, which in these methods, topography is represented as individual 3D points. The second

method is a surface to surface comparison in which TLS DEM is compared with that of SfM-MVS; however, in this method, a validation data of comparable spatial resolution is required to perform the most appropriate 3D model validation. The third way is a direct comparison of point clouds of TLS and SfM. This approach is appropriate if the model is used for visualization purposes, but point clouds generally include noise, so they are rarely used as the final topographic product. Considering the noise problem, without performing robust filtering, this validation method is not reliable in surveying.

The majority of studies use point to raster validation method, which compare ground-based survey points (measured with DGNS or TS) with the raster derived from SfM-MVS (Agüera-Vega et al., 2016; Gindraux et al., 2017; Harwin & Lucieer, 2012; Hill, 2019; Lucieer et al., 2014; Sanz-Ablanedo et al., 2018; M. W. Smith, Carrivick, & Quincey, 2016; T. N. Tonkin et al., 2014; Woodget et al., 2015). Some studies use raster to raster comparison, which compare two DSMs directly (Caroti, Martínez-Espejo Zaragoza, & Piemonte, 2015; Clapuyt, Vanacker, & Van Oost, 2016; Mancini et al., 2013; Reshetyuk & Mårtensson, 2016; Mark William Smith & Vericat, 2015), while minority of the studies compare point clouds of TLS and SfM directly using CloudCompare or other software packages (Cook, 2017; Harwin & Lucieer, 2012; Mancini et al., 2013; Martínez-Carricondo et al., 2018; Martínez-Espejo Zaragoza et al., 2017; Tomaščík et al., 2017).

Table 2.1 provides a summary of 50 related literature that assessed UAS-SfM accuracy in surveying and mapping. Root Mean Square Error (RMSE) was used as the evaluation metric for accuracy analysis. The results of the quantitative analyses given in Table 2.1 were combined to plot the correlation between RMSEz and the flight height (see Figure 2.2) as well as the relative frequency histogram (see Figure 2.3).

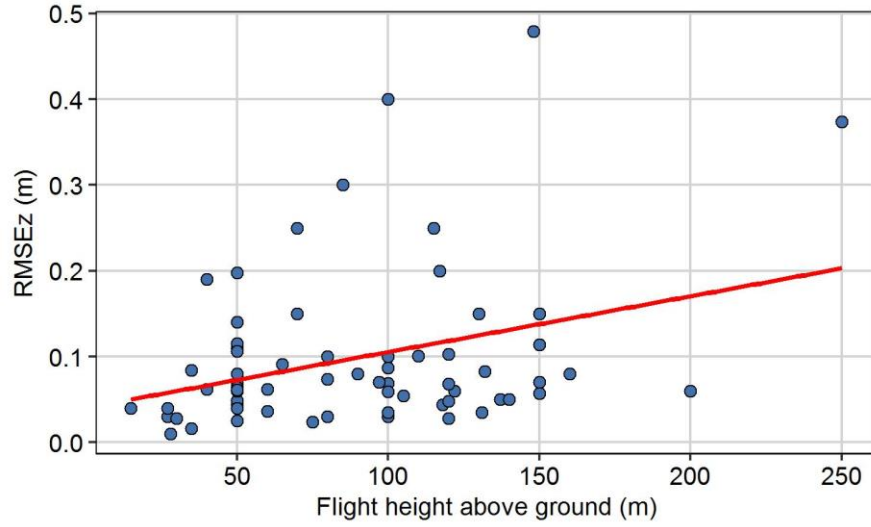


Figure 2.2. Scatter plot of SfM RMSEz versus flight height, plotted from the synthesis of previous studies given in Table 2.1.

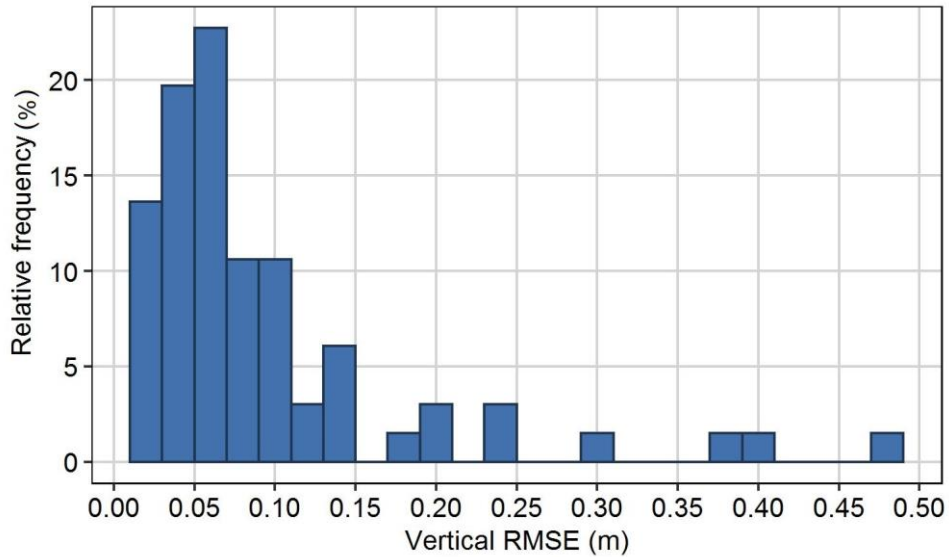


Figure 2.3. Relative frequency histogram of vertical error plotted from the synthesis of previous studies given in Table 2.1.

According to the literature, two flight planning parameters, flight height, and number of GCPs have the most significant impact on the accuracy of products, especially on the accuracy of elevation models. As shown in Figure 2.2, in most cases, there is a positive linear relationship between the flight height and the RMSEz; the error tends to increase with the increase in flight height. This is obvious that in photogrammetric projects, spatial resolution determines the accuracy of the product. In other words, Ground Sampling Distance (GSD) depends on flight height; the lower the flight height, the higher the GSD. However, as the plot illustrates, sometimes higher-flying altitude gives better

accuracy, which there are many other factors such as the number of GCPs, platform, sensor, image overlaps, weather condition, and software and processing algorithm (Reshetyuk & Mårtensson, 2016; Wierzbicki, Kedzierski, & Fryskowska, 2015). Lower flight height and higher overlap (> 70%) usually give higher accuracy, but it is worth to mention that the selection of right GSD for fulfilling the project demand is crucial. Selecting a very high-resolution survey has a great effect on the cost and time of the project.

The literature review also shows that the influence of the GCP number on photogrammetric SfM products is significant. Figure 2.4 shows vertical accuracy analysis of SfM as a function of GCP number extracted from 66 UAS-SfM projects.

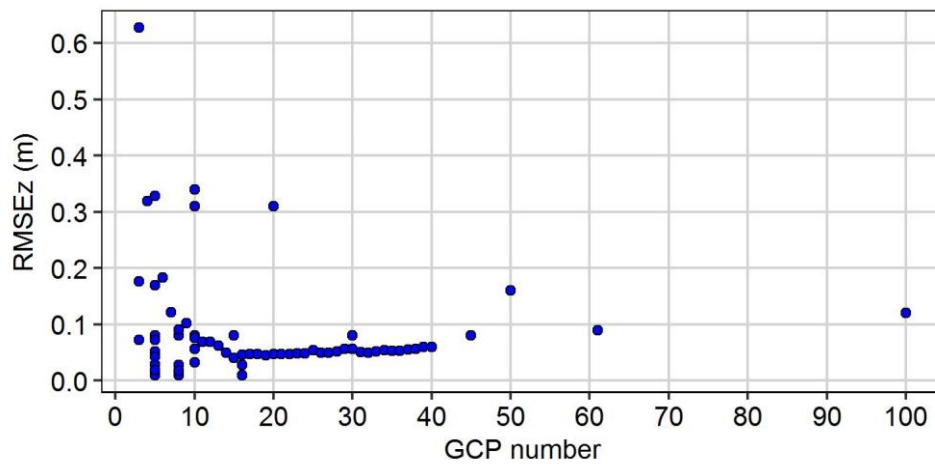


Figure 2.4. Plot of SfM RMSEz against GCP number. Data extracted from: Ruzgienė et al. (2015); Agüera-Vega et al. (2016); Reshetyuk and Mårtensson (2016); Coveney and Roberts (2017); Sanz-Ablanedo et al.(2018); and Oniga, Breaban, and Statescu (2018).

At least 3 GCPs are required for georeferencing. The plot shows that using 5-15 GCPs, high accuracy results can be achieved, and no significant improvement can be seen using more than 15 GCPs. However, this is highly dependent on the area extent and terrain type, where accuracy decreases in undulating topography; in such cases, there is a need to increase the number of GCPs (Agüera-Vega et al., 2016; Reshetyuk & Mårtensson, 2016).

Table 2.1. Summary of the literature contributed to the accuracy assessment of UAS-SfM-based mapping.

Reference	Terrain	UAV platform	RGB camera	Avg flight height (m)	Software used	Validation method	Horizontal RMSE (m)	Vertical RMSE (m)
Harwin and Lucieer (2012)	Natural coastal	Rotary-wing Octocopter	Canon 550D (18 MP)	50	Open source	DGNSS, TS	0.025	0.040
Mancini et al. (2013)	Beach dune	Rotary-wing Hexacopter	Canon EOS 550D (18 MP)	40	Agisoft PhotoScan	DGNSS, TLS	NA	0.190
Pérez et al. (2013)	Flat bare land	Rotary-wing Quadcopter	Pentax Optio A40 (12 MP)	50	Photomodeler	DGNSS	0.072	0.070
Cryderman et al. (2014)	Stockpile	Fixed-wing	Samsung NX1000 (20 MP)	118	Agisoft PhotoScan	DGNSS	0.039	0.044
Hugenholtz et al. (2014)	Gravel stockpile	Rotary-wing Quadcopter	Photo 3S	100	EnsoMOSAIC UAV	DGNSS	NA	0.100
Lucieer et al (2014)	Moss bed	Rotary-wing Octocopter	Canon 550D (18)	50	Agisoft PhotoScan	DGNSS	0.058	0.044
Lucieer et al (2014)	Landslide	Rotary-wing Octocopter	Canon 550D (18 MP)	40	Agisoft PhotoScan	DGNSS	0.070	0.062
Sona et al. (2014)	Rural flat	Fixed-wing	Canon Ixus (12 MP)	132	Various	DGNSS	0.095	0.083
Tonkin et al. (2014)	Moraine	Rotary-wing Hexacopter	Canon EOSM (18 MP)	117	Agisoft PhotoScan	TS	NA	0.200
Wang et al. (2014)	Opencast mine	Rotary-wing Octocopter	Canon 5D (21 MP)	50	Open source	DGNSS, TLS	NA	0.110
Caroti et al. (2015)	Church	Rotary-wing Hexacopter	Nikon D600 (24.3 MP)	27	Agisoft PhotoScan	TLS, TS	0.012	0.030
Gonçalves and Henriques (2015)	Coastal	Fixed-wing	Canon Ixus (12 MP)	131, 137	Agisoft PhotoScan	DGNSS	0.037-0.066	0.035-0.050
Rehak and Skaloud (2015)	Agriculture land	Fixed-wing (RTK mode)	Sony NEX 5R	120, 150	Pix4dmapper	DGNSS	0.030-0.068	0.028-0.07
Ruzgienė et al. (2015)	Flatland	Fixed-wing	Canon S100 (12 MP)	150	Pix4dmapper	DGNSS	NA	0.057

(Continued)

Table 2.1. (Continued)

Reference	Terrain	UAV platform	RGB camera	Avg flight height (m)	Software used	Validation method	Horizontal RMSE (m)	Vertical RMSE (m)
Smith and Vericat (2015)	Badlands	Rotary-wing Hexacopter	Ricoh CX5 (10 MP)	50, 150, 250	Agisoft PhotoScan	TLS, TS	NA	0.080-0.374
Uysal et al. (2015)	Hillslope	Rotary-wing Octocopter	Canon EOS M (18 MP)	60	Agisoft PhotoScan	DGNSS	NA	0.062
Whitehead and Hugenholtz (2015)	River and creek	Fixed-wing	Canon IXUS (16.1 MP)	122	Pix4dmapper	DGNSS	0.05-0.08	0.03-0.06
Wierzbicki et al. (2015)	Flatland with buildings	Fixed-wing	Sony NEX-5R	200	INPHO UasMaster	DGNSS	0.050	0.060
Woodget et al. (2015)	Fluvial landform (exposed and submerged areas)	Rotary-wing Tricopter	Panasonic Lumix (10.1 MP)	27	Agisoft PhotoScan	DGNSS, TS	NA	0.040-0.089*
Agüera-Vega et al. (2016)	5 different terrain morphologies	Rotary-wing Octocopter	Sony Nex 7 (24.3 MP)	50, 80, 100, 120	Agisoft PhotoScan	DGNSS	0.053-0.068	0.049-0.074
Bühler et al. (2016)	Snowpack	Rotary-wing Octocopter	Sony NEX-7 (24 MP)	97-130	Agisoft PhotoScan	DGNSS	NA	0.07-0.15
Clapuyt et al. (2016)	Pasture	Rotary-wing Octocopter	Canon EOS 550D (18 MP)	50	VisualSFM	DGNSS, ALS	NA	0.060
Fernández et al. (2016)	Landslide	Rotary-wing Octocopter	Sony Nex 5N, Canon G12	100	Agisoft PhotoScan	DGNSS	0.040	0.030
Gerke and Przybilla (2016)	Stockpile, and historical buildings	Fixed-wing (RTK & non-RTK)	Panasonic LumixGX1	75, 105	Agisoft PhotoScan	DGNSS	0.018-0.042	0.024-0.054
Hugenholtz et al. (2016)	Gravel quarry	Fixed-wing (RTK & non-RTK)	Canon S110 (12 MP)	Not specified	Postflight Terra 3D	DGNSS	0.032-0.034	0.030-0.089
Jaud et al. (2016)	Riverbed	Rotary-wing Hexacopter	Nikon D700 (12 MP)	100	Agisoft PhotoScan, MicMac	DGNSS, TLS	0.032	0.035
Jeong et al. (2016)	Urban	Rotary-wing Quadcopter	Galaxy NX (20.3 MP)	140	Pix4dmapper	DGNSS	0.022	0.050
Kršák et al. (2016)	Mining quarry	Rotary-wing Quadcopter	DJI FC200 (14 MP)	35	Agisoft PhotoScan	DGNSS, TS	NA	0.084

(Continued)

Table 2.1. (Continued)

Reference	Terrain	UAV platform	RGB camera	Avg flight height (m)	Software used	Validation method	Horizontal RMSE (m)	Vertical RMSE (m)
Long et al. (2016)	Coastal-sandy	Fixed-wing	CANON ELPH110 (16.1 MP)	65, 150	Agisoft PhotoScan	DGNSS	NA	0.091-0.114
Reshetnyuk and Mårtensson (2016)	Gravel quarry	Fixed-wing	Canon S100 (12 MP)	80, 160	Agisoft PhotoScan	DGNSS, TLS	0.030-0.080	0.030-0.080
Tonkin and Midgley (2016)	Moraine	Rotary-wing Hexacopter	Canon EOS-M (18 MP)	100	Agisoft PhotoScan	DGNSS	NA	0.059
Ajay et al. (2017)	Urban	Rotary-wing Quadcopter	DJI Phantom 3 (12 MP)	50	Agisoft PhotoScan	DGNSS	0.047	0.115
Benassi (2017)	Urban flat	Fixed-wing (RTK mode)	Sony Cyber-Shot (18.2 MP)	80	Various	DGNSS	0.020-0.030	0.020-0.10
Cook (2017)	River gorge	Rotary-wing Quadcopter	Canon IXUS (16 MP)	60, 85	Agisoft PhotoScan	DGNSS, TLS	NA	0.30-0.40
Coveney and Roberts (2017)	Urban including a river	Fixed-wing	Canon Ixus 120IS (12 MP)	90	Agisoft PhotoScan	DGNSS	0.076	0.080
Gindraux et al. (2017)	Glacier	Fixed-wing	Canon S110 (12 MP)	115	Agisoft PhotoScan	DGNSS	0.030-0.090	0.10-0.250
Koci et al. (2017)	Gully systems	Rotary-wing Quadcopter	DJI Phantom 3 (12 MP)	86-99	Agisoft PhotoScan	DGNSS	NA	0.4-1.2
Lizarazo et al. (2017)	Sandstone quarry (change detection)	Rotary-wing Hexacopter	Canon S110 (12.1 MP)	70	Open source	TS	NA	0.15-0.25
Tomašík et al. (2017)	Partially open forest (3 sites)	Rotary-wing Quadcopter	Sony Exmor CMOS	50	Agisoft PhotoScan	DGNSS	0.037-0.114	0.064-0.198
Agüera-Vega et al. (2018)	Rockslide	Rotary-wing Octocopter	Nikon 3100 (14.8 MP)	50, 110	Pix4dmapper	DGNSS	0.088-0.134	0.061-0.101
Avanzi et al. (2018)	Snowpack	Rotary-wing Hexacopter	Canon EOS M (18 MP)	60	Agisoft PhotoScan	Multi Station.	NA	0.036
Gabrilik et al. (2018)	Grassy with large height difference	Rotary-wing (RTK mode)	Sony Alpha A7	50	Agisoft PhotoScan	DGNSS	0.033	0.025

(Continued)

Table 2.1. (Continued)

Reference	Terrain	UAV platform	RGB camera	Avg flight height (m)	Software used	Validation method	Horizontal RMSE (m)	Vertical RMSE (m)
He et al. (2018)	Agriculture land, Building	Rotary-wing	GoPro Hero, Sony Alpha7R	15, 20, 40, 50	Developed by authors	DGNSS, ALS	0.040	0.040
Martínez-Carricondo et al. (2018)	Hillslope	Rotary-wing Octocopter	Nikon D-3100 (14.2 MP)	120	Agisoft PhotoScan	DGNSS	0.035	0.048
Oniga et al. (2018)	Urban flat	Rotary-wing Quadcopter	DJI Phantom 3 (12 MP)	28, 35	Pix4dmapper	DGNSS, TLS	NA	0.010-0.016
Rusnák et al. (2018)	River	Rotary-wing Hexacopter	Sony NEX 6	20, 30, 50, 60, 80	Agisoft PhotoScan	DGNSS	0.037	0.028
Salach et al. (2018)	Levees	Rotary-wing Hexacopter	Sony Alpha a6000 (24.3 MP)	50	Agisoft PhotoScan	DGNSS, ALS	NA	0.140
Sanz-Ablanedo et al. (2018)	Opencast coal mine	Fixed-wing	Samsung NX500 (28 MP)	120	Agisoft PhotoScan	DGNSS	0.086	0.103
Zulkipli and Tahar (2018)	Urban (moderate slope)	Rotary-wing Quadcopter	DJI Phantom 3 (12 MP)	148	Agisoft PhotoScan	DGNSS	0.276	0.479
Hill (2019)	Archaeological site	Fixed-wing (PPK mode)	Nikon Coolpix A	100	Agisoft PhotoScan	DGNSS	0.101	0.087

Accuracy metric in Woodget et al. (2015) marked with * is provided in standard deviation

2.3. Previous Studies

AS SfM-MVS yields different results in different terrain, the literature review was conducted thematically based on a wide range of terrain types (see Table 2.1) and influential parameters. The SfM-MVS faces a particular challenge in the survey of vegetated areas because vegetation movement in the wind can potentially cause inconsistency and image mismatching (Carrivick et al., 2016). Since it is required to provide topographic models that return bare earth points, vegetation needs to be filtered out. Tonkin et al. (2014), and Salach et al. (2018) reported that error increased with vegetation density and height. As it is much easier to validate bare earth points by utilizing TS or DGNS, the majority of accuracy assessment studies concentrate on bare surfaces. However, some research includes a topographic survey of vegetated areas as well as shallow rivers using UAS images and SfM-MVS algorithms. The following sections provide a summary of previous studies on UAS-SfM-based mapping, in particular, accuracy assessment papers.

2.3.1. Review articles

Available survey articles are either outdated or do not cover the specific accuracy evaluation methods in the context of surveying and mapping. A chronological summary of the academic review articles related to this study is provided in the following paragraphs.

During significant advances in UAV technology and processing software, Nex and Remondino (2014) surveyed the application of UAV in 3D mapping, focusing on geomatics applications. An overview of UAV applications, platforms, regulations, data acquisition, image processing, and the latest developments based on scientific papers and case studies were provided. Similarly, Colomina and Molina (2014) provided a review of the application of UAS technology in the field of photogrammetry and remote sensing, including regulations, data acquisition, and navigation and orientation systems. In this work, the development of aerial platforms and related technology to carry photogrammetric sensors is described in detail. Liu et al. (2014) presented a comprehensive overview of the application of rotary-wing UAVs in civil engineering, focusing on seismic risk assessment, disaster response, surveying, transportation, construction management, and flood monitoring and assessment. The technological

developments, including control theories, navigation methods, and image processing, were also summarized.

Pajares (2015) provided an extensive overview of the status of UAS applications in remote sensing, including some information on typical platforms and sensor descriptions. An overview of remote sensing platforms and sensors can be found in Toth and Józków (2016).

Bhardwaj et al. (2016) presented an overview of significant glaciological studies using UAV as a remote sensing platform. The review explored the polar and alpine applications of UAVs equipped with different sensors. The author concluded that UAVs have a high potential for use in glaciology and can play a significant supporting role in field-based and remote sensing-based glaciological observations. Nevertheless, it is reported that due to factors such as high elevation, inaccessibility, undulating terrain, and harsh climatic conditions in the Himalayan and Andean glaciers cause difficulties in fieldwork; thus, few studies have been published.

Exploratory research on the UAV regulations on a global scale was conducted by Stöcker et al. (2017), which revealed that in some countries, regulations forced by legal frameworks, significantly limit the use of UAVs (see Section 3.1.5). Verykokou and Ioannidis (2018) carried out a thorough survey on oblique aerial images. The study presents an overview of oblique aerial images focusing on georeferencing procedures.

Zhou and Geisari (2018) conducted a systematic survey to assort literature on the application of UAS in construction. Their findings show that UAS are widely used in construction site surveying, building inspection, quality control, safety inspection, progress monitoring, and maintenance. The study indicates that the primary reasons for using UAS (commonly rotary-wing equipped with a camera or LiDAR sensor) in construction applications are time- and cost-saving. Likewise, the application of UAVs in civil infrastructure has recently been reviewed by Greenwood et al. (2019). The review provides a summary of works related to UAV developments focusing on civil infrastructure. The paper also presents the recent UAV achievements in geotechnical engineering, construction management, and post-disaster reconnaissance.

2.3.2. Influence of flight height, GCP number, image overlap, and terrain morphology on accuracy of UAS-SfM products

In recent years, many studies have been published on identifying the influence of flight height, terrain morphology, and processing parameters on the accuracy of UAS-SfM products. In particular, the impact of flight height and GCP number have been widely investigated. Smith and Vericat (2015) produced 3D models of an area with rough topography by processing images taken from different distances and platforms (oblique ground-based, aerial UAS, and piloted gyrocopter). The SfM-MVS results were compared with TLS and TS validation datasets, and as a result, they concluded that the vertical images acquired from lower flight heights AGL, yielded more accurate results than that of higher heights. Moreover, the piloted gyrocopter at 50m heights AGL provided higher quality models than that of lightweight UAS flying at the same height. They also indicated that the oblique ground-based survey provided high-quality 3D models equivalent to TLS models; however, this method is not reliable over larger areas of complex terrain. Ruzgienė et al. (2015) used a fixed-wing UAS with a mounted digital camera to produce DSM and investigate its accuracy; they reached the conclusion that the correctness and quality of DSM and orthoimages mainly depend on sensor resolution, flight height, overlap, and number and accuracy of GCPs. From 150m flight height, they obtained accuracies of 0.072 m and 0.057 m for 5 and 10 number of GCPs, respectively.

Agüera-Vega and co-workers (2016) conducted a comparative study on 60 photogrammetric projects using an octocopter UAS and a nonmetric camera by applying four flight heights and three different GCP numbers on five terrain morphologies. Their study aim was to explore the influence of flight height, number of GCPs, and terrain morphology on the accuracy of digital surface model and orthoimage. The study results showed a significant impact of flight height and number of GCPs on vertical accuracy, while terrain morphology did not influence the RMSE_z. In the study, higher flight altitude decreased the vertical accuracy. The study also indicated that the horizontal accuracy was neither influenced by flight altitude nor by ground morphology; however, horizontal accuracy was affected by the number of GCPs. The most accurate results obtained from 5 to 10 GCPs. In their study, the optimum combination of flight height and GCP number was reported 50 m height AGL and 10 GCPs, which yielded RMSE_{xy} and RMSE_z values of 0.053 and 0.049 m, respectively.

Similarly, Reshetyuk and Mårtensson (2016) studied the influence of flight height and GCPs on the accuracy of UAS-SfM products. They conducted two surveys with a fixed-wing UAV equipped with a camera at flying heights of 80, and 160 m over a gravel quarry, the reported horizontal and vertical RMSE were 0.02 m for flat areas and 0.08 m for undulated terrain. The study asserts that increasing the number of GCPs from 5 to 16 improved the overall accuracy. This study showed that obtaining higher survey accuracy from a flight height of 80 m and below is possible, which is enough for many engineering works, including design and construction. Mesas-Carrascosa et al. (2016) analyzed the influence of flight parameters such as flight height AGL, longitudinal and side overlap, and the influence of GCPs in the production of orthomosaic of archaeological areas from UAS-based survey. The results indicated that flight height has the highest impact on accuracy, and it is suggested that the optimization of mission planning using balanced parameters leads to better results. Moreover, if the UAS is equipped with a low-cost GPS, the use of GCPs is highly recommended for accurate measurements.

In contrary to other studies, Tonkin and Midgley (2016) obtained high accuracy DSM using only 4 GCPs. They produced DSMs from UAV images (collected at 100m height) using a varying number of GCPs (3-101) to investigate the relation between the number and distribution of GCPs and the quality of produced DSMs. They selected a site with undulating topography and produced 16 projects of varying GCPs using PhotoScan image processing application; by comparing the results with 530 DGPS points, they reported that for all DSMs, the vertical accuracy was reasonable ($RMSE < 0.2$ m). Their results showed that improvements were found in DSM quality where four and more number of GCPs (4-101) were used; however, the difference in vertical RMSE between the DSM produced using 4 GCPs (0.064 m) and the DSM generated by applying 101 GCPs (0.059 m) is 0.005 m. Considering the time and efforts that those additional 97 GCPs require, this 5 mm error is quite negligible in construction surveying. Their study also indicated that evenly distribution of GCPs are crucial because vertical error increases with increasing distance from the GCP cluster.

James et al. (2017) presented a comprehensive description of optimizing UAS-SfM-based topographic surveys. In this work, the underlying photogrammetric methods involved in the process of bundle adjustment in structure from motion algorithms are provided to improve survey quality and consistency. Martínez-Carricondo et al. (2018) assessed the accuracy of UAS-based mapping focusing on the variation of ground control

points. They came to the conclusion that for achieving optimum planimetric results, GCPs must be placed on the edge of the study area; however, the vertical accuracy did not increase by adopting this configuration. The best results were achieved by stratified and dense distribution of GCPs inside the study area, which resulted in horizontal and vertical accuracy of 0.035, and 0.048 m, respectively. Sanz-Ablanedo et al. (2018) comprehensively studied the role of the number and location of GCPs on the geometrical accuracy of the UAS-SfM-derived DSM. They reported that using 4 GCPs per hundred photos, highly improved the accuracy, which made it possible to achieve horizontal accuracy of the same as GSD and vertical accuracy of $\pm 1.5 \times \text{GSD}$. Using fewer sparse GCPs (1 GCP per hundred photos) degraded horizontal and vertical accuracies to $\pm 4 \times \text{GSD}$ and $\pm 5 \times \text{GSD}$, respectively. Oniga et al. (2018) investigated the optimal number of GCPs to be used in a UAS survey to provide high-precision results. They carried out the study using a DJI Phantom 3 Standard UAS at 28 m and 35 m flying heights and adjusted the image blocks with 3 to 40 GCPs. By gradually increasing the number of GCPs and comparing the results with TLS data of the site, they concluded that using 1 GCP per 200 square meters, 3D data with accuracy of 1-2 cm can be produced.

2.3.3. RTK-enabled UAS-based survey

The widely used technique of indirect georeferencing of aerial images using ground control points cannot always be employed. For instance, in natural or nuclear disasters or other inaccessible or risky areas, using RTK-enabled UAS is a highly effective alternative approach. In the direct georeferencing technique, in which the onboard GNSS and IMU are used to locate and orient the data, there is no need for GCPs. However, in this method, maintaining the signal connection, accurate lever arm calibration between the camera perspective center and the GNSS antenna, and time synchronization of all fused sensors (i.e., between the onboard positioning system and the camera shutter) are crucial (Gabrlik et al., 2018). Several studies have been carried out to evaluate the potential of the RTK-enabled UAS survey, where satisfactory results have been obtained; however, in order to achieve higher accuracy, in most studies it is recommended to use 1 to 3 GCP to adjust the georeferenced photogrammetric block.

SenseFly company in a survey-grade eBee RTK accuracy assessment white paper, claims that in an ideal flight condition (bright sunny day, no-wind, and high overlap), eBee RTK fixed-wing UAS from 80 m height AGL can achieve horizontal and vertical

accuracies of 3 and 5 cm, respectively (Roze et al., 2014). Rehak and Skaloud (2015) used a fixed-wing UAS in RTK mode equipped with a calibrated camera for corridor mapping at 120-150m flight height. Their accuracy assessment based on ground control points showed that using UAS photogrammetry in RTK mode, terrain models can be obtained at the accuracy level of $1 \times \text{GSD}$ horizontal and $1.5\text{-}2 \times \text{GSD}$ vertical.

Likewise, Gerke and Przybilla (2016) assessed the use of RTK and non-RTK UAS surveys, including the influence of GCP on both surveys as well as the contribution of cross-flight on bundle adjustment. As a result of the study, the RTK-based UAS survey achieved vertical accuracy of up to 10 cm, while by adding the cross-flight data, the accuracy increased to 5 cm. The use of GCPs in the processing of directly georeferenced images significantly reduced RMS errors.

Hugenholtz et al. (2016) evaluated the spatial accuracy of UAS-derived orthoimages and DSMs in a comparative photogrammetric survey conducted at a gravel pit using a survey-grade RTK UAS and a non-RTK UAS processed with direct and indirect (using GPCs) georeferencing, respectively. As a result, they reported that the horizontal accuracy of the RTK UAS product was comparable to that of non-RTK UAS, but the vertical error of the RTK UAS 3D model was 2 to 3 times greater than the data from the non-RTK which was processed using GCPs. In conclusion, the authors recommended indirect georeferencing for applications where topographic measurements are concerned.

Benassi et al. (2017) carried out an empirical study on the accuracy of RTK-enabled fixed-wing UAS (senseFly eBee) in the repeated survey of four photogrammetric blocks, acquired at 80 m AGL over and urban area to assess the repeatability of GNSS-supported direct georeferencing. In the study, image processing was performed using three different photogrammetric SfM software packages (PhotoScan, Pix4D, and MicMac), and by comparing checkpoints with the GNSS data, they reported horizontal RMSE of 2-3 cm and vertical RMSE of 2-10 cm. Besides, using only 1 GCP, they georeferenced the data that were collected in RTK mode, which resulted in almost the same as the accuracy of conventional GCP orientation.

In the same way, Gabrlik et al. (2018) evaluated UAS-based modeling with both direct and indirect georeferencing techniques. They achieved horizontal and vertical accuracy with RMSE 0.033 and 0.025 m, respectively; while using six well-distributed GCPs, the RMSE_{XY} and RMSE_Z were reported 0.012 and 0.020 m. In light of these

studies, UAVs equipped with RTK GNSS are capable of achieving georeferenced images at centimeter-level accuracy. Hill (2019) performed multiple strategies for UAS data collection in an archaeological site. They used a PPK enabled fixed-wing UAS to produce orthoimages. Using the UAS in Post-Processing Kinematic (PPK) GNSS mode, they obtained orthoimages at decimeter accuracy without applying any GCP.

2.3.4. Oblique photogrammetry and combination of photogrammetric blocks

Oblique photogrammetry is usually used in 3D modeling, especially in urban mapping; however, the measurement accuracy of classical oblique photogrammetry from aerial images is limited and therefore, oblique imagery is often used for visualization purposes (Ostrowski, 2016). Structure from motion allows reconstruction with higher accuracy from oblique images. Ostrowski (2016) examined the accuracy of measurements in oblique aerial images using SfM software and concluded that using the SfM technique, higher accuracy measurements are possible from oblique aerial images. Jiang et al. (2017) used UAV-based oblique photogrammetry using two cameras onboard for inspection of a transmission line and achieved an overall model accuracy of 0.2 m.

Although UAS-SfM is very effective in mapping applications, in complex terrain with steep slopes, common image acquisition plan and processing techniques can result in surface deformation (Nesbit and Hugenholtz 2019; Koci et al. 2017; Cook 2017). Some studies claim improvements in the overall quality of processing results by merging data of different flight height or combining grid and oblique images. In this regard, Gerke and Przybilla (2016) reported that by adding the cross-flight data, the accuracy increased by 2 times. Duarte et al. (2017) studied the use of UAS-SfM by merging nadir and oblique images to assess building façade damages caused by the earthquake. The results indicated that combining nadir and off-nadir imagery is useful in detecting façade damages. Agüera-Vega et al. (2018) examined the reconstruction of the topographic map of a near-vertical road cut-slope derived from images taken by a multicopter UAS with the camera oriented horizontally and oblique (tilted angle 45°). The study carried out three photogrammetric projects using nadir images, oblique images, and the combination of nadir and tilted images, where the highest degree accuracies achieved from combined images. The reported horizontal and vertical accuracies from the combined project are 0.087 and 0.061 m, respectively, while these RMSEs were 0.117 and 0.079 m for nadir photography, and 0.134 and 0.101 m for the oblique projects.

Similarly, Rusnák et al. (2018) presented river landscape mapping by the combination of nadir and oblique photogrammetry. Merging photogrammetric blocks allowed mapping the bare ground under tree canopies as well as reduced the geometric error and improved the overall accuracy of the SfM project. Nesbit and Hugenholtz (2019) examined the effect of incorporating oblique images with different imaging angles (0-35°) into the grid UAS-SfM workflow of mapping badlands. Results show that the imaging angle has a significant impact on the accuracy of topographically complex areas. They came to the conclusion that combining oblique images acquired with angle (20-35°) and higher overlap with the horizontal photogrammetric block increases the accuracy by about 50% compared to processing with only nadir block of images.

2.3.5. Comparison of UAS-SfM and TLS 3D models

The comparison of UAS-SfM products with TLS as well as the use of TLS data as a validation data has been presented in many research articles, provided under the thematic sections in this literature review. Some comparison examples are given below. Mancini et al. (2013) produced a high-resolution topographic model of a beach dune system using a hexacopter UAV and SfM technique and achieved vertical RMSE of 0.19 m, which was validated by DGNSS. In addition to surface model comparison, Mancini et al. also conducted a point to point comparative analysis between the UAS-SfM-derived point clouds and TLS point clouds. They reached the conclusion that the vertical accuracy of the SfM product was comparable to the TLS products, which can be used as a reliable source of information for producing accurate topographic information, particularly for assessment of coastal flooding, erosion, and sediment budget. Considering the study site and the results, they suggested that the application of UAS-SfM is useful in terrain analysis, natural hazards, and disaster response.

Caroti et al. (2015) conducted an accuracy assessment of UAS based 3D modeling; they surveyed a church using TLS and UAS approaches and analyzed the data to reveal the attainable accuracy from UAS photogrammetry. The study obtained a 3D textured model with a horizontal RMSE of 0.012 m and vertical RMSE of 0.03 m, which shows the potential of the UAS-SfM approach in 3D modeling. Teza et al. (2016) evaluated the capability of SfM photogrammetry in morphological analysis for architectural applications, they selected two masonry towers and surveyed with both TLS and SfM

methods and compared the obtained point clouds. As a result, they indicated that SfM and TLS have comparable performance in morphological analysis.

Martínez-Espejo Zaragoza et al. (2017) obtained models of a complex building by integrating UAS photogrammetry and TLS point clouds. In their work, they modeled an ancient luxury hotel for restoration purposes. They concluded that the integration of SfM and TLS data is quite useful, especially in emergency cases.

2.3.6. Performance of structure from motion software

Structure from motion algorithms have facilitated the use of photogrammetric techniques to produce digital elevation models and orthoimages. There have been several studies testing the performance of different commercial and open-source photogrammetric software in 3D reconstruction. Below are some studies examining the capability of photogrammetric software in representing topographic surfaces.

Sona et al. (2014) carried out experimental tests using a fixed-wing UAS and a digital camera to assess the metric accuracy of UAS photogrammetry-derived products. They collected images from 132m height with 80% forward and side overlaps and compared the capabilities of different photogrammetric software packages (Erdas-LPS, EyeDEA, Pix4UAV, Agisoft Photoscan, and PhotoModeler) in the extraction of DEM and orthoimage generation. The results confirmed that UAV image processing using computer vision software (i.e., SfM-based software) is faster and yields results comparable to those of standard photogrammetric methods. In terms of quality of products, Agisoft PhotoScan outperformed other software.

Gómez-Gutiérrez et al. (2015) compared the use of Low Dynamic Range (LDR) and High Dynamic Range (HDR) images in the production of point clouds using SfM-MVS techniques. The accuracy of produced models was assessed using TLS. The results of the study showed that using HDR compositions, no significant improvements were observed. They also conducted a comparison of Agisoft PhotoScan and 123 Catch software packages in the production of 3D models; They demonstrated that Agisoft PhotoScan overcame the 123D Catch, producing high quality, denser, and more accurate point clouds in all cases.

Jaud et al. (2016) assessed the accuracy of high-resolution DSMs and orthophotos computed by PhotoScan and MicMac photogrammetric software packages in four different scenarios to analyze their sensitivity to different parameters. Both image

processing applications yielded relatively similar results with the accuracy of 3-4 cm; for example, in scenario 1, MicMac software resulted in RMSE of 0.039 m and 0.032 m in horizontal and vertical, respectively, while the results from PhotoScan were 0.045 m and 0.035 m.

Murtiyoso and Grussenmeyer (2017) compared four software packages in the 3D reconstruction of a building model. Three software packages (PhotoScan, Pix4D, and MicMac) were based on SfM, and one was based on standard photogrammetry. As a result, SfM-based applications provided the best results.

Alidoost and Arefi (2017) compared the capabilities of four SfM-based software, namely PhotoScan, Pix4Dmapper, 3Dsurvey, and SURE in the point cloud and DSM generation from UAV images. According to the visual and geometric assessments carried out in their study, it was reported that PhotoScan, Pix4Dmapper, and SURE produced 3D point clouds and DSM with similar accuracy and density, but 3Dsurvey generated products with less quality and accuracy.

Since reconstruction from a block of images by applying SfM is substantially more comfortable than that of traditional photogrammetry methods, Mölge and Bolch (2017) attempted to compare SfM-based and conventional photogrammetry software with respect to bundle adjustment and production of DTM from archival aerial images of a glacier. The results attested that SfM-based software packages (such as PhotoScan and Pix4Dmapper) are capable of producing DTM of comparable quality to conventional photogrammetry methods (ERDAS photogrammetry) and reduce processing efforts by about 3-6 times. However, they reported less reliability of SfM performance in the processing of glacier images with less overlap.

Most of the commercial software (e.g., PhotoScan, Pix4D, etc.) has automated the SfM process for 3D modeling from UAS images, but due to the black-box nature of commercial software packages, the reason for the failure of processing is always unknown. In the proposed framework of He et al. (2018) this issue is presented transparently, which can be defined by the user. He et al. proposed an automated aerial triangulation framework that allows accurate 3D reconstruction from UAS images by user-defined constraints for accuracy assessment. They conducted four photogrammetric projects, three on agriculture farms and one on a building site using two different UAS and cameras (DJI Phantom 2 equipped with GoPro Hero 3+ camera, and DJI S1000 with Sony Alpha 7R), and flying from different heights. Their automated framework yielded

planimetric and vertical accuracy of below 0.04 m, and in a comparative evaluation, demonstrated super performance over Pix4Dmapper.

2.3.7. Earth work and volumetric measurements

UAS photogrammetry is becoming an alternative for volumetric mapping due to its low-cost and rapid surveying. Hugenholtz et al. (2014) used UAS photogrammetry in volume calculation of a gravel stockpile with a 3.5 cm resolution. Data validation using RTK-GPS showed that UAS method yielded a DTM with a vertical accuracy of 0.10 m, where the volume difference between the UAS model and DGPS model was about 3.2%. It was indicated that UAS-SfM is capable of producing models with accuracies higher than airborne LiDAR, but lower than the TLS. Cryderman et al. (2014) evaluated the accuracy of UAS photogrammetry employed in a volumetric survey of a stockpile. By comparing the results with GNSS survey data, it was reported that UAS photogrammetric models could be considered equivalent to that of GNSS RTK surveys at a 95% confidence level; according to the ASPRS (2014) standards, the obtained accuracies ($RMSE_{XY} = 0.039$ m, and $RMSE_z = 0.044$ m) of UAS-SfM survey were sufficient for mapping at a scale of 1:200.

UAS-SfM is widely used in mining surveying. Wang et al. (2014) investigated the capability of UAS-SfM for 3D reconstruction of opencast mine. They compared the terrain models derived from low-altitude UAV images with the models provided from TLS data; their study results show a vertical RMSE of 0.11 m with a maximum 3D distance discrepancy of ± 0.4 m. Similarly, Kršák et al. (2016) analyzed the accuracy of low-cost photogrammetry in a mining quarry by comparing the UAS-SfM results with the TS data. As a result of comparison with the validation data, a vertical RMS error of 0.084 m was achieved, which was reported that the obtained accuracy meets the permissible error (0.12 m) defined by national legislation for creating surface mining maps.

2.3.8. Agriculture and forestry

UAS are used for agricultural and forestry monitoring, precision farming, yield estimation, vegetation monitoring, volume computation, woodlots assessment, fire surveillance, and identification of species (Nex & Remondino, 2014). In agricultural watersheds, furrows, ridges, presence of crops and their residues impact the direction of

water flow. In order to quantify runoff and sediment transport in agricultural catchments, precise agricultural soil microtopography is required. In such watersheds, there are usually slight elevation changes; discerning extremely detailed elevation variability requires a very high-resolution digital survey. Ouédraogo et al. (2014) evaluated the accuracy of UAS-SfM and TLS in the topographic survey of a plowed agricultural watershed. They used RTK-GPS for accuracy evaluation and data validation. UAS images were processed using PhotoScan and MicMac software packages. The results revealed that the TLS method produced the most accurate DEM with a vertical RMSE of 0.045 m compared to that of UAS-SfM, which yielded accuracies of 0.09 and 0.14 m using MicMac and PhotoScan, respectively. Eltner et al. (2015) quantified surface changes of rill and inter-rill erosion processes of a fertile field during a ten-month investigation period using DSM produced by SfM from UAS images. They obtained DSMs with an accuracy of less than 1 cm, which was verified by DSMs produced using a TLS; they also developed a method for automatic extraction of rill for volumetric quantification and analysis.

Precision agriculture or precision farming is an agricultural industry management concept based on observing (through new technologies such as remote sensing and geographical information systems) and responding to field variations (Rokhmana, 2015). A thorough study of the use of UAV in precision agriculture using RGB camera to model and test growth status can be found in Kim et al. (2018).

Dandois et al. (2015) studied to find the optimal flight height, overlap, and weather conditions for UAS-SfM remote sensing in the estimation of forest structure; as a result, the accurate estimates were obtained from images with high overlap ($> 80\%$) and clear lighting. Birdal et al. (2017) estimated coniferous tree heights in an urban forest using UAS photogrammetry method with image overlaps of 80 and 70%, and six GCPs; they extracted canopy height model using SfM-generated DSM and DTM data and reported height measurements with 28 cm RMSE validated based on field measurements with 94% correlation. Tomaščík et al. (2017) assessed the horizontal and vertical accuracy of UAS-based photogrammetric point clouds in three partially-open forest sites under different terrain complexity conditions (slope, canopy openness). They used a low-cost quadcopter and a digital camera and collected images of the study areas from an average flight height of 50 m and processed the acquired images using various GCP configuration (4-9 GCPs). As a result, Tomaščík et al. achieved horizontal and vertical point cloud accuracy of lower

than 0.2 m, which can be considered reliable data in various forest survey tasks such as forest inventory, canopy measurement, etc. Furthermore, the study reported a minor effect of GCP quantity on accuracy.

2.3.9. Coastal and riverine

Coastal zones are prone to degradation due to the dynamic rising of the sea and other natural and human-induced factors. Regular monitoring of topographical changes in coastal areas needs highly detailed and rapid mapping methods. Harwin and Lucieer (2012) assessed the accuracy of the point cloud produced from UAV imagery for natural coastal mapping using the SfM technique. They collected images with a high degree of overlap, and using a sufficient number of GCPs, the obtained RMSE ranged from 0.025–0.040 m. Gonçalves and Henriques (2015) analyzed the application of fixed-wing UAS equipped with a non-metric camera and SfM in the topographic monitoring of two sensitive coastal areas. They conducted a flight at 130m height, and the image processing using the SfM technique yielded a vertical accuracy of 0.035 to 0.05 m. An accuracy assessment of sandy coastal topography derived from UAV photogrammetry was carried out by Long et al. (2016). They used a fixed-wing UAV equipped with a digital camera and performed two flights at 65 m and 150 m heights, and processed the images using various GCP numbers. As a result, they obtained DSM with the highest accuracy of 0.09–0.11 m; they indicated that a correlation exists between vertical accuracy and the number of GCPs, the higher the number of GCPs, the higher the accuracy.

Woodget et al. (2015) conducted topographic surveys of exposed and submerged fluvial landform by means of UAS images and SfM-photogrammetry. They achieved DEMs with a spatial resolution of 0.02 m and an accuracy of 0.016 m to 0.089 m in submerged areas, in which the errors were reduced to 0.008 m to 0.053 m by applying refraction correction. Bathymetric LiDAR survey provides coarse spatial resolution (typically 1 m) and an accuracy of between 0.10–0.30 m for water depths (< 1 m) (Kinzel et al., 2007), on the other hand digital photogrammetry is capable of providing bathymetric topography of clear shallow-water (typical depth < 0.6 m) at typical spatial resolution and accuracy of about 0.1 m. Thus, Woodget et al. demonstrated the potential of UAS-SfM techniques in river topographic survey, where the average and maximum water depths were 0.15 m and 0.50 m, respectively.

Coveney and Roberts (2017) used a lightweight fixed-wing UAS with a camera on-board to produce the digital elevation model of an urban area including a river and to evaluate the potential of UAS-based DEM in the local environmental modeling and flood prediction. By cross-comparing the UAS-SfM orthoimage and DEM products with the DGNSS data, they achieved horizontal and vertical RMSE of 0.076 and 0.080 m, respectively. They examined the contribution of 0 to 61 GCPs in different projects of the same area with the same parameters, and they concluded that using 1 GCP per every 2 ha provided the best results for flood prediction which equals to 15 GCPs; they reported that no discernible improvements were observed by using more than 15 GCPs.

2.3.10. Snow and glacier

Monitoring of spatiotemporal distribution of snow depth is crucial for many environmental and ecological applications; particularly in the glaciological context, quantifying ice and snow volume change is very important. Bühler et al. (2016) studied snow depth mapping using UAS photogrammetry. They measured the snow depth in alpine terrain and reported RMSE of 0.07 to 0.15 m. Gindraux et al. (2017) assessed the accuracy of UAS-SfM-derived digital surface models of glaciers, focusing on the influence of the number and distribution of GCPs. They generated over 1300 DSMs using different GCP combination in an experiment conducted on three glaciers in the Swiss Alps during three different seasons. They evaluated the accuracy of the produced DSMs with thousands of GNSS validation points. Their results showed that DSM accuracy increased asymptotically with increasing GCP numbers. Using the optimum number of GCPs, they achieved horizontal and vertical accuracy of RMSE 0.03 and 0.10 m, respectively. In addition, Gindraux et al. reported that it is almost impossible to generate DSMs or orthophotos of fresh snow due to the lack of structure (a few matching points). However, they indicated that after full-day exposure to sunlight, snow develops sufficient structure and contrast to allow 3D reconstruction. The results also revealed that orientation and 3D reconstruction in ice is higher than fresh snow.

The work of Avanzi et al. (2018) shows the potential of UAS in snowpack mapping. Avanzi et al. modeled an area near a glacier in summer and winter using UAS photogrammetry with 90% forward and 70% side image overlaps. Comparing the results with a MultiStation validation data, they achieved centimetric accuracy results with vertical RMSE of 0.036 m on snow and 0.02 m in bare land.

2.3.11. Landslide

Lucieer et al. (2014) monitored the dynamic of an active landslide and mapped the displacements using a UAV equipped with a standard digital camera. They processed the data using SfM-MVS and generated DEMs and orthoimages of 1 cm resolution resulting in horizontal RMSE of 0.07 m and vertical RMSE of 0.06 m. By utilizing the UAV and SfM technique, Fernández et al. (2016) obtained DSM models and orthoimages of an olive grove over several years and analyzed landslide evolution and terrain displacements. The study concluded that landslide monitoring can be carried out using UAV photogrammetry with 0.1-0.15 m accuracy. Similarly, Mateos et al. (2017) used a combination of satellite-based and UAS-based remote sensing techniques to detect and monitor the temporal range of displacements of an urban area affected by landslides.

2.3.12. UAS-SfM accuracy in challenging terrain

SfM-MVS is a useful tool to aid in 3D mapping. However, uncertainty remains about optimal survey and processing designs to achieve optimal model accuracy and reduce processing times. Tonkin et al. (2014) conducted a topographic survey of a moraine using a rotary-wing UAS and compared the generated DSM with the 3D model produced based on TS survey points. They pointed out that the terrain model obtained from UAS was concordant with the ground survey model in less vegetated areas (RMSE = 0.2 m). Areas with more vegetation caused poor surface presentation (RMSE = 0.59 m).

Koci et al. (2017) carried out a thorough test of the accuracy of topographic models of hillslope gully systems (in a dry-tropical savanna) derived from UAS-based and ground-based SfM-MVS. In the study, SfM-MVS topographic models (DSM and dense point clouds) were compared with RTK-GPS point data and airborne LiDAR DEM. Results showed that ground-based SfM is more effective in quantifying gully morphology than the UAS-SfM, where ground-based SfM produced models with 0.04-0.1 m elevation error, while UAS-SfM yielded topographic models with 0.4-1.2 m vertical error. The study also indicates that although the SfM method showed difficulties in the reconstruction of vegetated surfaces, it has great potential to be used in integration with conventional methods for hillslope gully systems modeling and management.

Topographic change detection and study of geomorphic process is crucial in earth surface observations. Cook (2017) evaluated the efficiency of UAS and SfM in

geomorphic change detection. Cook carried out UAS-SfM-based topographic measurements on a challenging river gorge site and compared the results to a TLS data. Vertical RMS error of 0.30-0.40 m was reported, and cloud to cloud comparison showed that UAS-SfM point clouds well-matched the lidar point clouds; however, small scale textured surfaces such as water, and vegetated surfaces caused higher inaccuracies. Lizarazo et al. (2017) proposed an automatic workflow for detecting temporal elevation changes of land surfaces. For analyzing the performance of the method, they used multi-temporal UAS-based images and produced high-resolution DEMs of the study area with accuracies ranging from 0.15 to 0.25 m; the workflow demonstrated the effectiveness of UAS and the developed method in rapid monitoring of topographic changes. Tomaščík et al. (2017) obtained horizontal and vertical point cloud accuracy of lower than 0.2 m in the survey of partially-open forests.

Zulkipli and Tahar (2018) used a rotary-wing UAS and a 4K camera in engineering survey of a road, 6 GPCs were used, and the survey was carried out at the height of 148 m; in their accuracy assessment, they reported horizontal and vertical RMSE of 0.276 and 0.479 m, respectively. Work of Abu Sari et al. (2018) shows low accuracies of 3D mapping using UAV photogrammetry ($RMSE_x = 0.279$ m, $RMSE_y = 0.215$ m, and $RMSE_z = 1.341$ m); in their study, they used a low-cost quadcopter UAV, and a digital camera, the study area was surveyed from a 100 m height, and the images were processed by incorporating 10 GCPs. However, the authors concluded that vertical accuracy could be improved by incorporating oblique images.

2.3.13. Miscellaneous studies

Pérez et al. (2013) evaluated the accuracy of UAV photogrammetry in the surveying of a flat area from 50 m AGL using a non-metric camera mounted on a low-cost rotary-wing UAV. They produced a DEM and an orthoimage with horizontal and vertical RMS error of 7 cm and concluded that using a low-cost UAS, it is possible to provide high-resolution terrain data for engineering and geomorphologic uses.

Ruiz et al. (2013) evaluated the impact of using different positioning systems on the accuracy of the produced DEMs derived from UAV images. The experiment was carried out using a small quadrotor in a controlled testbed where millimeter-precision position information is available. The results revealed that the final accuracy of DEM is directly dependent on the positioning information.

Tahar and Ahmad (2013) compared two different UAV platforms: a fixed-wing and a rotary-wing in the photogrammetric mapping of a sloped area; they reported that the 3D model generated from the images of multi-rotor UAV, provided better results compared to that of fixed-wing UAV. However, in their study, the flight height of the fixed-wing UAV was much higher (320 m) than the multi-rotor drone (80 m), it is clear that with increasing flight height, the quality of product decreases.

Whitehead and Hugenholtz (2015) presented an assessment of UAS-SfM-derived orthoimage and DEM data in the context of digital geospatial data accuracy standards released by the American Society for Photogrammetry and Remote Sensing (ASPRS) in 2014. They reported that accuracy results in two case studies (RMSE = 0.05-0.08 m horizontal and RMSE = 0.03-0.06 m vertical) meet the requirement for Class 1 mapping accuracy.

Wierzbicki et al. (2015) examined the UAV image quality influence on the orthophoto production in various weather and lighting conditions as the primary factor influencing the image quality. The performed accuracy assessment showed that poor weather conditions (overcast, precipitation) decrease the radiometric quality of the images, thereby reducing the final product quality by an average of 25 percent.

El Meouche et al. (2016) investigated the use of UAV photogrammetry and its accuracy in land surveying. For this, they surveyed a site using a fixed-wing and a rotary-wing UAV equipped with a non-metric camera as well as using a TS to extract a vectorized plan. After conducting an accuracy evaluation and comparison between the plans produced by two techniques, they reported a maximum error of 4 cm for the UAV-based model; however, the UAV plan could not cover the whole area of interest because of vegetation.

Clapuyt et al. (2016) assessed temporal reproducibility of landform topography produced based on the UAS-SfM survey method. The study compared various SfM-derived topography datasets by changing the location of GCPs and camera focal length to assess the repeatability of the SfM method; the comparison results showed excellent performance with precision in centimeters order for reproductions with identical parameters. Ajay et al. (2017) investigated the robustness of 3D models generated from UAV images acquired from 50 m height AGL with low overlap (15-20%). They compared the results with DGPS and reported the horizontal and vertical accuracies as 0.047 m and 0.115 m, respectively.

In order to generate a digital terrain model using UAV photogrammetry, point cloud filtering and classification must be performed. Serifoglu Yilmaz et al. (2018) carried out a comparison of the performance of different software in retrieving ground point clouds generated from UAV images. They investigated the performance of ground filtering algorithms of seven software packages in two experimental sites; compared software packages include: adaptive triangulated irregular network algorithm in PhotoScan, the multi-scale curvature classification algorithm in Global Mapper, the cloth simulation filtering (CSF) algorithm applied in MATLAB script, and three other algorithms implemented into LiDAR data processing software packages. The best ground filtering results were obtained from the CSF algorithm, with an average overall accuracy of 95% for both sites.

Tziavou et al. (2018) presented the crucial parameters that affect the resolution of UAV images in a structural geological mapping case study. They provided recommendations on technical aspects that should be taken into consideration prior to flying a UAS to obtain optimum results for such applications.

2.4. Summary

To sum up, in view of the majority of the above literature, flight height and GCP number have been identified as being the most influential factors in the accuracy of UAS-SfM-based mapping. More precisely, accuracy mainly depends on sensor resolution, flight height, image overlaps, and the number, distribution, and accuracy of GCPs. In addition, processing software also plays a key role. In UAS-SfM-based surveying, vertical uncertainty is the primary concern in most of the studies. The results from the majority of studies show vertical RMSE between 0.04-0.06 m (see Figure 2.3), which meets the requirement for Class 3 mapping standard of ASPRS 2014, which is equivalent to 0.15 m contour interval as per ASPRS 1990. However, the average RMSE_z of studies is 0.10 m, which agrees with Class 4 of ASPRS 2014, and equivalent contour interval in accordance with ASPRS 1990 is 0.30 m. The achieved accuracies in the literature is applicable to many engineering and GIS works. Although UAVs equipped with RTK GNSS are capable of achieving georeferenced images at centimeter-level accuracy, maintaining the signal connection, calibration between the camera perspective center and the GNSS antenna, and time synchronization of GPS receiver and camera are decisive.

Nevertheless, the literature review shows that a well-defined image acquisition plan and using the right processing software can achieve higher horizontal and vertical accuracy.

However, a closer look at the literature on accuracy assessment of UAS-based mapping reveals several gaps and shortcomings. Although many studies have focused on the influence of GCP number and distribution in the accuracy of UAS-SfM models, only a few studies have analyzed the relationship between errors and their distance from the nearest GCP. Most authors have only mentioned that the error increases with distance from GCPs. This problem has not been sufficiently explored and requires a thorough statistical analysis. Given the sensitivity of the information obtained from UAS-based mapping and the variation in accuracy reported in the literature, further studies are needed to evaluate the accuracy of UAS-SfM in surveying applications, including profiles, cross-sections, and volumetric analysis.

On the other hand, a great number of studies have used rotary-wing UAVs at lower flight height (i.e., 50 m AGL). However, topographic surveying of a larger area at 50 m flight height with high overlap can create many problems in data acquisition and processing. Several flights are required to cover the project area; in specific weather conditions, this will cause illumination differences in image blocks. A 50 m change in flight height may have an impact of 1 cm in GSD, but the difference in the number of images (considering the same overlaps) can be threefold. The selection of high resolution has a significant impact on the cost and time of the project. After all, flying higher makes it possible to cover a large area in a single image, and higher overlaps can be achieved. In this study, the accuracy and data quality of two flight heights (100 and 170 m) using a fixed-wing UAS for topographic mapping purpose, and a close-range flight (16 m) using a rotary-wing UAS for 3D modeling and volumetric survey were examined.

Moreover, the quality of point clouds and DSMs generated using different software packages has rarely been analyzed in the literature; this is important because current software packages show considerable variations in point cloud density and surface quality. The automatic classification of the photogrammetric point cloud is also crucial for generating DTM; few studies have been focused on generating DTM using automatic and semi-automatic algorithms of SfM-based applications. This issue is also addressed in this thesis.

3. THEORETICAL BACKGROUND

This chapter presents a fundamental overview of unmanned aerial systems platforms, UAS photogrammetry, structure from motion, software, and terrain modeling and data acquisition techniques. To frame this section, basic theoretical information regarding UAS, platforms, classifications, sensors, applications, and regulations are provided; UAS photogrammetry and structure from motion is briefly described, commonly used software packages are explained, and terrain modeling methods and applications are discussed. It should be noted that the software, UAS platforms, and regulations reported here are likely to change following this research; however, the presented theoretical principles will remain.

3.1. Unmanned Aerial Systems

The idea of unmanned aerial vehicles dates back to the early 1900s before piloted flights. The innovation attempts with initially focusing on military use were for the reason of reducing human casualties and injuries in experimental studies. By the start of WWI, military forces exerted intense pressure on scientists, designers, and inventors to innovate in all aspects of aircraft design. The development continued during World War I. Efforts of inventors led to the emergence of modern aviation by the end of WWI. The development of aviation science both in piloted and unpiloted aircraft intensified with the start of World War II. During WWII, unmanned aircraft appeared more, and used in the training of anti-aircraft gunners and fly attack missions. During the Vietnam war, the US army extensively used UAVs in reconnaissance missions (Fahlstrom & Gleason, 2012).

The first experiments related to civil and geomatics applications were conducted in the late 1970s (Nex & Remondino, 2014). In the 1980s, efforts on the design of small UAVs focused on aerial vehicles with typical dimensions of 2 to 3 m to carry large-sized sensors and devices (Fahlstrom & Gleason, 2012). With the development and miniaturization of new technologies, more advanced UAV production began in the '90s. In recent years, with the advancement of technology in the miniaturization of electronic devices, there has been increasing interest in reducing the size of small UAVs to micro UAVs. Today, insect-sized micro UAVs are available that can fly indoors and outdoors.

3.1.1. Definition and terminology

An unmanned aerial vehicle is defined as an aircraft designed to operate without a pilot-in-command onboard; its flight can be operated and controlled from a distant location by a human operator using a remote controller, autonomously by onboard computers, or by a combination of both (Eisenbeiß, 2009; ICAO, 2011).

The term UAV (Unmanned Aerial Vehicle) differs from the term UAS (Unmanned Aircraft/Aerial system[s]). The UAV is a UAS component that only refers to the aircraft itself, not the communications units and the ground control. UAS include a UAV, a ground-based controller, and a communication system between the UAV and the controller (ICAO, 2011).

With the rapid-growing market of this thriving aeronautical sector, several terms with a slight difference are currently used by manufacturers, operators, and other associations to designate UAS, which generally refers to the same concept. The common terms are drone, UAV, UAS, and RPA/RPAS. The following paragraph explains an overview of the current designations that were adopted by the principal professionals of the UAV domain.

UAV is the most common term in the literature. This term is adopted to define the flying object used for professional and nonprofessional civilian applications. Although the term “Unmanned” is commonly used in the literature, some researchers use the phrase “Unpiloted Aerial Vehicle” (Hill, 2019), which is more appropriate because the term “Unmanned” is not inclusive, and there is no need to be gendered.

In the regulations created and implemented by the French Directorate for Civil Aviation (DGAC), the term “drone” is used to refer to commercial UAVs. According to Meriam-Webster's Dictionary, drone refers to an "unmanned aircraft or ship guided by remote control or onboard computers". In general, the drone term is mostly used by media as a designation to any unmanned aerial vehicle; this term is not universally considered appropriate and not used by UAV developers and user community (Fahlstrom & Gleason, 2012).

The acronym RPAS (Remotely Piloted Aircraft System) or RPV (Remotely Piloted Vehicle) is employed by the International Civil Aviation Organization (ICAO). This term seems to be the internationally preferred terminology which is used by international aviation agencies such as the ICAO, the European Aviation Safety Agency (EASA), Civil Aviation Safety Authority of Australia (CASA), the Civil Aviation Authority of

Newzealand, and the Belgian Unmanned Aircraft Systems Association (BeUAS). The term UAV can be considered as the generic title, but RPV and UAV are not always interchangeable because RPV is remotely piloted and controlled from a distant location, while a UAV can be remotely piloted or can be programmed to perform autonomous missions (Fahlstrom & Gleason, 2012).

The term UAS is an all-encompassing term that describes the entire operating equipment, including the UAV, the ground-based controller, and the communication system between the aircraft and the controller (ICAO, 2011; Nex & Remondino, 2014; Pajares, 2015). The term UAS was adopted by the US Federal Aviation Administration (FAA), the United States Department of Defense (DoD), the Civil Aviation Authority (CAA-United Kingdom), the European Aviation Safety Agency (EASA), and the Unmanned Aerial Vehicle Systems Association (UAVSA). Considering the literature adopted the term UAS (Gabrlik et al., 2018; Gillan et al., 2017; Whitehead & Hugenholtz, 2015; Woodget et al., 2015), it is the appropriate terminology to refer to the whole UAV system.

In summary, four designations are presently employed: in the US and UK, the term UAS is commonly used; in French-speaking countries the word “drone” is common; international aviation agencies use RPAS; while on the internet and in the media, the terms UAV and drone are more common.

3.1.2. Platforms and components

The physical components of manned and unmanned aircraft of the same type are usually similar; the main differences are the absence of a cockpit, window, and the environmental control system (ICAO, 2011). Small UAVs used for civilian and commercial purposes are different from military ones in terms of energy supply, weight, and payloads. UAS consist of three major components: an unmanned aircraft, a human-operated or autonomous flight control system (ground control system), and the communication system also referred to as command and control link that connects the remotely-piloted aircraft and the ground control station (Fahlstrom & Gleason, 2012; ICAO, 2011).

The airborne part of the system is called the air vehicle that consists of a body, propelling unit, flight controls, and electric power system; the payload onboard the air vehicle is known as an independent subsystem (Fahlstrom & Gleason, 2012).

Ground Control System (GCS) is the operational control center for the UAV system, which processes and displays video data, telemetry data, visible satellites, power consumption, flight parameters, and much more. The GCS of large UAS is more complicated than that of small-UAS. The GCS for large UAVs consists of pilot and payload operator console, mission commander workstation, communication antenna, and communication rack; while the GCS for the small UAS can be carried in a backpack which includes a remote control and a display with a microprocessor that can be a laptop computer, an iPad or even a smartphone.

The main reason for having a UAV system is to carry a payload. Payloads as a subsystem are selected according to the mission requirement. For military missions, the payload of armed UAVs can include sensors as well as fireable, droppable, or launchable weapons. The payloads for mapping, inspection, reconnaissance, and surveillance missions often include only sensors such as LiDAR, Radar, including SAR, photo, video, infrared, and thermal cameras. An overview of remote sensing platforms and sensors is documented by Toth and Jozkow (2016). As the aim of this thesis is accuracy evaluation of UAS photogrammetry, the research concentrates on photographic cameras.

As a source of energy, small UAVs often use lithium-polymer batteries (Li-Po), while larger aerial vehicles rely on standard airplane engine fuel. Small UAVs are equipped with a flight controller board with advanced computing technology, including position and movement sensors. These sensors are the Inertial Measuring Unit (IMU) and the GNSS. The connection to the ground control station is provided by telemetry. The sensors give information about the aircraft position and status through the flight control software. The system allows to control the flight and its parameters as well as to view and monitor the camera. Manual, semi-autonomous, and autonomous flight modes are available. The autonomous flight mode is commonly preferred in photogrammetric tasks. By defining the flight path in the software, the aircraft follows the coordinates of the predefined path.

Generally, there are two types of airframes for UAVs, fixed-wing, and rotary-wing. In terms of take-off methods, UAVs can take off either in autonomous mode or assisted mode. The cost of UAVs varies depending on the platform type, application purpose, degree of autonomy, type of payload, and instrumentation (Nex & Remondino, 2014). Today, most of the survey-grade UAVs are equipped with IMU, GPS, and microelectromechanical systems, which are capable of performing flights in auto-pilot

mode. The degree of autonomy of a platform depends on the software used. Manufacture-included and third-party software packages are used to perform automated functions such as flight path routing, capturing images, stabilization, and landing (Greenwood et al., 2019). Since small UAVs have full electric motors powered by small batteries, they usually have short flight endurance. However, UAVs equipped with high-capacity batteries, and UAVs based on combustion engines have longer endurance and higher payload capacity, which allow mounting professional cameras, LiDAR, and SAR instruments onboard. For surveying and mapping of larger areas, fixed-wing UAVs with autonomous flight capability is preferred, which these systems are usually expensive.

3.1.3. Classification

The classification of UAVs is quite different in each country according to their application, and there is no one international standard. Every country has its own regulation and classification scheme. In terms of application, UAVs are generally classified as military, civil, and commercial UAVs. Military and non-military UAVs fall into one of the six functional categories: target and decoy, reconnaissance, combat, logistics, research and development, and civil and commercial. The simplest classification defined by FAA is based on their weight; which UAVs are categorized in three classes: micro UAVs also called as micro air vehicle (MAV) which is the smallest UAVs weighing less than 1g, miniature UAVs or small UAVs also called as sUAS which is less than 25 kg, and the class heavy UAV is used for heavier unmanned aircraft's weighing more than 25 kg.

Another classification is by size (very small, small, medium, and large), range of travel (very low-cost close-range, close-range, short-range, and mid-range), and endurance (Fahlstrom & Gleason, 2012). Very small UAVs or micro UAVs are extremely small in size and are similar to birds and insects. Micro UAVs can weigh even less than 1 g, and the dimensions can vary from a large insect size to 50 cm long. They can be flapping or rotary-wing micro design. Small UAV, which also called mini-UAV, is the UAV class that its size does not exceed 2 meters. This category UAVs can be rotary or fixed-wing; however, they are often designed in the fixed-wing hand-launched models. Medium and large class UAVs are usually used by the military. They can carry payloads of more than 100 kg.

Unmanned aircraft used in photogrammetry can generally be divided into three types: fixed-wing, rotary-wing (rotorcraft), and vertical takeoff and landing (VTOL) aircraft (Greenwood et al., 2019). Figure 3.1 shows examples of different small unmanned aircraft used in UAS photogrammetry.

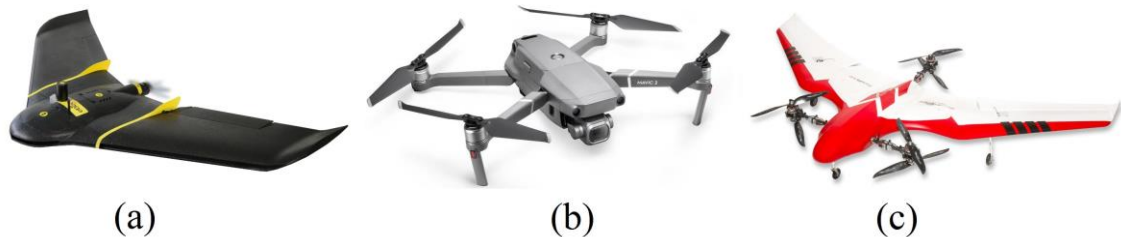


Figure 3.1. Examples of small UAVs: (a) fixed-wing senseFly eBee+; (b) multirotor DJI Mavic 2 Pro; (c) VTOL FireFly 6 (www.sensefly.com; www.dronezon.com; www.precisionhawk.com).

Fixed-wing UAVs fly similar to conventional aircraft; however, airframes can vary. These UAVs fly by forwarding thrust using a vertically rotating propeller, which is turned by an electric motor. The wing consists of control surfaces that allow the UAV to rotate freely around three axes. The UAV axes (longitudinal, lateral, and vertical) intersect each other at the aircraft's center of gravity at a right angle. Roll, pitch, and yaw are controlled by ailerons, control surfaces, and a rudder.

Rotary-wing UAVs can be single rotor (helicopter) or multirotor. Multirotor UAVs consist of multiple rotating rotor blades that rotate horizontally. Rotorcraft platforms are defined according to the number of rotors as tricopters (3 rotors), quadcopters (4 rotors), hexacopters (6 rotors), and octocopters (8 rotors). As the number of rotors increases, the bearing capacity also increases. VTOL UAVs are a combination of fixed-wing and multirotor UAV designs, which are in fact fixed-wing UAVs with vertical takeoff and landing capability (Greenwood et al. 2019).

The structure of a fixed-wing UAV is much simpler compared to the rotary-wing. Fixed-wing UAVs can fly with higher speed and provide longer flight durations; thus, a larger area can be surveyed per given flight, making them ideal for mapping applications. Fixed-wing UAVs have natural gliding capabilities, which can be advantageous in case of power loss. One of the disadvantages of such UAVs is the need for a launcher or a runway for takeoff. Another drawback is the fact that they need to stay in constant forward motion, so they cannot stay stationary, for this reason they are not suitable for inspection works and other stationary applications. While rotary-wing UAVs can take off and land vertically, which allow operating in smaller areas more flexible without substantial area

requirement; this is critical in applications where precise placement of UAV is required. The hovering capability of rotary-wing UAVs makes them perfect for stationary applications such as inspections. Due to the lower speed, rotary-wing UAVs can cover a smaller area per flight in comparison to fixed-wing UAVs.

3.1.4. Applications

Military application is the first recorded use of heavy UAVs, which were used by the British Royal Navy for gunnery target practice in 1935; these unmanned aircraft were flown under radio control. The military and other use of UAS has developed rapidly since its beginning. With the growth of new technology in the early 1990s, satellite communications and GNSS navigation were used to fly UAVs at very long distances from their control devices. In the past, the primary purpose of using UAS was to prevent pilots from being deployed to risky missions that entail hazards for the pilot of an aircraft. In the past, civilians were limited to hobby activities of flying model aircraft. However, UAS has a notably broader potential scope, including commercial, security, and scientific applications (ICAO, 2011). Today, UAS are used beyond the military purpose for civil and commercial applications. Recently, with the development of small-sized UAS and their accessibility to civilian users, UAS have been widely used in various civil and commercial applications. Flying at very low heights is one of the significant potentials of small UAS. Military applications include reconnaissance and security surveillance, attack and defense, training and target practice, and demining.

UAS has a high potential for civil and commercial tasks and has been used in many fields. The application of UAS is rapidly expanding, and these uses mainly comprise monitoring, communications, photography, and measurements. Common applications include search and rescue, border and maritime patrol, forest fire detection, contamination measurement, oil spill detection, natural disaster monitoring and emergency management, nuclear leaks, agriculture, road traffic surveillance, environmental monitoring, power and pipeline inspection, renewable energy, natural resources, structural monitoring, photogrammetry services, and other earth observations (Greenwood et al., 2019; Liu et al., 2014; Nex & Remondino, 2014; Pajares, 2015).

UAS as a useful tool has almost unlimited applications and is continually growing. For example, a UAV team is used for patrolling and surveillance of forests and road networks. Similarly, RPAs are used in search and rescue and emergency missions.

Recently, UAVs are widely used in 3D modeling of archaeological sites, digital visualization, preservation and recording, and defining the excavation status. UAVs are used for vegetation monitoring, volume computation, woodlots assessment, fire surveillance, and identification of species (Nex & Remondino, 2014). Nowadays, remote sensing application using UAS is of high interest in precision farming for identifying potential problems and accurate decision making. Producers use UAVs to monitor plant health and estimate yields. There are various agricultural and forestry usages, such as estimating canopy cover, plant count, crop type, and plant height. UAVs allow spatiotemporal monitoring of land and water, industrial air pollution monitoring, thermal analysis, coastline monitoring, volcano monitoring, and documentation of natural resources. A comprehensive study of the UAS applications can be found in Pajares (2015).

Photogrammetric applications of UAS are pervasive and in high demand in engineering and geosciences. Digital mapping using aerial photography and lidar is rapidly growing. Recently, UAS-based photogrammetry, commonly known as UAV photogrammetry, is widely used in many applications, including topographic mapping, digital terrain modeling, cadastral mapping, 3D mapping and modeling, orthomosaic production, volumetric surveys, aerial surveys, as-built surveys, and geological and hydrological mapping.

3.1.5. Regulations

In recent years, UAVs are accessible to civilians and are widely used for various purposes such as research, business, and entertainment. As a safety concern, rules and regulations are introduced by civil aviation authorities in many countries. In some regulations, the UAV operator must be certified, whether it is used for professional or entertainment purposes.

Since 2005, serious regulatory actions regarding the UAV activities in civil airspace have been taken by the International Civil Aviation Organization (ICAO). The ICAO serves as a focal point for harmonization and global interoperability, the development of a regulatory concept for the UAS standard and recommendation practices, and also contributes to the identification of communication requirements for UAS activities and the development of technical specifications (ICAO, 2011).

According to the ICAO, aircraft are categorized in many classes such as airplanes, rotorcraft, gliders, and balloons. They can be land, sea, or amphibious. Whether the aircraft is with or without a pilot does not affect its status as an aircraft, all the aviation standards, personnel licensing, and regulations must be applied. Generally, UAV regulations are applied for all UAVs that are used for commercial purposes; however, for other civilian UAVs, regulations are applicable for certain UAV classes based on weight, operational range, and utilization purpose (Stöcker et al., 2017). Regulations vary from country to country, or even may not exist.

In response to the proliferation of UAVs and increasing interest to drones in the United States, the registration program was initiated by the Federal Aviation Administration (FAA) in 2015 (Greenwood et al., 2019). Due to the increasing use of UAVs in civilian applications, regulations and security criteria have been defined by international communities to avoid dangers and ensure public safety (Nex & Remondino, 2014; Stöcker et al., 2017). The regulations cover safety and privacy issues to prevent mid-air collisions, people injuries, and property damages. Some of the main rules are as follows:

- Flights close to airports or manned aircraft are prohibited.
- The maximum gross weight of UAV must be less than 25 kg.
- Weather conditions must be considered before a flight.
- Safety and privacy distance from people and buildings must be maintained.
- Operating flights near crowded areas is prohibited.
- Flights higher than 120 m AGL must be avoided.
- The operator must be cautious and considerate, and the visual line of sight must be maintained (without binoculars or night vision goggles).
- The operator is responsible for causing damages to people or their properties.

UAS safety and privacy rules apply to all commercial and non-commercial UAS. There are also rules that apply exclusively to qualified UAS operators, defining the examinations and prerequisites for pilots. In some countries, qualification certification is required to carry out flights. However, specific regulations apply to certain civil UAS scenarios, which are defined and restricted by the weight of the UAV and/or the operational range, the flight area, or its utilization purpose (Stöcker et al., 2017).

3.2. UAS Photogrammetry

The American Society for Photogrammetry and Remote Sensing (ASPRS) has defined photogrammetry as the "art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena" (Wolf et al., 2014, p. 14). As its name implies, photogrammetry is primarily involved in analyzing and measuring photos; however, film cameras have been replaced by digital cameras. Photogrammetry is traditionally a part of geodesy that belongs to the Remote Sensing (RS) field (Linder, 2016). In parallel with the development of technology, the scope of photogrammetry has also expanded to include other data analyses, such as digital images, laser ranging measurements, radiated acoustical energy patterns, and magnetic phenomena.

Photogrammetry consists of two main branches: metric photogrammetry and interpretative photogrammetry. Metric photogrammetry consists of making 2D and 3D measurements in photos, which enables finding geometric properties of objects. Reconstruction and production of planimetric maps (orthoimages) and topographic maps from digital images is one of the most common applications. Interpretative photogrammetry deals with extracting information and identifying objects from images through image processing and systematic analysis. Interpretative photogrammetry is included in the branches of remote sensing and image interpretation. In addition to photographs, remote sensing uses a variety of spaceborne (satellite), airborne (aircraft), and terrestrial data such as multispectral cameras, infrared sensors, thermal sensors, lidar, and radar sensors, and provides qualitative and quantitative information about objects (Wolf et al., 2014). Two principal photography classifications used in this science are terrestrial and aerial. Photogrammetry provides invaluable data, which are crucial in earth observation and environmental studies.

UAS photogrammetry has many advantages over classical aerial photogrammetry. Traditional photogrammetry is based on photographs obtained by survey-grade analog metric cameras, usually mounted on manned aircraft. The workflow of this method is often lengthy and needs a large amount of work (Carrivick et al., 2016; Wolf et al., 2014). The price of a small unmanned aircraft is considerably lower than the crewed one. There is no operational cost, and most UAVs are equipped with a GNSS receiver that allows automatic mission planning and real-time data acquisition. Known coordinates of the

center of images significantly reduce the block adjustment processing time. Digital photogrammetry is well used in surveying and mapping at several scales from aerial and ground-based platforms (Agüera-Vega et al., 2016; Anders et al., 2013; Avanzi et al., 2018; Duarte et al., 2017; Eisenbeiß, 2009; Fernández-Hernandez et al., 2015; Gabrlík et al., 2018; Honkavaara et al., 2009; Nex & Remondino, 2014; Rehak & Skaloud, 2015; Rosnell & Honkavaara, 2012; Strozzi et al., 2010).

Although UAS is very useful, especially in the survey of risky and remote areas, UAS also has its limitations. Small and low-cost UAVs cannot carry heavy cameras and LiDAR sensors, which limits the use of professional high-resolution multi-spectral cameras. Moreover, Small drones can be swept away by wind gusts, which cause overlap problems. However, with the advancement and miniaturization of technology, ultralight sensors that can be mounted on UAVs have recently been developed (Salach et al., 2018), and also the above-mentioned limitations have been removed in survey-grade unpiloted aerial systems. UAS-based remote sensing methods often need additional data processing for solving positional uncertainties. In GPS-denied environments, such as remote valleys, or in places where the signal can be interrupted (e.g., high rise buildings), post-processing methods must be pursued. Onboard IMU sensor enables to measure sensor payload orientation and positioning through post-processing of IMU data (Greenwood et al., 2019). However, UAS-based photogrammetric technique using feature detection algorithms such as SfM and MVS minimizes the position estimation problems associated with UAV. Technological advancement in digital photogrammetry and the development of algorithms in the automation of the photogrammetric process allow accurate calibration of non-metric digital cameras.

3.2.1. Structure from motion

Structure from Motion (SfM) is an advanced photogrammetric technique that has emerged from advances in computer vision and traditional photogrammetry, which utilizes a series of 2D images of an object or a specific region obtained by a moving sensor as input to extract features and produce high-quality 3D structures (Agüera-Vega et al., 2018; Carrivick et al., 2016; Snavely et al., 2008). Recently, SfM is widely used in geosciences applications as a low-cost topographic survey technique to produce dense 3D point clouds, digital elevation models, and topographic maps (Agüera-Vega et al., 2018; Carrivick et al., 2016; Coveney & Roberts, 2017; Lucieer et al., 2014; Martínez-Espejo

Zaragoza et al., 2017; Micheletti et al., 2015; Nesbit & Hugenholtz, 2019; Rusnák et al., 2018; Sanz-Ablanedo et al., 2018; M. W. Smith et al., 2016).

Motion-based reconstruction or structure from motion was introduced by Ullman (1979) in the late 1970s. SfM became popular in the 2000s through the further efforts of Lowe (1999, 2004), Snavely et al. (2006, 2008), Furukawa and Ponce (2009), and other researchers in the development of computer vision algorithms. SfM is used to reconstruct a sparse 3D point cloud model of the photographed object, which this model is then refined to a denser and finer resolution by applying Multi-View Stereo (MVS) technique (Carrivick et al., 2016; M. W. Smith et al., 2016). In the computer vision literature, the full process is prevalently abbreviated as SfM, while the complete reconstruction is accomplished by performing an entire SfM-MVS workflow, which employs multiple algorithms based on 3D computer vision, and photogrammetry techniques (Carrivick et al., 2016). Traditional photogrammetry is the closest available technique to SfM-MVS and has greatly contributed to its workflow (Micheletti et al., 2015; M. W. Smith et al., 2016). SfM and MVS are complementary, SfM does not require camera parameters, but can estimate the parameters and calibration for MVS algorithm.

Since SfM is more related to computer vision sciences, an in-depth discussion of SfM procedures and algorithms is beyond the scope of this thesis; interested readers are directed to Lowe (1999, 2004), Snavely et al. (2008), and Carrivick et al. (2016). Nevertheless, the main concepts underlying the SfM method and its differences with respect to conventional digital photogrammetry is briefly presented. SfM technique is based on a new generation of image matching algorithms that can reconstruct 3D models from a bundle of unstructured images; in other words, SfM allows unstructured image acquisition (Agüera-Vega et al., 2018; Mancini et al., 2013; M. W. Smith et al., 2016).

3.2.1.1. *SfM-MVS workflow*

Different algorithms are used for each step of the SfM-MVS method. Although photogrammetric principles are embedded in the SfM-MVS workflow, many aspects of SfM-MVS have entirely different roots, arising from developments in computer vision algorithms. The specific procedure applied is not detailed by many commercial SfM-MVS software packages. Nevertheless, the typical SfM-MVS workflow implemented by most software packages includes the following steps (Agisoft, 2018; Carrivick et al., 2016; Pix4D, 2017; M. W. Smith et al., 2016):

- I. **Feature detection:** Identifying features (keypoints) is the first step in SfM in which the software automatically identifies numerous common points between multiple images and defines a unique identifier to them, regardless of image scale or perspective. Each feature points found in an image is called a keypoint. Detection of features is a low-level process that is the starting point of computer vision applications (Govender, 2009). Thus, this step is very important, which the success of 3D reconstruction depends on this initial step. Feature detectors should be powerful and be able to track down the same features in multiple images regardless of image scaling, rotation, or illumination differences. Many feature detection algorithms have been developed. The Scale Invariant Feature Transform (SIFT) developed by Lowe (2004) is one of the most effective and widely used feature detection algorithms that can be used for images with large scale variations (Agüera-Vega et al., 2018; Govender, 2009; Harwin & Lucieer, 2012; Snavely et al., 2008). Govender (2009) compared the feature detection algorithms for SfM and found that the SIFT feature detection algorithm showed the lowest reprojection error than other algorithms.
- II. **Identification of correspondences (match points):** After locating keypoints in each image, similar keypoints in multiple images are identified. Nevertheless, there is no assurance that there will be a partner for any given keypoint in another image; therefore, thresholds such as distance ratio are applied to discard points that do not match well. Similar to stereophotogrammetry, the matching descriptor's success depends on the image texture and good overlap.
- III. **Identifying geometrically consistent matches and filtering keypoint correspondences:** To be sure that only accurate match points remain, another keypoint correspondence filter is applied to attempt to identify and eliminate any remaining mismatches. Figure 3.2 shows valid and invalid matches that were identified and filtered after performing mathematical operations using Agisoft PhotoScan.

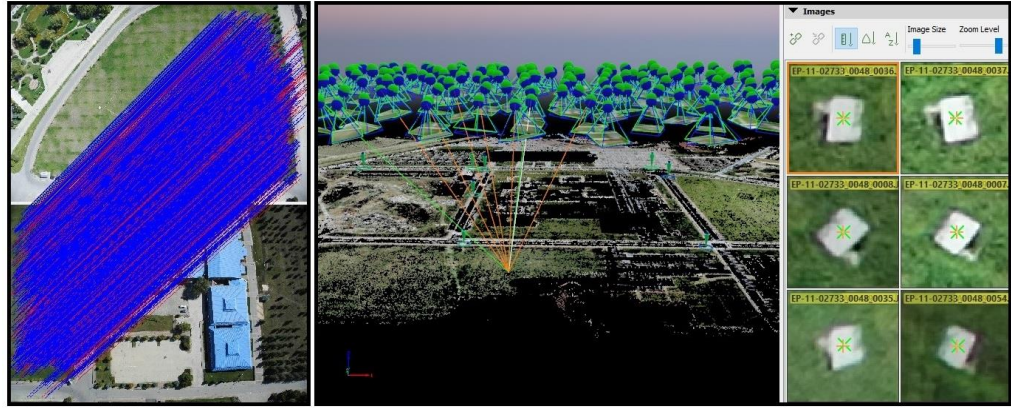


Figure 3.2. Tracks between two images in PhotoScan (right); valid matches are shown in blue, while invalid matches are given in red. The left screenshot shows the identification of the same feature in multiple images in Pix4D.

- IV. **Structure from motion:** Using the geometrically correct matches filtered in the previous step and by applying bundle adjustment algorithms, SfM simultaneously estimates the 3D structure (geometry) of a scene, camera positions and orientations (extrinsic calibration), and the camera intrinsic calibration parameters. While conventional photogrammetric techniques usually require separate camera calibration, SfM can estimate the camera internal calibration parameters by defining the calibration matrix using both the metadata of images (EXIF tags) and the redundancy of a large number of matches. Bundles of light rays that connect camera centers to 3D points are adjusted by minimizing a nonlinear cost function, which this process results in jointly optimal 3D structure (sparse point cloud) and camera parameters. In photogrammetric image processing, the accuracy of the 3D reconstruction is critically dependent on the bundle block adjustment. Different optimization procedures are implemented by different software packages. In this process, filtering algorithms are often used to some degree to eliminate outliers and gross errors. For a detailed description of bundle adjustment, readers are directed to Granshaw (1980) and Triggs et al. (1999).
- V. **Scale and georeferencing:** SfM provides camera locations and geometry of the scene, so the output of the SfM step is a sparse 3D point cloud, which is unscaled and produced in an arbitrary coordinate system unless images are directly georeferenced using RTK-enabled UAS survey. A minimum of three ground control points (GCPs) are required to georeference the SfM-derived 3D point cloud. Georeferencing transforms the model linearly using seven parameters (XYZ for

translation, omega, phi, and kappa for rotation, and 1 parameter for scale). See Section 3.2.4 for a detailed description of georeferencing and bundle adjustment in traditional and conventional photogrammetry.

- VI. **Optimization of camera alignment using known GCPs:** Since internal and external camera orientation parameters are estimated using image data during image alignment, there may be some errors in the final model, which can lead to non-linear deformation of the final reconstructed model. GCPs provide additional external information about 3D geometry. To optimize image alignment using GCP information, the bundle adjustment can be re-run. The optimization is performed using transformation algorithms, which further refines the reconstructed scene geometry based on GCP information.
- VII. **Point cloud densification:** The final step in the SfM-MVS workflow is to apply MVS algorithms to the sparse point cloud and camera parameters that are already scaled and georeferenced. Multi-view image-matching algorithms used in image processing can recognize a vast number of interrelated features over a set of images. The goal of MVS is to increase the number of points and provide a full 3D reconstruction of the scene. MVS can increase point cloud density by several orders of magnitude. There is a wide range of algorithms for MVS, which Patch-based Multi-View Stereo (PMVS) proposed by Furukawa and Ponce (2009) is one of the most widely used algorithms (Carrivick et al., 2016; Seitz et al., 2006). Using dense point cloud as input, other 3D representations such as mesh models and digital surface models can be produced.

SfM approach is very effective for processing images acquired from platforms with irregular image acquisition plan. Irregularities in the path and flight height variations are often experienced in small UAS (Mancini et al., 2013). On the contrary, a well-designed image acquisition plan is a prerequisite for classical photogrammetry (Mancini et al., 2013; M. W. Smith et al., 2016; Wolf et al., 2014). However, although this is not obligatory in SfM, for accurate surveying, a well-defined image acquisition plan leads to more accurate results (Agisoft, 2018; Pix4D, 2017). A more detailed explanation of SfM-MVS can be found in Mancini et al. (2013), Micheletti et al. (2015), Carrivick et al. (2016), Smith et al. (2016), and Martínez-Espejo Zaragoza et al. (2017).

Structure from motion is one of the significant developments in digital mapping. Recently, the SfM-MVS technique has been widely used in digital surveying because

SfM-MVS is a rapid, economic, and highly automated image-based approach, which is able to produce topographic information from a block of images acquired using ground based or aerial platforms. One of the advantages of this method over the traditional approach is its independence from the spatial scale. Moreover, this method is cost-effective and fast compared to ground-based surveying methods; in some cases, the accuracy of the SfM-derived 3D data is nearly comparable to that of terrestrial data (Agüera-Vega et al., 2016; Gabrlik et al., 2018; Gonçalves & Henriques, 2015; Rehak & Skaloud, 2015; Reshetyuk & Mårtensson, 2016).

3.2.1.2. Software

Advances in computer hardware and SfM photogrammetry software have significantly reduced the financial expenses of generating topographic data. In parallel with advances in computer vision, SfM software has developed quickly over the last decade. Several computer vision-based software solutions are available with the ability to process unstructured image collections and create 3D models. In general, SfM-MVS software falls into one of the following three categories (Carrivick et al., 2016): (1) individual algorithms that perform specific tasks in the reconstruction process; (2) stand-alone applications, which perform the entire reconstruction process from generating dense point clouds to 3D mesh, digital surface models, and orthomosaics; and (3) Internet-based processing or cloud computing platforms in which the user can upload images to the online platform and after computation returns the 3D model to the user. Two categories of SfM software packages are available: commercially developed and open source.

Open-source software packages with a high level of customization are available (e.g., MicMac) in which the user can modify the processing parameters and build codes, which usually require some expertise in programming. For an in-depth examination of the implemented algorithms, the user needs to spend a great deal of time and resources in analyzing the software code (Benassi et al., 2017). Moreover, the workflow is more complex, and several applications may need to be used in sequence to produce final models. On the other hand, according to comparative studies, in addition to ease of use, most commercial solutions are more accurate and include a complete modeling workflow in one software package. Although commercial applications perform the photogrammetric process with a high level of automation and produce 3D models and

orthomosaics, users can customize only a few parameters. Due to the black-box nature of the commercial software packages, which users are given less control over processing parameters and minimal information is provided to assess the quality of the final model, the reason for the failure of processing is always unknown. Basically, for understandable reasons regarding the protection of intellectual property rights, no commercial software package provides comprehensive information about the algorithms. Brief information about the three commercial software packages used in this research is presented below.

3.2.1.2.1 Agisoft PhotoScan:

Agisoft PhotoScan is one of the most popular commercially available SfM-MVS software packages, developed by Agisoft LLC. This stand-alone software is available in standard and professional versions, which the professional photogrammetric application costs 3,499 USD. Besides its high price, the software requires a powerful computer for processing large projects. The camera position and orientation parameters provided by onboard IMU and GPS are stored in images' metadata as EXIF. PhotoScan extracts the stored data and employs for georeferencing and bundle adjustment process. This software has the capability of producing dense point cloud, generating 3D models and textured models, producing DSMs, classifying point cloud, generating DTMs, processing multi-spectral images, and scripting Python process chains (Agisoft, 2018). PhotoScan has a user-friendly graphical interface and intuitive workflow that performs the photogrammetric process based on SfM algorithms with a high level of automation. Although user intervention in processing parameters is limited, PhotoScan is one of the most advanced software packages, where about 66% of studies in the literature review have used this application to process UAS images. Due to commercial reasons, very little information is available about the algorithms used.

3.2.1.2.2 Pix4Dmapper:

Pix4Dmapper Pro is also an SfM-based photogrammetric software developed by Pix4D. The professional photogrammetry version costs 4,990 USD. This application is very user-friendly; it allows the user to choose the camera model, then it extracts the camera position and estimates the accuracy from the image metadata. Tie points extraction and feature matching is based on SIFT algorithms (Benassi et al., 2017). The processing is automated, and the results are automatically exported to the output folder.

Pix4Dmapper is also capable of producing dense point cloud, generating 3D textured models, producing DSMs and DTMs, processing multi-spectral images, and volume calculations (Pix4D, 2017). Though this software is robust in 3D reconstruction from high and low overlap images, it has not been widely used in the literature.

3.2.1.2.3 3Dsurvey

3Dsurvey is an aerial image processing software developed especially for UAS-based land surveying, which claims survey-grade accuracy in their brochure (3Dsurvey, 2018). The perpetual license costs 3,300 USD. In addition to the dense point cloud, DSM, DTM, and mesh model, it provides surveying analysis options such as creating profiles, contours, volumes, and 2D and 3D CAD drawing tools as well as importing and analysis of third-party source data. 3Dsurvey also provides multi-spectral and thermographic image processing tools.

3.2.2. Camera

Digital cameras are the most fundamental device in UAS photogrammetry. A digital camera is also called a digital frame camera. Digital-frame cameras are classified by their sensor size and the number of pixels in the digital image (Wolf et al., 2014). The sensor of a digital frame camera is a two-dimensional array of sensitive CCD (charge-coupled device) elements called pixels. For indicating common image sizes, the term megapixel (1 million pixels) is used. For instance, a 16-megapixel camera may have a sensor with arrays of 4000-pixel rows and 4000-pixel columns. The lens used for aerial mapping is the most important and expensive part of the camera. For traditional photogrammetric tasks generally, mapping cameras (metric cameras) are used. The UAS onboard cameras are not that level of quality; lenses are smaller in size and lighter in weight. Standard digital cameras with higher resolution (usually more than 12 megapixels) can do the job, but for accurate mapping, cameras with large sensors are recommended to maximize sensor sensitivity and minimize lens distortion errors (O'Connor, Smith, & James, 2017).

A digital image is a computer compatible two-dimensional array of pixels in which each pixel consists of an integer (referred to as digital number) that quantifies the brightness degree of a particular location. Pixel is the smallest element or the basic building block of a raster image. A digital image has a fixed number of pixels arranged

in rows and columns. The number of pixels in an image is referred to as the resolution. The physical size of an individual pixel is called geometric (or spatial) resolution. Spatial resolution is crucial in feature recognition and clarity in digital images.

Non-metric cameras have variable interior geometry and lens distortion. To use such cameras in photogrammetric mapping, all interior camera parameters must be determined, and lens distortion should be modeled. In order to determine the accurate spatial information from photographs, cameras are carefully calibrated before use (Wolf et al., 2014). Various methods are available for camera calibration, which the laboratory calibration method is the most frequently used technique. After calibration, comparisons are made by performing precise measurements of a target with known accurate positions.

Today, camera parameters can be determined analytically by specific software (such as Agisoft Lens) or by processing software using a camera self-calibration process. Since UAS is equipped with an inertial measurement unit (IMU), the three orientation parameters of the camera (roll, pitch, and yaw) are measured by IMU. The exterior orientation parameters (X, Y, Z, omega, phi, and kappa) are computed during the aerial triangulation process.

The images required for SfM-MVS can be acquired by non-metric low-priced digital cameras (such as smartphone cameras) to professional-grade and expensive DSLR cameras (Carrivick et al., 2016). Images captured from video footage can also be used for 3D reconstruction using SfM. It is reported that the quality of the 3D products derived from images of low-priced digital cameras can often compete with those of more expensive sensors (Carrivick et al., 2016; Thoeni et al., 2014). Although the processing time of images acquired by DSLR cameras is much longer due to their high quality, they offer the most appropriate imagery for the SfM-MVS (Carrivick et al., 2016).

3.2.3. Photogrammetric project planning

In photogrammetric projects, project planning is the first and most important step that should be thoroughly performed by knowledgeable and experienced experts (Wolf et al., 2014). The planner decides according to the final needs. In a given photogrammetric project, a variety of products can be developed, including aerial images, orthoimages, digital planimetric maps, digital elevation models, topographic maps, cross-sections, cadastral maps, etc. Proper flight planning and selection of ground control points, lead to good-quality aerial photography, which ultimately results in a successful

photogrammetric project (Wolf et al., 2014). Two items have the main role in flight planning: a flight map, which shows the coverage and location of aerial photography, and specifications including camera, flight height, scale, imagery overlap (forward lap and side lap), and other factors that influence aerial photography.

The purpose of photography is crucial in the planning of aerial photographic missions. Optimum equipment and procedures can only be selected with the defined purpose. For topographic mapping or other purposes where accurate quantitative photogrammetric measurements are necessary, images with good metric qualities are needed, while for qualitative analysis, such as interpretation of photos or construction of aerial orthomosaics, high pictorial qualities are required.

Prior to the development of the flight plan, studying the area maps of a project is crucial. Topography has considerable effects on flight plan parameters such as flight path, flight spacing, and imagery overlap. In addition to topographic maps that provide an overview of the area, it is also essential to review the aeronautical charts to obtain information concerning high towers and restricted air space such as airport approaches. Since understanding the geometry of aerial images is crucial in photogrammetry, a brief description is given in the following paragraphs.

3.2.3.1. *Geometry of vertical images*

In photogrammetry, it is essential to understand the geometry of images. The number of pixels in an image, the flight height AGL, and the lens focal length determine the ground resolution and the scale of the image. Vertical images are commonly used in aerial mapping. Aerial images are called vertical images when the optical axis of the camera mounted on an aircraft is as vertical as possible (Wolf et al., 2014). The photo is termed truly vertical if the optical axis is precisely vertical. In aerial photography, as the aircraft moves and so does the camera, therefore, small tilts are inevitable, no matter how precautions are taken to retain the camera axis vertical.

Photogrammetry deals with three types of aerial photography: truly vertical, tilted or near-vertical, and oblique. They are defined by the angle which the optical axis of the camera makes with the nadir (vertical direction pointing to the ground). In truly vertical photography, the tilt angle is 0° . Near-vertical photography is the most used type of aerial photography in which the camera axis points to the nadir direction, and the tilt angle varies between 0° and 3° . In oblique photography, the angle that the camera axis makes

with the nadir ranges between 35° and 55° in fixed-wing aircraft, while in rotary-wing UAS, it can range up to 90° (see Figure 3.3).

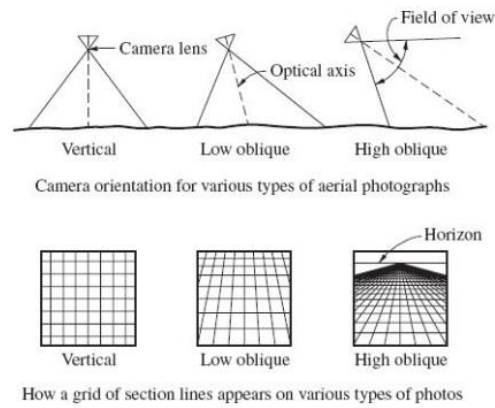


Figure 3.3. Vertical and oblique photography (Wolf et al., 2014).

Figure 3.4 illustrates the geometry of a vertical photograph taken from an exposure station L.

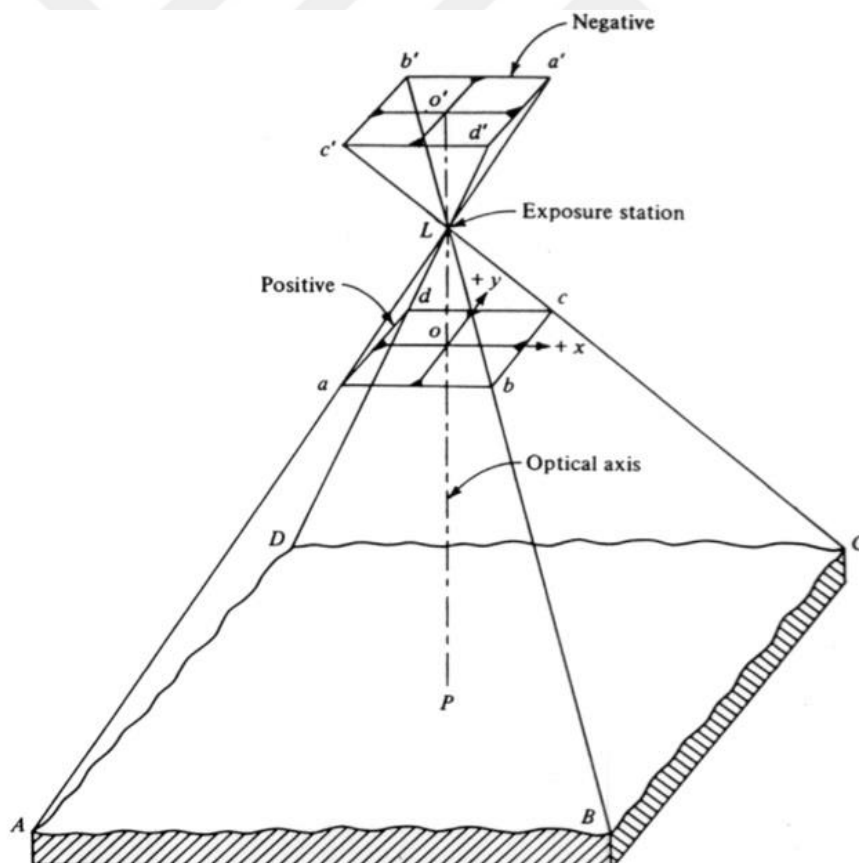


Figure 3.4. Geometry of a vertical photograph (Wolf et al., 2014).

3.2.3.1.1 Scale and ground coordinates of a vertical image

Scale is used in both maps and aerial images to find the actual size of objects on a map or image relative to their actual size on the ground. In photogrammetry, the scale of a vertical image can be defined in the same logic as it is interpreted in planar mapping. A map scale is defined as the ratio of a distance on the map to the corresponding distance on the ground. Similarly, the scale of an image is the ratio of a distance on the image to the corresponding distance on the ground (Wolf et al., 2014). However, because of the nature of map projections, the scale of a map is not affected by variation in terrain, while the scale of a vertical aerial image varies with fluctuations in terrain elevation due to its perspective projection (Wolf et al., 2014). Scales can be presented in unitless ratios, dimensionless fractions, or unit equivalent ratios. Figure 3.5 shows a two-dimensional side view of a vertical photograph over flat terrain. Since positive photos are used in measurements, the negative is excluded in the figure.

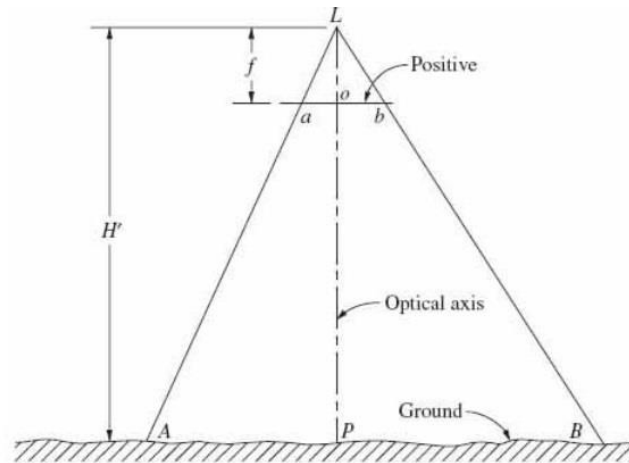


Figure 3.5. Side view of a vertical photograph over flat terrain (Wolf et al., 2014).

Referring to Figure 3.5 and in accordance with trigonometric principles, the scale of a vertical photograph (S) over flat terrain is the ratio of the distance on the photo (ab) to the corresponding distance on the ground (AB). That scale can also be expressed as the ratio of camera focal length (f) and flight height AGL (H'); therefore, the scale of a vertical image is computed using the following equation:

$$S = \frac{ab}{AB} = \frac{f}{H'} \quad (3.1)$$

As it is seen in the above equation, the scale of a vertical image is directly proportional to the focal length of the camera and inversely proportional to flight height AGL.

Figure 3.6 shows a two-dimensional side view of a vertical photograph taken over variable terrain from exposure station L ; where h is the elevation of points A and B . In such areas exact scale of a specific location (i.e., h_1) or average scale of all other areas (h_{avg}) of photograph can be calculated using equations (3.2) and (3.3).

$$S = \frac{ab}{AB} = \frac{La}{LA} = \frac{f}{H - h} \quad (3.2)$$

$$S_{avg} = \frac{f}{H - h_{avg}} \quad (3.3)$$

In the above equation, h_{avg} is the average elevation of the terrain covered by a vertical photograph. The average scale is the approximate scale, which is normally convenient to use for defining the overall mean scale of a vertical photograph taken over variable terrain.

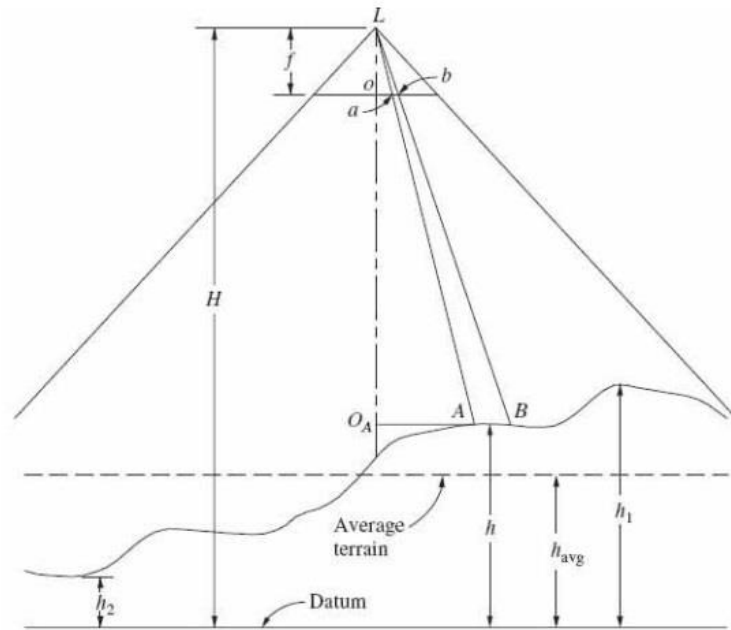


Figure 3.6. Side view of a vertical photograph over variable terrain (Wolf et al., 2014).

In addition to the above equations, there are other methods to determine the scale of a vertical aerial photograph in which the above values are not required. One of the methods is to measure a distance in the photograph and the corresponding distance on the ground. The scale will be a simple ratio of distances. The scale of a vertical aerial image acquired with a digital camera can also be determined by the ratio of the physical size of a pixel in the image and the ground coverage of that pixel.

The ground coordinates of a point whose image appears in a vertical photograph can be calculated with regard to an arbitrary ground coordinate system. The arbitrary X and Y axes on the ground are exactly on the same vertical planes as the image x and y axes, and the system's origin is at the center point of the datum (point vertically below the exposure station in the datum plane) (Wolf et al., 2014). Figure 3.7 shows a vertical photo taken at a flight height H above the selected datum. To calculate the X and Y coordinates of point A, the following equation can be written from similar triangles $La'o$ and $LA'A_o$:

$$\frac{oa'}{A_oA'} = \frac{f}{H - h_a} = \frac{x_a}{X_A} \quad (3.4)$$

From which

$$X_A = x_a \left(\frac{H - h_A}{f} \right) \quad (3.5)$$

Similarly, from similar triangles La'' and $LA''A_o$,

$$\frac{oa''}{A_oA''} = \frac{f}{H - h_a} = \frac{y_a}{Y_A} \quad (3.6)$$

From which

$$Y_A = y_a \left(\frac{H - h_A}{f} \right) \quad (3.7)$$

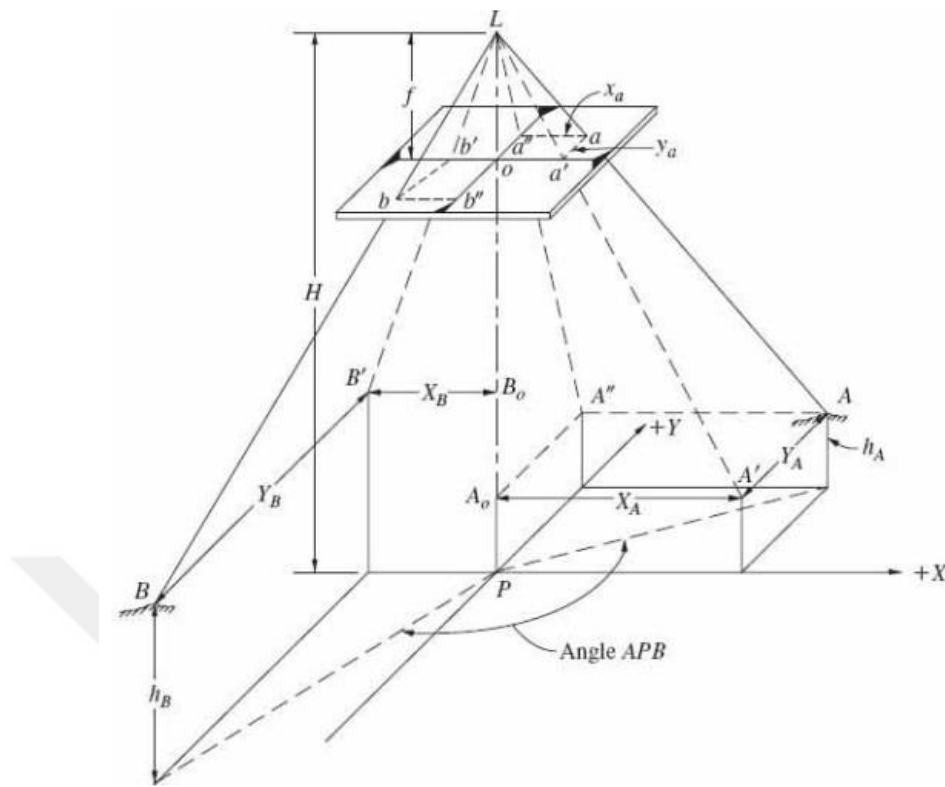


Figure 3.7. Ground coordinates of a vertical photo (Wolf et al., 2014).

3.2.3.1.2 Image overlap

Vertical aerial photos of an area acquired for photogrammetric processing are normally taken by series of overlapping flight passes, called flight strips. Two types of overlap are common in photogrammetry: forward lap and side lap. Forward lap, which is also called end lap, frontal overlap, or longitudinal overlap, is a photogrammetric term used to describe the amount of image overlap between successive photos along the flight strip, which is commonly given in percent. Figure 3.8 illustrates two overlapping aerial photos taken from an aircraft equipped with a camera.

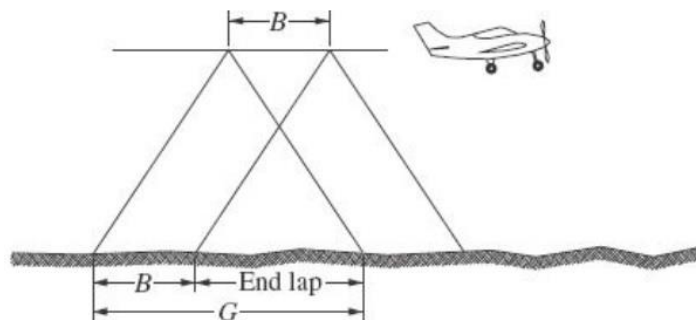


Figure 3.8. Forward lap of successive photos along a flight line (Wolf et al., 2014).

The overlapping pair of images is called a stereo pair, which is used for stereo viewing and processing. In the above figure, B is the distance between the centers of two photographs or between exposure stations of a stereo-pair; B is also called air base. G is the distance that each image covers on the ground. The typical amount of forwarding lap for a photogrammetric task is between 55-65 percent of the total image coverage. In UAS photogrammetry, the amount of frontal overlap is recommended to be at least 70%. This is due to the light weight of the aircraft, which is subject to strong air dynamics causing the camera to rotate. For single-track corridor mapping, the recommended minimum overlap is 85% (Pix4D, 2017).

Side lap is also a photogrammetric term used to represent the amount of lateral overlap between images of adjacent flight strips. Figure 3.9 illustrates two overlapping flight strips. The distance between the center of photos in two flight strips (W) is called line spacing. Side overlap is required to prevent gaps in the coverage of aerial photography, which might occur due to factors such as drift (often caused by strong winds), tilt, flight height variation, and terrain variations (Wolf et al., 2014). The typical amount of side lap for photogrammetric work is 30%; however, for very precise photogrammetric works, it may increase to 60%. In UAS photogrammetry, due to its light weight, the amount of side overlap is recommended to be at least 60% between flying tracks.

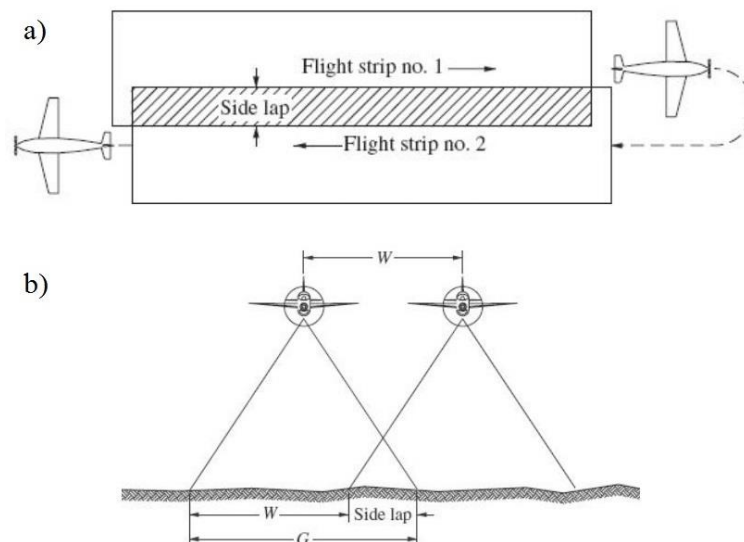


Figure 3.9. Side overlap of adjacent flight strips: (a) top view (b) side view (Wolf et al., 2014).

In UAS photogrammetry, the image acquisition plan, especially the amount of frontal and side overlap highly depends on the type of terrain and objects to be

reconstructed (Pix4D, 2017). For particular cases such as forest and dense vegetation, snow, sand, and flat terrain like agriculture fields, at least 85% frontal overlap and 70% side overlap is recommended (Pix4D, 2017). In general, maintaining high overlap between images will result in better bundle adjustment and high key-points for 3D reconstruction using structure from motion algorithms. The photographs of multiple side-lapping strips used to cover an area are usually referred to as photogrammetric block or block of photos.

3.2.3.2. *Designing of a photogrammetric block*

In UAS photogrammetry, designing a flight plan is directly dependent on the required resolution (scale) of imagery and mapping accuracy. Defining the GSD or the required resolution and accuracy of the project is the first step of the design. After determining the scale and accuracy, the design processes can be followed. Generally, designing includes developing the flight plan (defining flight route, flight height, and imagery overlap), planning the ground controls, selecting the essential instruments, software, and procedures according to the final product requirement, and cost estimation and scheduling. The following information should be known before planning, some of which should be calculated:

- Focal length of the camera lens;
- Pixel size;
- Number of pixels (image dimension);
- Flight height above a datum or photo scale;
- Size and shape of the study area;
- The amount of side and front overlap;
- The required scale or resolution of the map; and
- Aircraft speed.

Ground coverage of an image can be computed using its ground sampling distance (GSD). GSD is the distance between two successive pixel centers, which is practically measured on the ground. After computing the ground coverage, the number of flight strips, number of images, flight height, aircraft speed, and other factors can be computed and laid out on the project map. While designing the flight strip, in a rectangular project, the flight line should be laid out on the smallest dimension of the project area and also the largest CCD array should be perpendicular to the flight path. In this way, the number

of flight lines and the number of turns will be reduced, which results in saving energy and increasing the efficiency of the aircraft. During the designing process, the planner will need to compute the following parameters which are required in design operations.

The distance between flight lines or flight line spacing (F_{LS}) is calculated using the following equation:

$$F_{LS} = G_W \times (1 - \text{side overlap}) \quad (3.8)$$

where G_W is the ground coverage of image along the width of the camera CCD array.

The number of flight lines (N_{FL}) is calculated as follows:

$$N_{FL} = \left(\frac{P_w}{F_{LS}} \right) + 1 \quad (3.9)$$

where P_w is the width of the project area. The N_{FL} result is always rounded up.

For computing the total number of images to cover the project area, first, the airbase should be computed. The airbase (B) which is the distance between two consecutive images is computed using the following equation:

$$B = G_H \times (1 - \text{forward overlap}) \quad (3.10)$$

where G_H is the ground coverage of one image in the height direction of the camera's CCD array.

The number of images (N) per flight line of length L is given by

$$N = \left(\frac{L}{B} \right) + 1 \quad (3.11)$$

It is worth mentioning that in order to provide continuous stereo coverage, two images are added at the start of the flight lines (beyond the project boundary), and two images at the end of flight lines. Considering this, the equation above changes to:

$$N = \left(\frac{L}{B} \right) + 5 \quad (3.12)$$

while the total number of images per flight is equal to

$$\Sigma N = N_{FL} \times N \quad (3.13)$$

The flight altitude above a given datum is computed in accordance with the required photo scale or GSD and the camera focal length. The datum can be the average ground

elevation or the mean sea level. The UAS height AGL according to the required GSD can be calculated using the scale equation. From equation (3.1) we know that:

$$Scale = \frac{f}{H} = \frac{ab}{AB} = \frac{S_w}{G_w} \quad (3.14)$$

the flight height (H) is equal to:

$$H = \frac{f \times G_w}{S_w} \quad (3.15)$$

where f is the focal length of the camera, G_w is the ground coverage of one image in the width direction, and S_w is the sensor width.

The distance covered by the width of one image on the ground is calculated as follows:

$$G_w = I_w \times GSD \quad (3.16)$$

where I_w is the image width in pixels.

By combining the equations (3.15) and (3.16), we obtain the flight height AGL as follows:

$$H = \frac{I_w \times GSD \times f}{S_w} \quad (3.17)$$

From the above equation, it can be seen that the spatial resolution (GSD) is directly proportional to the flying height above the ground. The higher the flight height, the lower the resolution of images. On the other hand, flying at higher altitudes gives higher overlap which improves the data quality especially in homogeneous areas such as forests and agricultural (Pix4D, 2017).

To maintain the required forward overlap, the speed of the aircraft should be controlled. Once the speed of the aircraft (V) and the distance between successive images (B) are determined, the time (t) between two successive images can be calculated using the following equation:

$$t = \frac{B}{V} \quad (3.18)$$

Advancement in technology has made the UAS photogrammetry flight planning quite easy. Flight and data management software (e.g., eMotion 3, Mission Planner, DJI GO, Litchi) allows the user to perform a fully autonomous flight mission by entering essential flight parameters such as area extent, image overlaps, GSD. Image acquisition plan depends on the purpose of reconstruction, terrain, and object to be reconstructed.

The recommended ideal image acquisition plan using UAS, which is applicable for many terrain mapping cases is a regular grid pattern (see Figure 3.10) with at least 75% longitudinal overlap and 60% side overlap; besides, to obtain the desired GSD, the aircraft should be maintained at a constant height as much as possible (Pix4D, 2017).

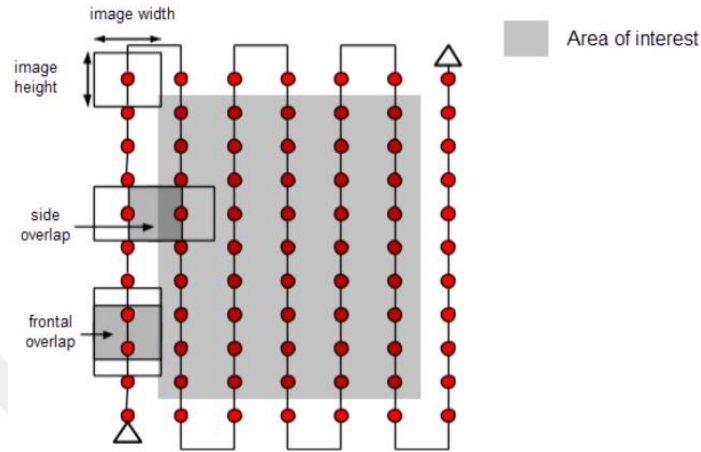


Figure 3.10. Regular grid image acquisition plan (Pix4D, 2017).

In the planning and scheduling processes, consideration of weather conditions is one of the most critical issues in aerial photography. The ideal day for aerial photography is the day free of fog, smog, haze, smoke, dust, and heavy winds. In addition to these constraints, the sun's altitude is another factor to be considered. Long shadows are produced by low sun angles that can affect detail. In general, the minimum acceptable sun elevation angle in aerial photography is 30° (Wolf et al., 2014). Some photographers recommend photography in the middle of an overcast day to obtain soft images with even lighting by taking advantage of clouds as a light diffuser; this can significantly reduce shadows, glare, and blurriness; however, studies show that poor weather conditions (i.e., overcast, precipitation) decrease the radiometric quality of the images, thereby reducing the final product quality by an average of 25%. (Wierzbicki et al., 2015).

3.2.4. Georeferencing and bundle adjustment

Ground Control Points (GCPs) are points with known spatial coordinates marked on the ground. These points are measured precisely by terrestrial survey methods such as GNSS or TS. GCPs are used for image georeferencing, which includes scale calculation, orientation, and transforming positions to a desired coordinate system. GCPs are essential elements for the aerial triangulation process, so they must be well placed and accurately measured on the ground. Two types of GCPs can be used. If there are existing identifiable

features on the ground, such as manholes, sewer grills, or parking strips, they can be used as GCPs. For the areas with no existing identifiable features, GCPs should be pre-marked on the ground and signalized in a way to be visible on images (see Figure 3.11) and homogeneously distributed in the area of interest. Ground measurements can be performed before or after the flight.

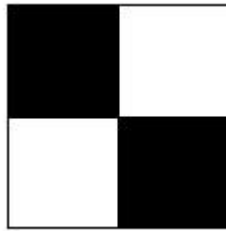


Figure 3.11. *An example of pre-marked ground control point.*

Ground control points can serve as adjustment points or as checkpoints (CPs) for accuracy validation of the final product. GCPs are usually marked on a flat surface and evenly distributed within the study area to be visible in at least two images. The number and location of GCPs used to scale a photogrammetric model have a significant impact on the mean error and error distribution within the model (Agüera-Vega et al., 2016; Greenwood et al., 2019). The number of GCPs depends on the area extent and terrain height difference; the greater the variation, the higher the number of GCPs are required to increase the absolute accuracy. However, using a higher number of GCPs (i.e., more than 10) in small areas does not significantly contribute to higher accuracy; practically, 5 to 10 GCPs are sufficient (Gerke & Przybilla, 2016; Pix4D, 2017; T. Tonkin & Midgley, 2016). Acquired images can be georeferenced directly during the flight or during data processing. If a UAV is equipped with a GPS receiver, this allows images to be directly georeferenced. Using a UAS equipped with a GNSS RTK receiver, the camera positions are calculated in real-time and images are directly georeferenced, which there is no need for GCPs (See Section 2.3.3). However, if the data-link connection with the base station is interrupted, the real-time corrections for camera positions will also be affected. The signal interruption will lead to uncertainties that can be improved by using GCPs. Even if the UAV is equipped with a non-RTK ordinary GPS receiver, this will capture georeferenced images with enough metric accuracy to adjust the image bundles and produce maps for emergency response (Nex & Remondino, 2014). If the navigation positioning system is not available, or the metric accuracy of the system is not sufficient

for the intended survey purpose, ground control points (GCPs) are required for georeferencing and scaling.

For validating the processing accuracy, checkpoints with known 3D coordinates are used in the process of defining GCPs. When GCPs are defined as CPs, they are not included in the computation of bundle block adjustments, but the software uses these points to find the difference between the coordinates of the interpolated surface and the actual points to determine the accuracy of the adjustment.

After completion of the ground control survey and image acquisition, the aerial triangulation process can be started. Aerial triangulation is based on accurate mathematical models on the basis of least square, which is performed on a photogrammetric block. Within this process, the position and orientation of each image are determined. Interior orientation, exterior orientation, relative orientation, and absolute orientation are the concepts that are included in the process of aerial triangulation. In the procedure with known internal and external orientation information, a reliable set of image matches (tie-points) are extracted using stereophotogrammetry techniques, which these match points are the key input for bundle adjustment. Recently, powerful SfM-based photogrammetric software packages (e.g., Agisoft PhotoScan, Pix4Dmapper, PhotoModeler, etc.) have been developed that the process of calibration and image orientation is achieved automatically. SfM-based software packages allow extracting tie points from a sequence of two-dimensional images.

In the bundle adjustment process, which is based on non-linear least-squares minimization, at least three GCPs are required; these GCPs are treated as weighted observations in the least-square minimization (Nex & Remondino, 2014; Wolf et al., 2014). The least-square minimization approach reduces possible deformations and systematic errors of the image block, which leads to the correct estimation of 3D structures (Nex & Remondino, 2014).

Georeferencing is one of the essential processes in the photogrammetric image processing. For the production of georeferenced maps using a photogrammetric mathematical model, following information are crucial: the exterior orientation parameters of each image, the interior geometry parameters of the camera, the size of the CCD array (number of pixels), the physical size of the CCD (usually in microns), and ground control points. The position and orientation of photographs in the object space are defined by exterior orientation. The six parameters of exterior orientation are the exposure

station position (X , Y , and Z) and angular orientation (Ω [ω], Φ [ϕ], and $\Kappa$ [κ]). The ω , ϕ , and κ are the rotational angles around the X , Y , and Z axes, respectively, which are equivalent to roll, pitch, and yaw of the navigation system (see Figure 3.12). All parameters are calculated through space resection during the aerial triangulation process (Wolf et al., 2014). Space resection is calculated using collinearity equations (3.19) & (3.20). The camera position is determined by the intersection of rays in space, which this process is called space resection. Collinearity, as shown in Figure 3.13, is the state in which each photograph's exposure station, an object point, and its photographic image are all along a straight line. In Figure 3.13b, the image coordinate system is rotated so that to be in parallel to the object space coordinate system. The equations expressing this condition are called the collinearity condition equations.

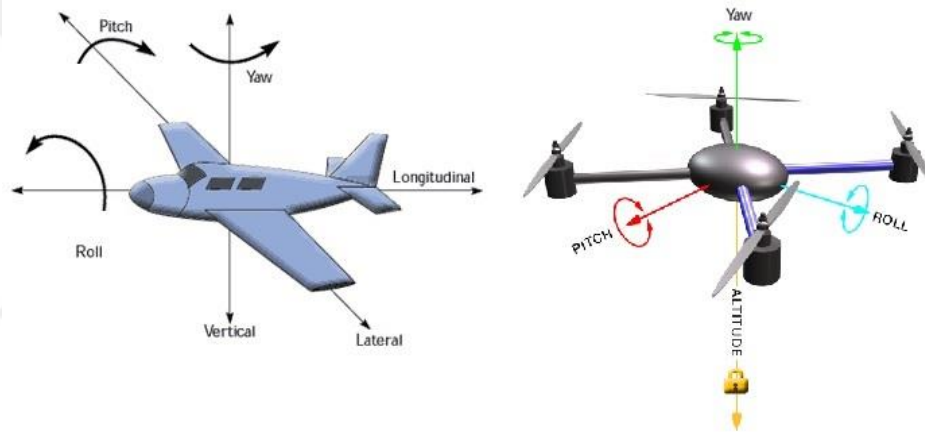


Figure 3.12. Rotational angles in fixed-wing and rotary-wing aircraft (www.novatel.com; www.arducopter.co.uk).

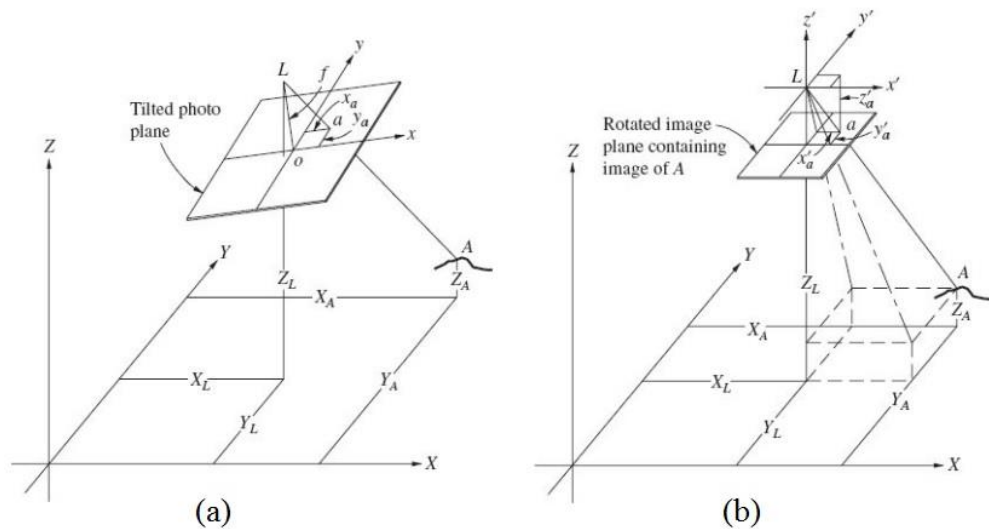


Figure 3.13. (a) collinearity condition, and (b) rotated image coordinate system (Wolf et al., 2014).

$$x_a = x_0 - f \left[\frac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)} \right] \quad (3.19)$$

$$y_a = y_0 - f \left[\frac{m_{21}(Y_A - Y_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(Y_A - Y_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)} \right] \quad (3.20)$$

where x_a and y_a are the measured image coordinates of point a ; x_0 and y_0 are the coordinates of the principal point; f is the focal length of the camera; $m_{11}, m_{12}, \dots, m_{33}$ are elements of rotation angles (omega, phi, and kappa); X_A, Y_A , and Z_A are the coordinates of point A in object space; and, X_L, Y_L , and Z_L are the coordinates of the exposure station in object space. Since the above equations are nonlinear, they are linearized by applying the first-order Taylor series conditions at a set of initial approximations. A detailed explanation of space resection and collinearity equation can be found in the book *Elements of Photogrammetry with Applications in GIS* (Wolf et al., 2014).

Most mapping UAVs are equipped with GNSS, which is used for the navigation of aircraft and relative orientation of images. The presence of GNSS in the aircraft leads to efficient aerial triangulation and reduces the number of required ground control points for absolute georeferencing. However, most non-RTK GPS and IMUs used in small UAS are not sufficiently accurate to replace aerial triangulation. Absolute orientation is performed using ground control points with known coordinates. Once the process of aerial triangulation is successfully completed, the digital elevation model and orthoimage can be produced.

3.2.5. Photogrammetric mapping products

Although the imagery acquired by UAS can be used in various areas and have different applications in remote sensing, this section will focus on two major mapping products, which are digital elevation models (DEMs) and orthoimages. Mapping or spatial data collection methods are generally categorized into two categories planimetric and topographic. The planimetric method is used when only the horizontal position of features is required in a planar coordinate system based on a selected map projection. While the topographic method not only provides the position of planimetric detail but also includes elevation information. Recently DEMs and orthoimages, which are provided in digital formats, are usually used in combination as an alternative to traditional

topographic and planimetric maps. Digital maps are often used in GIS and CAD applications for design and analysis purposes. Multiple images are used to generate digital elevation models. Using photogrammetric software and image matching techniques, fine quality DEMs can be generated from UAS imagery. Terrain modeling and digital elevation models are described in detail in Section 3.3.

An orthoimage is an aerial image that is geometrically corrected from terrain relief and sensor tilt effects through the differential rectification process to convert it to a unified scale map (Wolf et al., 2014). Orthorectification is performed on aerial images to show the image features in their true orthographic positions. Different designations such as orthophoto, orthomap, digital ortho, as well as orthomosaic (combined orthoimages) are seen in the literature. The only difference between a map and an orthoimage is that symbols and lines are utilized in maps to plot features to scale, whereas an orthoimage is a planimetrically corrected image of features composed of pixels. Orthoimages can be used the same as maps for two-dimensional measurements such as distances, angles, areas, and positions. Digital orthophotos are more detailed than planimetric maps; thus, they are widely used in geographic information systems analyses as a valuable source of information. Various information layers can be generated for databases using orthoimages. Orthoimages are generated from perspective aerial images through differential rectification process, which the process is described in detail by Wolf et al. (2014). The differential rectification process is performed by software using a DEM and a digital aerial image with known exterior orientation parameters. The scale of images taken from a UAS over a terrain varies at different locations of the image; the orthorectification process on raw digital images eliminates the image distortions and scale variations resulting from sensor distortion, camera tilt, and terrain relief. The software applies the collinearity equation repeatedly for each point in the DEM array to create the digital orthophoto (see Figure 3.14).

The DEM or other topographic dataset used in the process must fully represent features on the ground surface. Usually, the digital surface model created from photogrammetric point clouds is used in the process. Figure 3.15 illustrates the production process of digital orthophoto, and Figure 3.16 shows true orthoimage versus unrectified aerial image.

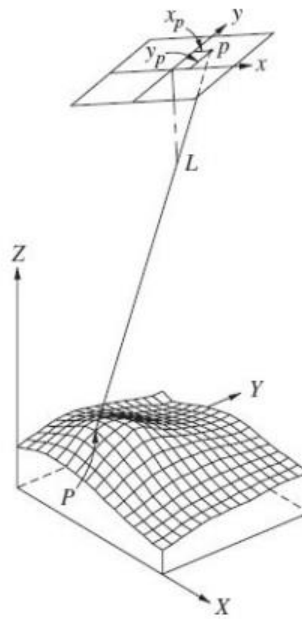


Figure 3.14. Collinearity relationship for the point P on image and its corresponding point on a DEM (Wolf et al., 2014).

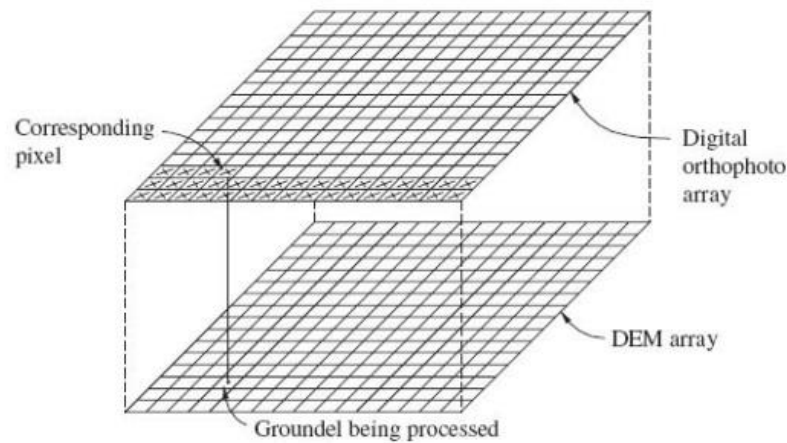


Figure 3.15. Schematic illustration of digital orthophoto production process (Wolf et al., 2014).

After the ortho-rectification process, the quality of orthoimage should be evaluated because some problems in the images and DEM may cause defects. Common causes of defects are as follows: if images are not entirely covered by DEM, this will cause an imperfect image. Spike error or anomalies in DEM may cause image smearing. Inaccurate DEM, and erroneous camera position and orientation cause image missing, double image, and mismatching on adjoining orthomosaics.



Figure 3.16. (a) raw aerial image and (b) rectified orthoimage.

3.3. Terrain Modeling and Data Acquisition Techniques

For computer-based modeling of three-dimensional structures and quantifying terrain variability, topographic information is usually needed in digital format. Digital elevation models are the primary database for topography-related analysis, such as engineering planning, infrastructure design, risk assessment, hazard monitoring, agricultural management, and natural resources exploration. Today, with the advancement in technology, it is possible to use maps produced by photogrammetric methods from the preliminary planning of a large project such as a highway or transmission line to the design and construction operations. Satellite stereo images can be used to provide small scale maps; highly detailed digital topographic maps can be obtained using UAS photogrammetry or UAS LiDAR (Ajayi et al., 2017; Carrivick et al., 2016).

A Digital Elevation Model (DEM) is a three-dimensional representation of surface elevations in a region that can be represented as a raster grid, vector-based triangulated irregular network (TIN), or contours (Li et al., 2004; Wolf et al., 2014). Typically, the terms DEM, DTM, and DSM are used to refer to different types of continuous 3D data, which are often defined as raster images in which the pixel values represent elevations (Ajayi et al., 2017; Li et al., 2004).

The term Digital Terrain Model (DTM) is usually used when the elevations refer to the earth's terrain (bare ground surface) without considering objects such as buildings and trees. A DTM is an approximation of the continuous terrain surface by a series of discrete

points with unique elevation values that are interpolated using mathematical functions to represent the surface (Hirt, 2014; Li et al., 2004). DTMs can be represented in different mathematical forms, such as in matrix forms, Fourier series and polynomials, contour lines, triangulated irregular networks, and regular or irregular grid 2D raster formats (Li et al., 2004). The feature that distinguishes a DTM from a simple DEM is that a DTM can be augmented with 3D lines called breaklines to show abrupt changes in terrain.

The term Digital Surface Model (DSM), also known as reflective surface, refers to surface elevations, including all objects on or above the terrain such as trees, buildings, and other features. DSMs can be generated from LiDAR data or from the photogrammetric process called image auto-correlation (Wolf et al., 2014). DEM is generally used as a generic term for both DSMs and DTMs (Li et al., 2004). Triangulated Irregular Network (TIN) is a digital network of adjacent triangles used to model terrain using horizontal coordinates and vertical elevations.

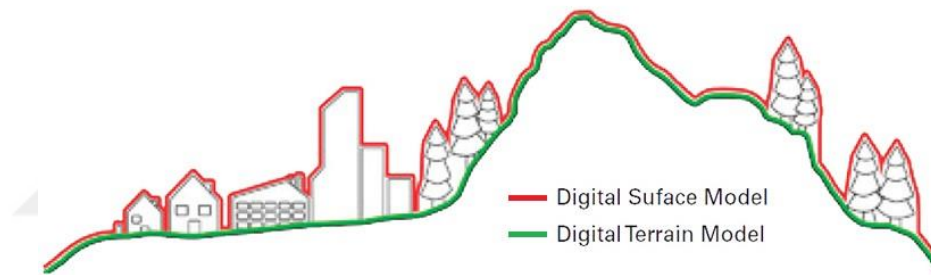


Figure 3.17. DSM and DTM (www.geoimage.com.au)

In a regular grid DEM, elevations (Z values) are digitally stored in an array of cells. DEMs are used in various computer processing algorithms such as volume calculations, contour generation, orthophoto generation, slope and aspect calculation, and other three-dimensional representations. Digital elevation models have a variety of applications in the fields which require terrain analysis. The most common applications are in the following fields: geodesy and geomatics, GIS, base mapping, engineering and design, geology and geomorphology, hydrology, seismology and risk assessment, geography, archaeology, precision agriculture and forestry, telecommunication, aviation, etc.

Digital elevation models can be generated at different scales and accuracy using either terrestrial or remote sensing surveying techniques. Ground-based methods using a range of surveying instruments such as GNSS, TS, and TLS are effective techniques for creating high accuracy DEMs. Different terrestrial surveying techniques such as

traversing, geometric, trigonometric, and tacheometric surveying are used in topographic mapping. In point-based survey methods, professional surveyors with good geomorphologic knowledge determine where to be measured to get accurate interpolation. Field surveying methods give excellent accuracy, but for larger areas can be costly and time taking process. Using direct survey methods, usually terrain surface is represented by TIN and contour lines. In most of the computational analysis (such as map overlay) continues grid data is required; therefore, interpolation methods are used to convert a TIN to a grid DEM; the common GIS-based interpolation methods are inverse distance weighting, nearest neighbor, Kriging, surface splines, and moving least squares (Li et al., 2004; Wolf et al., 2014).

Today, using remote sensing techniques by taking advantage of aircraft and satellites, obtaining DEM of large areas has become much easier. Using airborne and spaceborne remote digital surveying methods, elevation information of inaccessible and risky areas can be provided, while providing DEM of such areas using ground-based methods can be challenging. Remote sensing methods for obtaining elevation data are lidar, radar, stereophotogrammetry and UAS-based structure from motion.

Bangen et al. (2014) carried out an intercomparison of DEMs of a bare earth topography created using different high precision conventional survey technologies, namely TS, RTK GPS, TLS, and ALS. Using these instruments, complete replicate surveys were conducted at each site, and as a result of pairwise comparison, mean discrepancies between RTK GPS and TS DEMs were reported ≤ 0.05 m, while RTK GPS survey was about 2.4 times faster than TS. In their study, ALS method provided lower accuracy than TS and RTK GPS, but ALS exceeded all other methods in terms of data coverage; the accuracy of DEM created from TLS data were lower than ALS because of misinterpretation of vegetation returns as ground returns. In summary, they indicated that every single method has its strengths and weaknesses, so in topographic surveys of complicated sites, it is recommended to use a hybrid technique. Following sections provide a brief description of conventional surveying techniques for acquiring topographic data.

3.3.1.1. Total station surveying

A total station is in fact, an electronic-optical theodolite integrated with electronic distance meter (EDM), microprocessor, and storage system. TS is used in modern digital

surveying and construction for measuring slope distances, horizontal and vertical angles, and in the setting out of features such as buildings and roads. Using this instrument high-precision 3D position of single points can be determined. In topographic surveying, TS is very effective where fewer points are required. Using TS for an accurate representation of topography usually, break-lines are surveyed to show slope breaks. In enclosed areas and some circumstances where sky view is limited such as narrow valleys, the use of TS is inescapable. Integration of DGNSS and TS gives maps in real-world coordinates. Topographic surveying using a standard TS requires at least two operators (a professional surveyor and an assistant) to perform the operations.

Recently, robotic total stations (RTS) have been developed that allow remote operations. RTS is designed to reduce the number of survey staff members and speed up the acquisition. RTS is an instrument that automatically aims, searches, and tracks the reflector targets at high precision (Roberts & Boorer, 2016). In total station surveying, it is possible to acquire data at a rate of hundreds of points per hour. However, RTS can increase productivity, but providing high accuracy digital elevation models of large areas using physical surveying is very expensive and extremely time-consuming. Additionally, since in terrestrial surveying, each point of interest is determined by the surveyor, survey design is influenced by subjectivity (Bangen et al., 2014). The following figure shows a digital contour model and terrestrial instruments (TLS, TS, and GNSS).

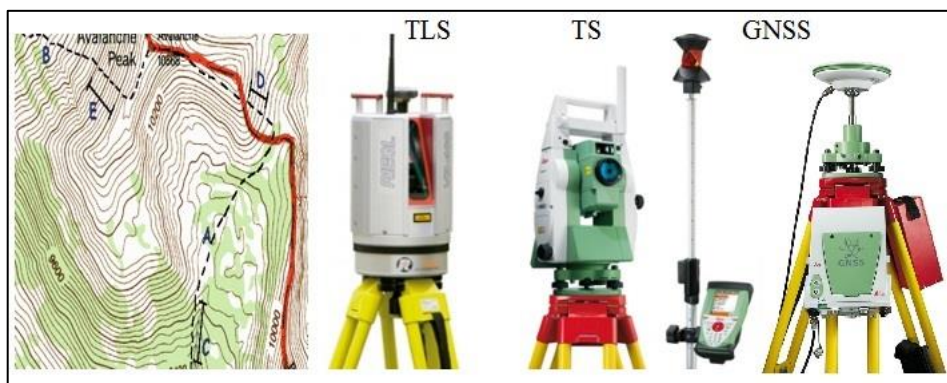


Figure 3.18. An example of digital contour map and ground-based surveying instruments (www.leica-geosystems.com; www.riegl.com).

3.3.1.2. Differential GNSS surveying

Global positioning system (GPS) is a satellite-based radio-navigation system designed and developed by the United States. The system provides a real-world geographic location (geolocation) of an object and time information to a GPS receiver.

GPS can provide geolocation when there is an unobstructed line of sight to at least four GPS satellites. Since the 1990s, the global positioning system (GPS) has been used for surveying and mapping (Rizos, 2007). Differential GPS (DGPS) is basically enhancements to the GPS which makes use of two receivers and provides improvements (positional corrections) to GPS signals by eliminating pseudorange errors using a network of fixed, known ground-based reference stations (Awange, 2012). Differential GPS can provide centimeter-level accuracy using post processing or real-time methods. Initially, GPS was mainly employed in surveying and mapping to provide control points for triangulation-based survey networks. Since the mid-1990s, by expanding the DGPS network, it has been used not only for providing control points but also as a surveying method (Rizos, 2007).

The selective availability (SA) program (discontinued in May 2000) which could degrade the signal quality for non-military users, forced some other countries to develop their own navigational satellite systems. The term Global Navigation Satellite System (GNSS) is used to describe a group of global satellite systems that transmit signals containing positioning and timing data for navigational purposes to GNSS receivers on Earth. GNSS include Russia's GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistema - Global Navigation Satellite System) which is currently fully operational, China's BeiDou Navigation Satellite System, and Europe's Galileo which two latter are not currently fully operational. The term (DGNSS) is used to refer to improved GNSS used in high-accuracy positioning.

Recently, RTK positioning technique is widely used in surveying and mapping. RTK provides high accuracy geolocation in real-time based on GNSS measurements. RTK uses a rover GNSS receiver and a fixed base station to reduce errors. The rover receiver can be mounted on a survey pole or on the surveyor's back. The base station transmits its observation corrections to a rover receiver using a radio or mobile telephone. For increasing the accuracy of RTK positioning and more efficient real-time survey, a network of reference stations is used (Rizos, 2007; Rydlund Jr & Densmore, 2012). This geodetic network is called Continuously Operating Reference Station (CORS) which usually broadcasts corrections over an internet connection. For a cm-level accuracy in rapid surveying, the distance to the reference station should not be more than ten or so kilometers (Rizos, 2007). However, there are other methods of post-processing that allow the use of farther reference stations.

Surveying using GNSS with dual-frequency capability is a rapid and accurate method that provides real-time data with centimeter to even sub-centimeter accuracy and high productivity. Unlike TS technique, GNSS surveying is not limited by constraints such as line of sight. When the sky view is clear and uninterrupted, DGNSS surveying can provide thousands of points per hour of measurement; and DEM can be created by interpolation of survey data (Bangen et al., 2014; Carrivick et al., 2016).

3.3.1.3. Remote digital surveying

Remote digital surveying which includes digital photogrammetry and laser scanning, is the latest automation and advancement in surveying engineering (Ajayi et al., 2017; Carrivick et al., 2016; Li et al., 2004). Photogrammetric and laser scanning methods have remarkably increased point acquisition rate. These techniques produce high density (high-resolution) 3D point clouds with extensive spatial coverage. Photogrammetry uses aerial and satellite images to produce DEMs and orthomosaics. In satellite stereoscopic photogrammetry, images of satellite passes (different view angles) are combined to get effective stereo view. In traditional photogrammetry there are manual and automatic processing methods. Recently, UAVs equipped with digital cameras are widely used to acquire images from low altitudes and produce DEMs by using advanced SfM image processing software packages. Providing high details, speed, objectivity, and data collection from inaccessible areas are the advantages of surveying based on remote sensing. However, non-RTK RS methods are extremely dependent on GCPs for georeferencing. Lidar and Radar surveying are briefly described in the following paragraphs.

RADAR:

Radio Detection and Ranging (RADAR) is also a method of elevation data collection using radio waves. Spaceborne Stereo-Radar and Radar Interferometry are commonly used satellite methods. Stereo-radar works the same as stereophotogrammetry but uses radar wave instead of photographic cameras, which can penetrate vegetation canopy. In radargrammetry, DTM data is provided through parallax measurement. RADAR is very effective due to the fact that it can penetrate through clouds and can obtain surface information in any weather conditions (Li et al., 2004). By utilizing side-looking airborne radar (SLAR), stereo radar mapping can be performed using either

aircraft or satellite. Synthetic Aperture Radar (SAR), acquires images with high sensitivity to terrain variations. SAR uses phase difference in two radar signals for measuring elevation differences; since signals are from two receivers, it is called synthetic aperture radar. Interferometric Synthetic Aperture Radar (InSAR) is a geodetic method with millimeter-scale accuracy that uses two or more SAR images of an area for identification of the Earth's surface movements through the phase shifts determination between two echoes (Li et al., 2004). Figure 3.19 illustrates SAR data acquisition.

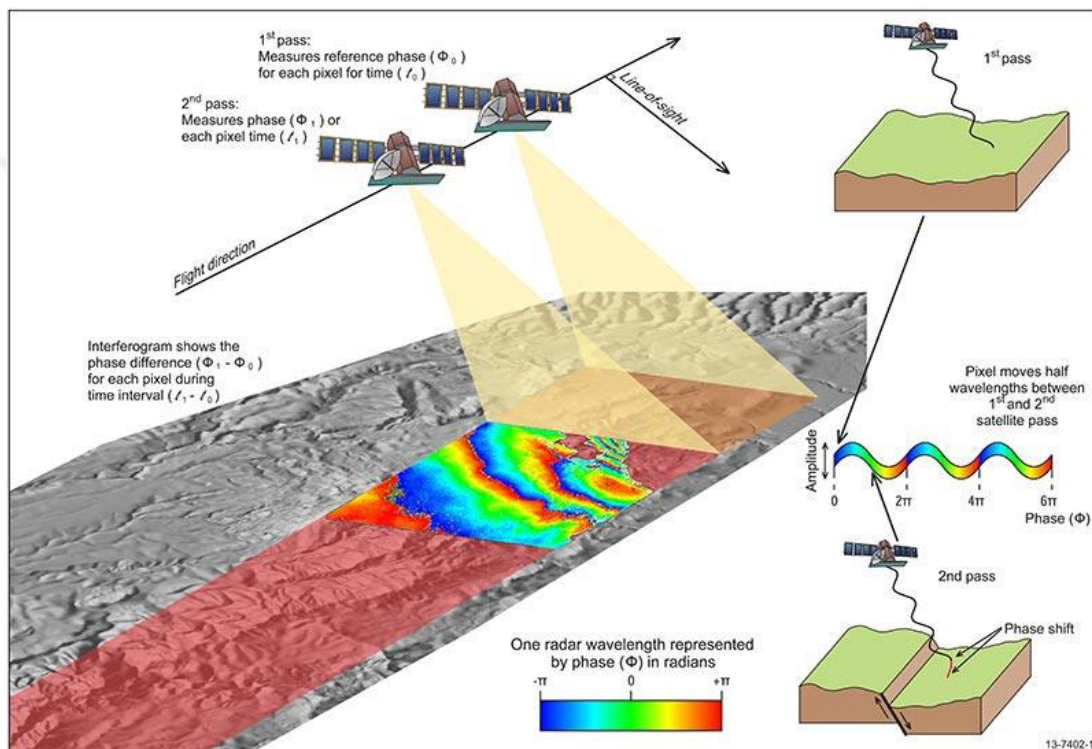


Figure 3.19. SAR image acquisition by two satellites at different times
Source: Geoscience Australia (www.ga.gov.au/scientific-topics).

LiDAR:

Light Detection and Ranging (LiDAR) is a surveying method for 3D mapping which uses a laser scanner sensor for measuring targets using pulsed laser lights. Lidar can be airborne, spaceborne, or terrestrial. Laser scanning has created a significant change in modern surveying. Laser scanners can acquire millions of points per hour by emitting thousands of laser pulses per second and measuring the time delay of reflected pulses (Gallay, 2013; Mark W. Smith, 2016). Lidar allows rapid construction of high-resolution full 3D surface models using point clouds. Unlike the photogrammetry method, the laser scanning as an active remote sensing technique is independent of daytime, weather, and

texture diversity of landcover which enables reliable terrain 3D reconstruction for all land cover including water, snow, and sand (Gallay, 2013). Some of the advantages of this method are the capability of measuring shallow water depth (< 2 meters) with decimeter accuracy (Greenwood et al., 2019; Mitchell, Thayer, & Hayman, 2010), vegetation canopy height as well as ground elevation, extensive area coverage, and data fusion with color-camera to produce colored point clouds. Point cloud is used for further analysis, classification, interpolation, and generation of DEM. Lidar is often mounted inside an aircraft for collecting data to produce high-resolution 3D maps with the exact size and shape of objects (see Figure 3.20).

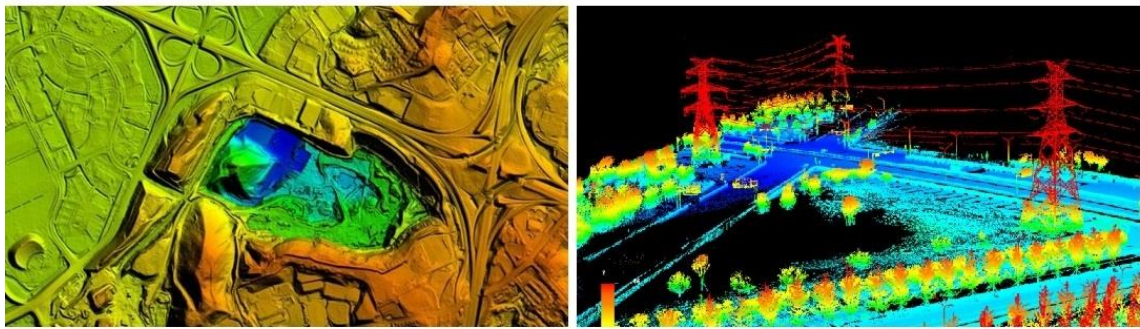


Figure 3.20. Examples of laser scanning point cloud and elevation models (www.pinterest.co.uk; www.adacq.com).

Airborne laser scanning:

Airborne laser scanning integrates laser scanner with DGNS and inertial measurement unit (IMU) for positioning and orientation, which the data accuracy largely depends on these systems. Besides, other factors such as flight height, atmospheric conditions, object reflectance, slope, and vegetation cover density can affect ALS data accuracy (Gallay, 2013). Studies have revealed that horizontal accuracy of ALS elevation models to be between 0.1 and 0.5 m and the vertical accuracy between 0.1 and 0.15 m (Carrivick et al., 2016; Gallay, 2013; Li et al., 2004).

The full waveform feature of some laser scanners that digitize the complete returned pulse gives more options and control to the user in the analysis and interpretation process. The significant advantage of ALS over other remote sensing methods is in the ability to penetrate through sparse vegetation canopy enabling to reconstruct the digital terrain model of bare earth under the canopy (Gallay, 2013). Using ALS, vegetation height and bare ground elevation can be determined simultaneously. Laser scanners with the ability to scan in the green wavelength penetrate through water, and infrared pulses

reflect from the water surface; differential timing of these laser pulses permits bathymetric survey of shallow and clear water.

Terrestrial Laser Scanning:

Terrestrial Laser Scanning which is also known as t-LiDAR, is the ground-based application of LiDAR technology adopted for rapid topographic and other 3D surveys (Mark W. Smith, 2016). The basic principles are the same as those applied in airborne laser scanning systems. However, due to shorter survey ranges, the density of point cloud data in TLS is several times greater than that of ALS, and survey accuracy is much higher (Mark W. Smith, 2016; X. Zhou et al., 2017). The survey range in TLS varies from a few meters to thousand meters, and the precision is optimized at a specific range because the laser beam scatters with increasing distance from the instrument. In addition, most of laser scanners are integrated with a camera to provide RGB color values to each point.

TLS offers high-resolution full 3D data at an unprecedented speed that cannot be provided by ALS, TS or DGPS (Bangen et al., 2014; Mark W. Smith, 2016). However, during the interpretation and analysis, the misleading errors and the size of the laser footprint at long ranges should be considered (Mark W. Smith, 2016). Although the TLS method is currently being used as the most reliable method in highly detailed topographic surveys, this method is not the perfect solution because limitations such as cost, weight, line of sight, and logistics remain a problem. While recent advancements in photogrammetry, particularly the structure from motion method has overcome these constraints. Moreover, the amount of data collected with TLS or ALS for a specific area can be excessive for processing with a conventional computer, particularly with full waveform scanning, data volume may increase tens of times compared to the single return technique (Gallay, 2013).

4. METHODS

This chapter outlines the research methods adopted in this thesis and presents a practical approach to achieve the study objectives. For clarification purposes, the methods are presented in three main processes: project planning and data acquisition, SfM photogrammetry-based image processing, and accuracy assessment. Figure 4.1 illustrates the overall workflow of the methods adopted in this study. Section 4.1 is dedicated to project planning and data acquisition. In this section, project planning and issues related to field data acquisition are addressed, the area of interest is briefly outlined, justifications for the selected study site and instrumentation are presented, and field surveys focusing on UAS data acquisition are described. The objective of Section 4.2 is to generate 3D dense point cloud, 3D triangulated mesh surface, DSM, and orthomosaic from vertical and oblique UAS images using three different software packages (Agisoft PhotoScan, Pix4Dmapper, and 3Dsurvey). Different photogrammetric computer applications were used to examine their performance and the influence of processing software on the accuracy of the final products. In this section, a detailed description of the SfM-MVS workflow and generation of models are given. Section 4.2 also discusses DTM generation using automatic and semi-automatic algorithms provided in the utilized photogrammetric software packages. Finally, section 4.3 analyzes and evaluates the accuracy of SfM-MVS products generated from images of various flight heights and GCP numbers.

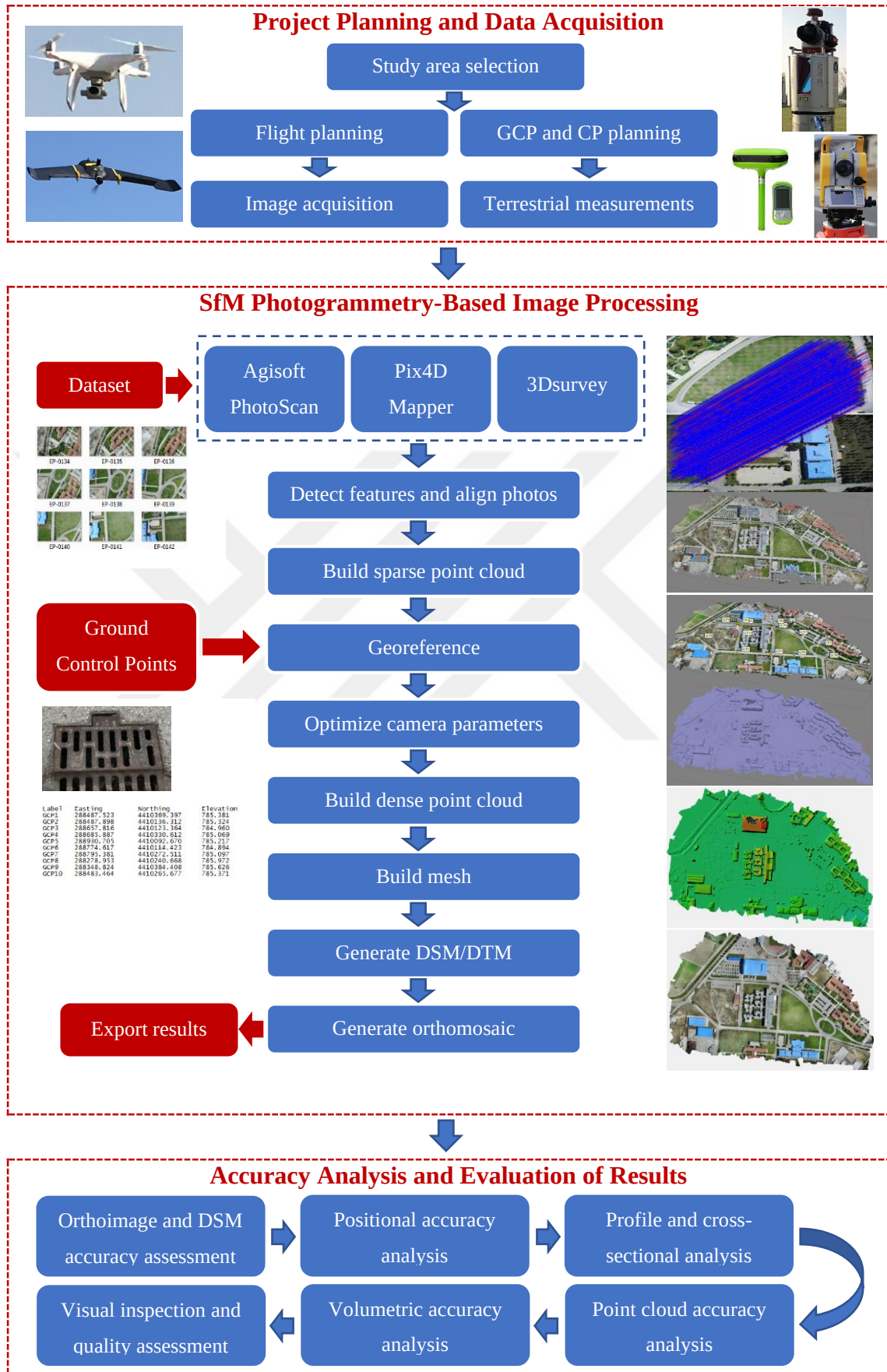


Figure 4.1. Workflow of the methods used in this research

4.1. Project Planning and Data Acquisition

Project planning is the first and most important step in photogrammetric projects to be carried out extensively. In a particular photogrammetric project, various products can be developed, the final decision on the selection of products, scale, and accuracy is made according to the project requirements. In this research, the study area comprises part of the campus of Eskisehir Technical University, where a building and a road section were selected to be surveyed by UAS and TLS for 3D modeling, volumetric analysis, and profile and cross-sectional analysis. Ground control points (GCPs) and checkpoints (CPs) were decided to be measured using RTK GNSS. In order to achieve the aim of the research, two types of aerial image acquisition plans were designed: vertical and oblique. For aerial mapping of the entire study site, two nadir image acquisition plans were designed to be surveyed using senseFly fixed-wing UAS at average flight heights of 100 and 170 m AGL, and 75% frontal and 65% side overlaps to achieve 2.5 cm and 4.0 cm GSDs. To obtain 3D models of the selected building with a spatial resolution of 0.5 cm, the oblique image acquisition plan was adopted to acquire images of the building using DJI Phantom 4 Pro at an average flight height of 16 m and approximately 80% overlaps.

According to the new ASPRS standard (2014), the GSD of the source imagery should be two times higher or at least equal to the required accuracy. Based on ASPRS RMSE accuracy metric, for planimetric works, an accuracy of $1 \times \text{GSD}$ is recommended that can be used in the highest accuracy works, $2 \times \text{GSD}$ is suitable for standard mapping and GIS tasks, and $3 \times \text{GSD}$ and greater is not recommended for measurements, but can be used for visualization and less accurate estimations. The vertical accuracy (non-vegetated) for Class 1 is 1 cm, for Class 2 is 2.5 cm, and for classes 3 and 4 are 5 and 10 cm, respectively. A fixed-wing UAS covers larger areas by flying at higher altitudes, and higher overlaps can be achieved, which considerably reduces the processing time. Considering this issue, 2.5 cm and 4 cm GSD were selected for vertical aerial surveys. Detailed justification for GSD selection and image overlaps is presented in Section 2.4. Theoretical details regarding project planning and data acquisition are discussed in Section 3.2.3.

4.1.1. Study area

Eskisehir Technical University İki Eylül campus was selected as the study area (see Figure 4.2). The campus is located at $39^\circ 48' 57.4''$ latitude and $30^\circ 31' 55.4''$ longitude

in Tepebasi district of Eskisehir, Turkey. The study area covers approximately 35 hectares of the campus, which comprises buildings of various heights, parking lots, roads, and vegetation. The purpose of adopting the campus as the study area was the presence of vegetated and non-vegetated land cover, as well as the ease of obtaining licenses for conducting several close-range flights. The existence of different land cover was essential for achieving the aim of the study. Another determinant was the existence of a building for volumetric and 3D modeling comparisons between UAS-SfM and TLS. Since the purpose of this study was to quantify and evaluate the accuracy of UAS-based mapping and 3D modeling by comparing them to ground-based survey data, the requirements were met in this study area.

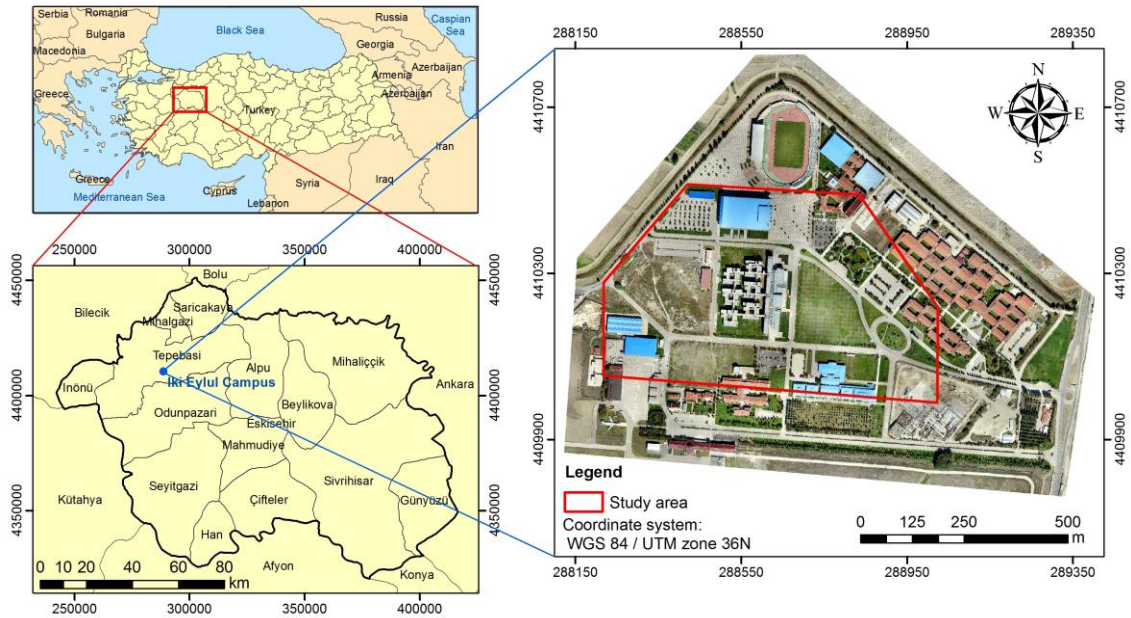


Figure 4.2. Study area

4.1.2. Equipment and software

In this section, the equipment and software packages used in this study are briefly described.

4.1.2.1. SenseFly eBee Plus UAS characteristics

SenseFly eBee Plus fixed-wing UAS is a photogrammetric autonomous mapping system that has a large area coverage featuring RTK/PPK upgradeability. This drone, made of carbon-expanded polypropylene foam and some composite components, is designed for survey-grade photogrammetric mapping. The aircraft weighs 1.1 kg,

including battery and supplied camera, and has a wingspan of 110 cm. The UAV flies by forwarding thrust using a vertically rotating electric propeller, flight speed is between 40-110 km/h, and the maximum flight duration is about one hour. The UAS has an onboard GNSS receiver with optional RTK/PPK functionality that is used for navigation and image geotagging. Images are geotagged with the estimated position of the drone. The information about the approximate 3D position and rotational angles (roll, pitch, and yaw) are provided by the built-in GNSS and inertial measurement unit. SenseFly eBee Plus is controlled using eMotion flight planning software, which is used to interface with the eBee and perform autonomous missions. The ground station software (eMotion 3) provides a full 3D flight environment for photogrammetric mission block flight planning. The supplied payload sensor is a compact high-resolution SODA RGB camera; the system also has the capability to mount light weigh multi-spectral and thermal cameras. The SODA camera is specially developed for UAS photogrammetric works. Figure 4.3 illustrates the eBee UAS equipment during the flight mission. The technical specification of the UAS and the supplied camera are given in Table 4.1.



Figure 4.3. *SenseFly eBee Plus with its ground control system during fieldwork*

Table 4.1. *Technical specifications of SenseFly eBee Plus unmanned aerial system (www.sensefly.com).*

Hardware	Wingspan	110 cm
	Weight (incl. supplied camera & battery)	1.1 kg
	Radio link range	3 km nominal (up to 8 km)
	Supplied camera	senseFly S.O.D.A.
	Optional cameras	Parrot Sequoia, ThermoMAP
Operation	Automatic 3D flight planning	eMotion 3 application
	Cruise speed	40-110 km/h
	Wind resistance	Up to 45 km/h
	Max. flight time	59 minutes
	Max. flight range	45 km
	Launching	Hand launch
	Landing	Automatic, linear with ~5 m accuracy
Possible results	Absolute X, Y, Z accuracy (if RTK/PPK activated or with GCP)	3-5 cm
	Absolute X, Y, Z accuracy (non-RTK mode and without GCP)	1-5 m
	Nominal coverage at 120 m	220 ha
	Max. coverage at 2,000 m	40 km ²
SODA camera	Sensor size	13.2 x 8.8 mm
	Sensor type	RGB (20 megapixel)
	Aperture	F/2.8-11
	Focal length	10.6 mm (35 mm equivalent is 29 mm)
	RGB resolution	5472 x 3648 px (3:2)
	ISO range	125-6400
	Ground resolution at 120 m	2.9 cm/pixel
	RGB shutter	Global shutter

4.1.2.2. DJI Phantom 4 Pro characteristics

DJI Phantom 4 Professional is a low-cost quadrotor made of rigid composite material. The UAV can take off and land vertically, and the flight mission can be performed autonomously or manually. Phantom 4 Pro has a control range of 7 km and a flight duration of approximately 30 minutes. The UAV is equipped with an RGB camera that has 20-megapixel resolution and capable of shooting 4K video at 60 fps. This drone is suitable for close-range oblique photography due to higher control and maneuverability. The technical specification of the UAS and the supplied camera are given in Table 4.2. The system during the flight mission is shown in Figure 4.4.

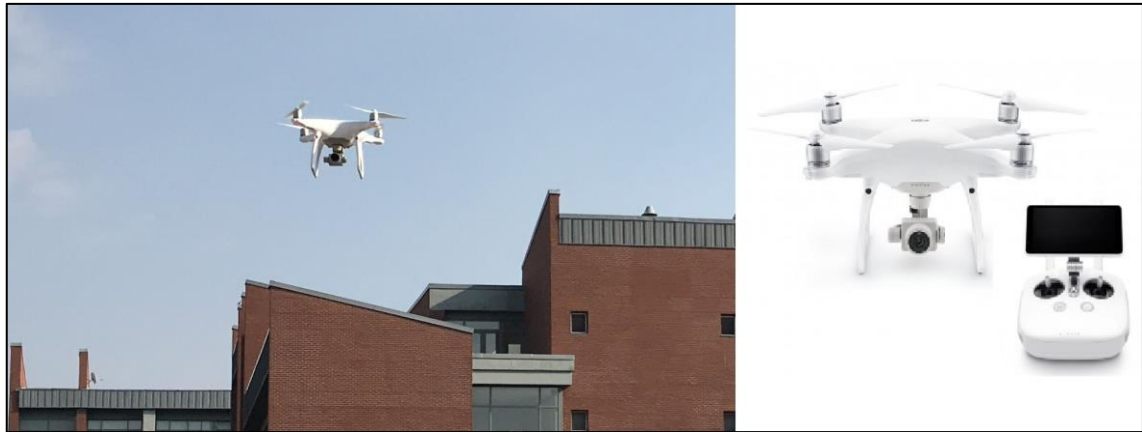


Figure 4.4. *DJI Phantom 4 Pro with its control system during fieldwork*

Table 4.2. *Technical specifications of DJI Phantom 4 Pro (www.dji.com).*

Aircraft	Weight (Battery & Propellers Included)	1.375 kg
	Diagonal size (Excluding Propellers)	350 mm
	Max speed in positioning mode	50 km/h
	Satellite Positioning Systems	GPS/GLONASS
	Maximum flight time	Approximately 30 minutes
	Automatic 3D flight planning	DJI GO 4 application
Camera	Sensor size	13.2 x 8.8 mm
	Sensor type	RGB 20 megapixel
	Aperture	F/2.8-11
	Focal length	8.8 mm (35 mm equivalent is 24 mm)
	RGB resolution	5472 x 3648 px
	RGB shutter	Rolling shutter

For more details about fixed-wing and rotary-wing UAS, their advantages and drawbacks, see Section 3.1.3. Figure 4.5 shows compact cameras used in eBee Plus and Phantom 4 Pro.



Figure 4.5. *SenseFly eBee Plus (left) and DJI Phantom 4 Pro (left) UAS cameras*

4.1.2.3. RIEGL VZ-2000 3D Terrestrial Laser Scanner

Terrestrial Laser Scanner (TLS) is a ground-based light detection and ranging (LiDAR) instrument that provides fully 3D surveys, used for terrain and landscape mapping. TLS transmits pulses of lights and records the returned pulses and the time. The scan mechanism comprises a fast-rotating polygon mirror and a slow rotating optical head. TLS can record thousands of points per second of measurement with relative positioning at mm-cm level accuracy. In addition to position information, it can record attributes such as timestamp, amplitude, reflectance, and RGB color. The integrated imaging system provides an incomparable density of geospatial data through a dense array of 3D vectors to target points relative to the point cloud location. The advantages and disadvantages of TLS are given under section 3.3.

RIEGL VZ-2000 3D TLS provides high speed, remote data acquisition using a narrow infrared laser beam and a fast scanning mechanism. This scanner is capable of performing eye-safe laser measurements up to 2.5 km with 5 mm accuracy. RIEGL VZ-2000 offers different resolutions starting from 2 cm to 14 cm at 100 m distance, where it varies with distance from the object of interest; the point cloud density is much greater closer to the scanner and declines with range. The main features of this TLS are: high laser pulse repetition (up to 1.2 MHz), high speed (up to 500,000 measurements/sec), eye-safe operation at Laser Class 1, wide field of view ($100^{\circ} \times 360^{\circ}$), multiple target capability, fully customizable scan parameters, remote control, onboard inclination sensor, laser plummet, integrated L1 GPS receiver with antenna that provides simultaneous georeferencing in real-time, optional external GNSS receiver, high-resolution Nikon DSLR camera, cloud connectivity via Wi-Fi and 3G/4G LTE, optional waveform data output, and automatic onboard registration. Figure 4.6 shows the RIEGL laser scanner during the field survey.



Figure 4.6. RIEGL VZ-2000 TLS during scanning

4.1.2.4. JAVAD TRIUMPH-1 GNSS and Trimble M3 Total Station

JAVAD TRIUMPH-1 dual-frequency GNSS receiver was used for the RTK measurements of ground control points and checkpoints. It has an internal radio modem, a Bluetooth wireless technology module, a UHF modem, and a GSM/GPRS module. This geodetic instrument that tracks GPS and GLONASS signals simultaneously, in fixed RTK mode has $\pm 1 \text{ cm} + 1 \text{ ppm}$ horizontal and $\pm 1.5 \text{ cm} + 1 \text{ ppm}$ vertical accuracy, as stated in the manufacturer's specifications. RTK DGNSS technique normally provides high positioning, and the best results can be achieved if the distance to the nearest base station is within 10 km. Since the distance from the study area to the base station (CORS) is about 9 km, using RTCM (Radio Technical Commission for Maritime Services) and FKP (Flaechen-Korrektur-Parameter) standards, it is possible to achieve vertical and horizontal accuracy within 2 cm.

Table 4.3. JAVAD TRIUMPH-1 GNSS specifications.

Operating temperature	-40 C° to + 55 C° with batteries
Survey mode (Base or Rover)	Static, Fast Static Kinematic (Stop and Go) RTK DGNSS, SBAS DGPS
Static, Fast Static accuracy	Horizontal: $0.3 \text{ cm} + 0.5 \text{ ppm} * \text{baseline length}$ Vertical: $0.5 \text{ cm} + 0.5 \text{ ppm} * \text{baseline length}$
Kinematic, RTK	Horizontal: $1 \text{ cm} + 1 \text{ ppm} * \text{baseline length}$ Vertical: $1.5 \text{ cm} + 1.5 \text{ ppm} * \text{baseline length}$
Tracking Specifications of standard channels	Total of 216 channels: all-in-view (GPS L1/L2/L2 Galileo E1/E5A, GLONASS L1/L2, SBAS)

A total station (TS) is a widely used electronic/optical instrument for measuring distances, horizontal and vertical angles, and slopes. Trimble M3 TS offers efficient mechanical technology, which the bright color touch screen, and the ergonomic controls make the survey work much more comfortable. The Trimble M3 TS allows us to take reflectorless measurements of inaccessible points such as top of buildings, towers, etc. In this study, Trimble M3 TS was used for validating GNSS RTK and TLS measurement, as well as for measuring the GCPs and CPs for the building. The TS was also used to validate the volumetric calculation results of the TLS point cloud. The technical characteristics of the Trimble M3 is given in Table 4.4. Figure 4.7 illustrates the instruments used for positional measurements for the purpose of georeferencing and accuracy assessment of UAS-SfM products.

Table 4.4. *Technical specifications of Trimble M3.*

Main unit weight without battery	4.1 kg
Telescope field of view	1°30' (2.6 m at 100 m)
Ideal measuring range in prism mode	300-3000 m
Measuring range in reflectorless mode	200 m
Distance measurement precision in prism mode	$\pm (2 + 2 \text{ ppm} \times D) \text{ mm}$ (−10 °C to +40 °C)
Distance measurement precision in reflectorless mode	$\pm (3 + 2 \text{ ppm} \times D) \text{ mm}$ (−10 °C to +40 °C)
DIN18723 angle measurement accuracy	2"/0.6 mgon



Figure 4.7. JAVAD TRIUMPH-1 GNSS (right) and Trimble M3 total station (left).

4.1.2.5. *Software packages*

Software packages used in this study are summarized in the table below.

Table 4.5. *Software packages utilized for data processing and analysis.*

Software	Function
eMotion 3, and DJI GO 4	Flight planning and management
RiSCAN PRO	Registration and processing of TLS scans
Agisoft PhotoScan Professional version 1.4.3	SfM photogrammetric image processing
Pix4Dmapper version 4.3.31	SfM photogrammetric image processing
3Dsurvey version 2.7.0	SfM photogrammetric image processing
AutoCAD Civil 3D 2015	Creating profiles and cross-sections from DSM, and point cloud volumetric calculations
ArcGIS Desktop / ArcMap 10.5	Post processing, accuracy assessment, and map creation
Global Mapper version 20.0	Point cloud and DSM analysis, generating contours.
R Statistics programming language	Statistical computations, accuracy analysis, and plotting graphics

4.1.3. Ground control points and checkpoints measurement

Ground control points are points with known spatial coordinates marked on the ground and measured precisely by conventional survey techniques such as total station or GNSS (see Section 3.2.4). GCPs and CPs were measured accurately using GNSS with differential corrections in real-time kinematic (RTK) mode by connecting to the nearest (approximately 9 km) Continuous Operating Reference Station (CORS). For the GCPs and CPs of vertical surveys with GSD 2.5 and 4.0 cm, the accuracy of RTK DGNSS is sufficient. For the oblique survey of the building, which the GSD is 5 mm, the GCPs and CPs were measured by integration of RTK GNSS and TS with high accuracy (3-5 mm). Since the number and distribution of GCPs have a significant impact on the accuracy of the 3D reconstruction, a great number of articles have examined the influence of the number and distribution of GCPs in the final photogrammetric products, which most of them used a higher number of GCPs. Accurate measurement of the 3D coordinates of GCPs and marking them during the image processing is a time-consuming task, and in difficult terrain, it is not possible to measure a large number of GCPs. At least 3 GCPs are required for scaling and georeferencing; according to the literature, in small areas, 5-15 number of GCPs can provide optimum results (Agüera-Vega et al., 2016; Reshetyuk & Mårtensson, 2016). Hence, in this study, two GCP clusters (5 GCP, and 10 GCP) were used to analyze their influence on the accuracy of DSM, point cloud, and orthomosaic. In order to examine the influence of GCP distribution on the accuracy, or in other words, to find the relationship between the vertical accuracy and the distance to the nearest GCP, the positions of 5 GCPs were selected in a way that some checkpoints are outside the GCP polygon. In order to form a set of 10 GCPs, five additional GCPs were selected to minimize the distance between the checkpoints and the nearest GCPs. Figure 4.8 shows ground control points, checkpoints, and test areas for specific analysis. From GCPs 1-5 were used for the 5 GCP scheme, and for the 10 GCP layout, GCPs from 1-10 were used.

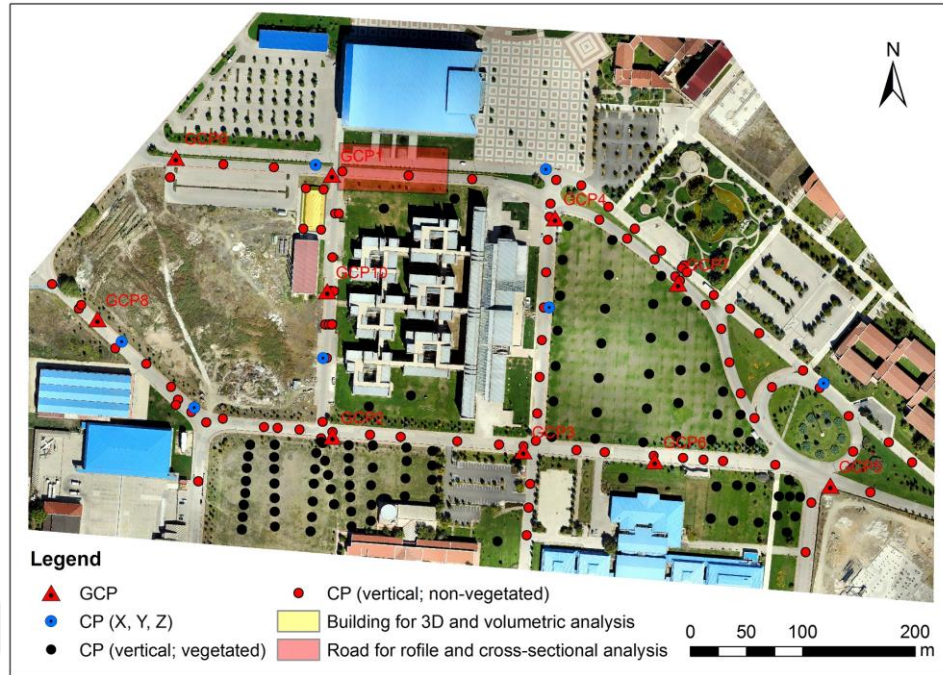


Figure 4.8. Ground control points, checkpoints, and specific assessment areas.

The corners of existing sewer grids (60 x 60 cm) were used as GCPs. Seven CPs were also chosen from the visible features inside and outside of GCP polygon for horizontal and vertical (X, Y, Z) accuracy assessment of orthomosaics and DSMs. A total of 200 CPs were selected without marking in vegetated and non-vegetated areas to assess the vertical accuracy of DSMs and DTMs. Measurements of control points and checkpoints were carried out using JAVAD TRIUMPH-1 GNSS receiver in RTK survey mode. RTK measurements were conducted at 60 epochs for each point with a fixed solution of cm-level accuracy by connecting to the nearest geodetic network station. All measurements were performed in Universal Transverse Mercator (UTM) coordinate system; the World Geodetic System 1984 (WGS 84) reference ellipsoid is the horizontal datum, and as the vertical datum, the Earth Gravitational Model 1996 (EGM96) was selected. The EGM96, which was revised in 2004, has a higher- fidelity geoid model than the WGS 84. A minimum of 6 GPS and 5 GLONASS satellites above 15 degrees in elevation were maintained in all measurements. During the fieldwork, by maintaining a higher number of satellites, PDOP values were in the range of 2.0 to 4.0. The Position Dilution of Precision (PDOP) is a measure of the geometric quality of navigational satellite configuration in the space. Lower PDOP values of 4.0 or less indicate proper satellite geometry, while a PDOP > 7.0 indicates poor satellite geometry. The horizontal and vertical accuracy of all measured GCPs is within 1.5 cm, which was controlled using TS.

Since all checkpoints (except for the building) were measured by RTK GNSS, this accuracy was accepted, and network adjustment was not performed to maintain the relative accuracy between the control points and the checkpoints. Figure 4.9 illustrates RTK and TS field measurements. Coordinates of 10 GCPs and their measurement accuracy are shown in Table 4.6.



Figure 4.9. RTK DGNSS and TS measurements of ground control points.

Table 4.6. Coordinates and accuracy of measured GCPs.

GCP	Easting	Northing	Elevation	Accuracy (m)
GCP1	288487.523	4410369.397	785.381	0.014
GCP2	288487.898	4410136.312	785.324	0.011
GCP3	288657.816	4410123.364	784.96	0.008
GCP4	288685.887	4410330.612	785.069	0.009
GCP5	288930.705	4410092.67	785.217	0.010
GCP6	288774.617	4410114.423	784.894	0.014
GCP7	288795.381	4410272.511	785.097	0.011
GCP8	288278.953	4410240.668	785.972	0.010
GCP9	288348.824	4410384.408	785.626	0.009
GCP10	288483.464	4410265.677	785.371	0.012

4.1.4. Terrestrial laser scanning and data processing

4.1.4.1. TLS data acquisition

The RIEGL VZ-2000 3D laser scanner was used for scanning the selected building and part of the adjacent road to compare with UAS point clouds in 3D modeling and volume calculations. To obtain maximum coverage, the TLS survey was performed from 12 stations (see Figure 4.10), where 10 of them were selected around the building, and the other two points were chosen slightly away from the building to cover the roof as much as possible and also to cover part of the selected road for profile analysis. There was no suitable higher place to scan the rooftop, so there are gaps in point cloud on the two sides of the roof. In order to cover only the test area, the scan range was limited to 500 m. For obtaining true color point cloud, a Nikon DSLR D810 camera was mounted on the top of the scanner, and the image acquisition trigger was set to automatic mode to take full-frame pictures (360°) after finishing each scan. Since the first station was used as the base for registration and adjustment of other stations, the tripod was accurately leveled using the inclination sensor. The building was scanned using three angular scan resolutions, Panorama 20 (0.020°; 4 cm at 100 m distance), 60 (0.060°; 10 cm at 100 m), and 80 (0.080°; 14 cm at 100 m) to compare the scan time, data size, and point cloud density. Since the main scan positions were close to the building, the Panorama 20 pattern, can provide 2-mm point spacing. The utilized TLS presents a 2D view to check the scans during the survey. The data collection took approximately 4 hours. The data size for Panorama patterns 20, 60, and 80 were 17.00, 3.75, and 3.19 GB, respectively. The scan of each position for Panorama patterns 20, 60, and 80, took ~ 210, 90, and 52 seconds, respectively. The main challenge in data acquisition using a laser scanner is to perform measurements while there are no obstacles (such as a person or a vehicle) in the field of view. For this reason, the scan was performed at the weekend to minimize obstructions.

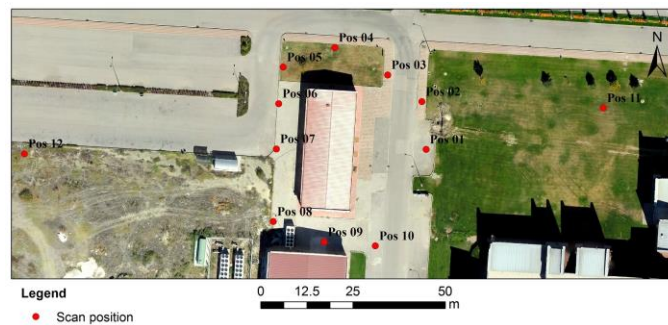


Figure 4.10. Scan positions for building and road survey

4.1.4.2. TLS data processing

RiSCAN Pro 2.5 was used for data downloading, point cloud registration, and cleaning and filtering. Merging separate scans into a single point cloud data is referred to as scan registration, which is the most important part of the TLS workflow. The utilized TLS offers automatic onboard registration, but it is not accurate, so the scan positions need to be accurately registered. There are manual and automatic methods for registering scans in RiSCAN Pro software in which the automatic method often requires user interaction and manual assistance on failure, especially in low-resolution scans. The scan positions can be registered in different ways such as registration using tie points (reflectors used during the scan process), via inclination sensor, by modifying the position and orientation of each scan using graphical adjustment tools (by rotating and translating scans in 3D view), and by coarse registration using tie points. In all the above methods, scan positions are registered pairwise; therefore, there will be some differences between the first and last scan positions. RiSCAN Pro provides a plugin called Multi-Station Adjustment (MSA) to minimize these errors. The MSA improves the registration of the scan positions by applying several iterations to compute the best fit for the scan positions. For accurate registration of scan positions, using MSA function is crucial. Figure 4.11 shows the 12 scans before registration. As the figure shows, the scans are not aligned because the internal GPS is not accurate enough to adjust the scans properly; additionally, the rotation angles (roll, pitch, and yaw) considerably affect the alignment.

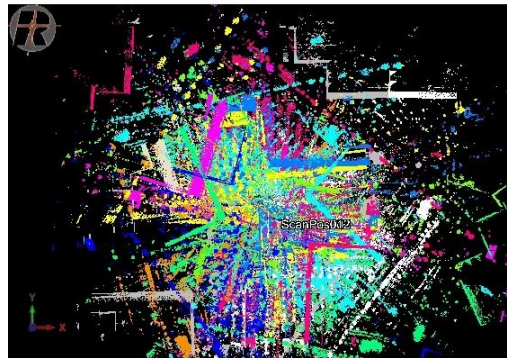


Figure 4.11. Scan positions in single color before registration

In order to register and adjust the scans accurately, the following procedures were undertaken. In the first step, Automatic and coarse registration methods were applied to adjust the scan positions pairwise. Figure 4.12 shows automatic registration inability in

registering the scan position 7 in a lower resolution project, where the scan was registered manually.

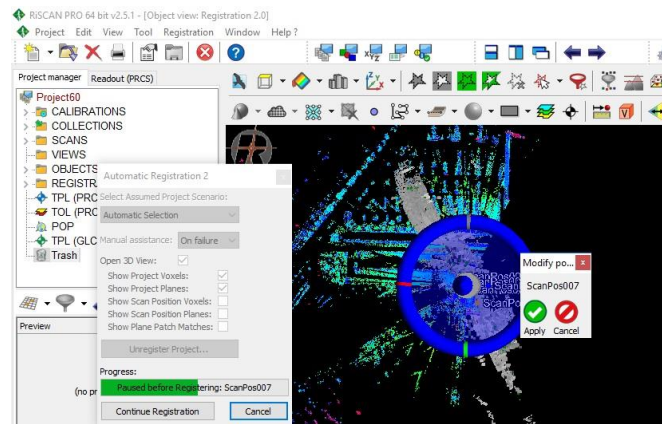


Figure 4.12. Automatic registration failure

Once the scans were approximately adjusted, the multi-station adjustment was performed. In this method, first, polydata were created for each scan position using the plane patch filter algorithm (see Figure 4.13). Plane patch filter is a robust algorithm that divides the point cloud into equal-sized cubes of a specific size and tries to estimate a best-fit plane for each cube based on the least-squares method (Riegler, 2017). The algorithm extracts plane patches and searches for patches using the following parameters: minimum point count, maximum standard deviation, maximum deviation, and minimum reflectance.

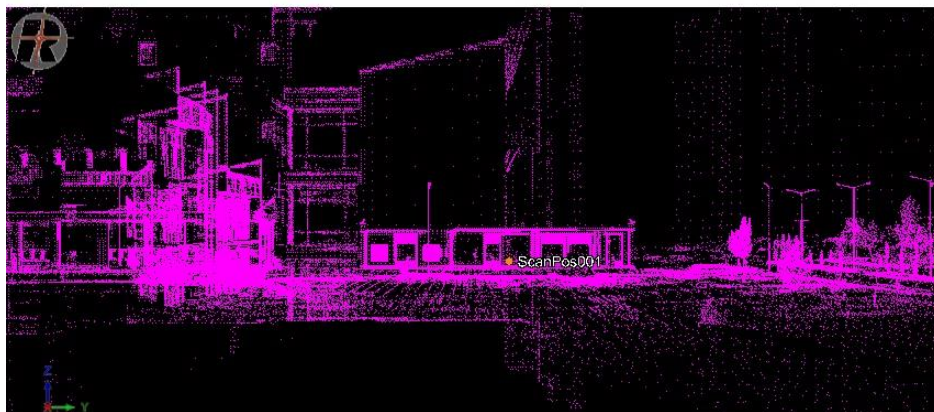


Figure 4.13. Polydata created using plain patch filter

After preparing the data using the above algorithm, the MSA can be started. Since the scan positions were surveyed using the instrument's internal GPS, in the MSA process, the position and orientation of the first station were locked, and the position and orientation of other scan stations were adjusted based on the first station. In the MSA, the

prepared plane patches were used as input data. The MSA algorithm uses the following parameters for nearest point search: search radius, maximum tilt angle, and maximum polydata (plane patch) observations. Minimum change of error and outlier threshold are used as adjustment parameters. The adjustment analyses and calculations were performed in four iterations by changing the parameter values until the desired adjustment accuracy was achieved. The first attempt resulted in a standard deviation of 0.460 m, the second iteration yielded 0.087 m, the third iteration 0.036 m, and finally, in the fourth repetition, the adjustment resulted in 0.005 m accuracy. Figure 4.14 illustrates histograms of residues for four adjustment computations, and Figure 4.15 shows the TLS point cloud after multi-station adjustment.

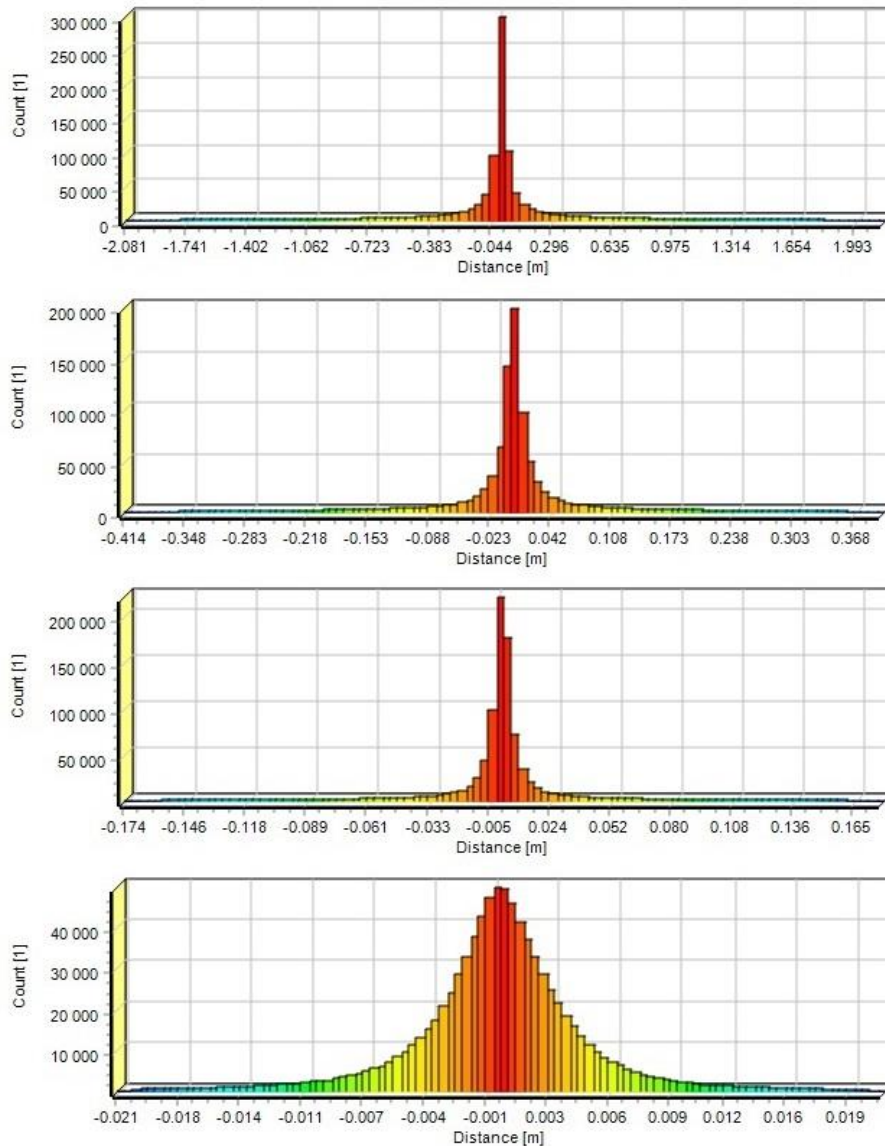


Figure 4.14. Histograms of multi-station adjustment residues, four iterations from top to bottom.

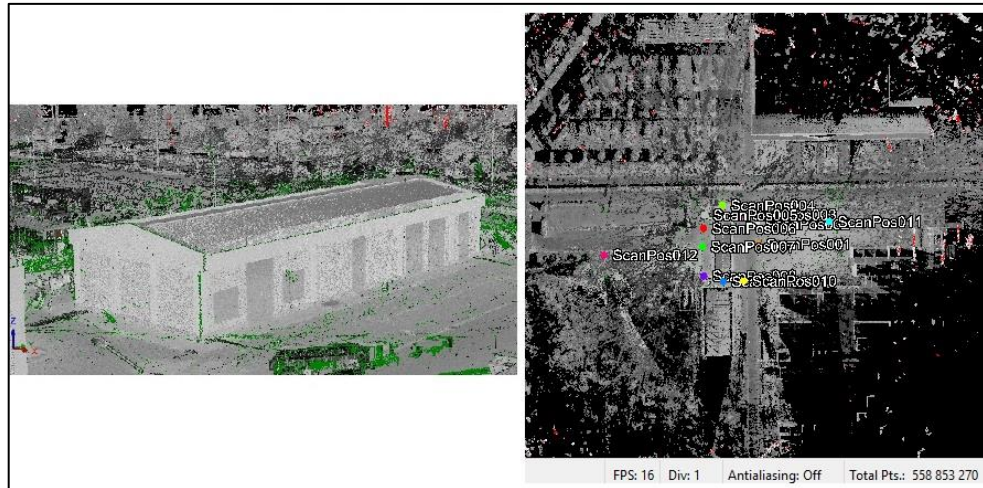


Figure 4.15. TLS point cloud after multi-station adjustment (2D and 3D reflectance view).

For absolute georeferencing of the point cloud, distinct tie points with known coordinates visible in the point cloud were used, and the point cloud was georeferenced accordingly. After the adjustment step, post-processing such as cleaning and filtering was performed. Each scan was colored using the camera images to obtain a true color point cloud. The data were filtered using the octree data filtering algorithm to obtain the desired point density. This filtering procedure is done by using an octree structure. The structure of octree is based on a cube that is divided into eight cubes of equal size, which are again divided, and so on (Riegler, 2017). Figure 4.16 shows the colored and filtered point cloud of the building, filtered using two octree increment values (0.005 m and 0.05 m). In the octree filter, points closer than 10% of increment were merged. Finally, the point cloud was exported for further process and analysis. A total of 12 scans produced a point cloud comprised of 558,853,270 million points for the angular resolution 0.020° , and 67,447,586, and 50,525,632 million points for angular resolutions 0.060° and 0.080° , respectively. The total number of points for the building before filtering was 56,655,406 million points, after applying octree filtering at 0.005 m increment, the number of points reduced to 27,232,659 million, and by applying octree 0.05 m, the number of points degraded to 431,126 million. Similarly, the point cloud density for the building data was 246031 samples/ m^2 before filtering and reduced to 94168 samples/ m^2 , and 1084 samples/ m^2 for the octree 0.005 m and 0.05 m, respectively. Data reduction is essential in TLS survey projects because large and computationally burdensome TLS datasets tend to challenge the computer and software during analysis. Since scanning at an angular

resolution of 0.020° yielded a very dense point cloud, the result of this resolution will be used to compare with UAS point clouds.

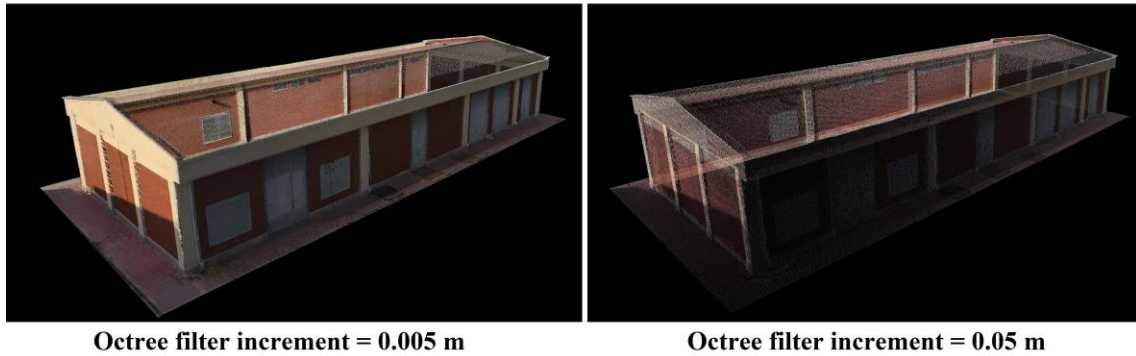


Figure 4.16. *Colored and filtered point clouds of the building filtered using two octree increment values.*

4.1.5. Flight planning and image acquisition

Flight mission planning is usually performed with the use of specific software. The flight height is calculated using the required GSD and internal parameters of the onboard camera. Frontal and side overlaps are specified, and waypoints are computed; depending on the purpose of the mission, the flight height and the amount of overlap vary. Highly detailed 3D modeling usually requires lower flight height and higher overlap, while higher flight height and less overlap can do the job for emergency surveying, which requires quick mapping of a wider area with lower resolution.

As discussed above, three image acquisition plans were designed (two nadir plans, and one oblique). The following paragraphs describe flight planning and image acquisition using fixed-wing and multirotor unmanned aerial systems.

4.1.5.1. Nadir image acquisition

Two nadir image acquisition plans were designed to conduct a complete survey of the study area using senseFly eBee Plus fixed-wing UAS at 100 and 170 m AGL, and 75% and 80%, frontal and 65% and 70% side overlaps, respectively. The area of interest was defined, and flight paths were designed on an aerial map in eMotion 3 flight and data management software. By identifying the survey area, ground sampling distance, and image longitudinal and side overlaps, the flight speed was set, and flights were carried out according to the flight path in automatic navigation mode. Figure 4.17 shows the flight mission planned in the eMotion 3 flight planning application. In the image acquisition process, an operator was responsible for monitoring the take-off and landing, the battery

status, the connection between UAV and ground control system (via computer stationed at the operating station) for ensuring that UAV is on its designed pathway. Photogrammetric projects at different flight heights were conducted to determine the influence of flight height on the accuracy of products. The photogrammetric characteristics of both flights are shown in the following table.



Figure 4.17. Flight mission planned in eMotion 3.

Table 4.7. Flight and data acquisition parameters.

Parameter	Value	
Height above ground level	100 m	170 m
Average flight speed	12.32 m·s ⁻¹	11.53 m·s ⁻¹
Flight GNSS mode	Standalone	Standalone
Number of strips	13	9
Distance between strips	39 m	66 m
Distance between images (Base)	17	51
Ground resolution	2.4 cm·px ⁻¹	4 cm·px ⁻¹
Single image ground coverage	129 x 86 m	219 x 146 m
Number of images	548	155
Forward overlap	80%	70%
Side overlap	70%	65%

The two flights were conducted on different sunny days; in the first mission, the UAV was flown at 170 m AGL with no wind, which resulted in regular images and high image overlaps. The second flight at 100 m AGL was carried out in a day with a gentle breeze (wind speed = 5 m/s), the image overlap was set higher to achieve the minimum

required overlap; although the flight direction was against the wind, the flight resulted in lower forward image overlap ($\sim 60\%$) than the designed one. Obtaining higher overlap in lower flight height AGL using a lightweight fixed-wing UAV is challenging, the SenseFly technical team confirms that the eBee cannot achieve the desired longitudinal overlap consistently at 100 m and lower AGL, especially when there is wind. The manufacturer's recommendation is to fly with no wind or use a perpendicular flight plan to increase the image coverage. Since in surveying works, the optimal weather condition is not always available, the author decided to accept the flight result, and no attempt was made to obtain higher overlap with no wind. Because acquiring moderate overlaps at lower flight heights AGL is always possible, and on the other hand, collecting images at lower flight height and higher overlap significantly prolongs the processing time. In addition, most of the evaluation studies in the literature have been conducted with high overlap. It is clear that high image overlap ($> 80\%$) often result in higher accuracy. In view of the above issues, it is important to examine the result of moderate overlap (60%) achieved under such conditions.

4.1.5.2. Oblique close-range image acquisition

To assess the performance of UAS-SfM at a closer-range as well as to perform a volumetric accuracy analysis and evaluate the results of different aerial surveys, oblique image acquisition with 0.5 cm spatial resolution was planned to survey the selected building with an overhanging eave that had been previously surveyed using TLS. This is important because the majority of volumetric studies have calculated the volume of stockpiles and earthworks from DSMs; however, the volume of objects with more vertical details like buildings with overhang elements cannot be accurately calculated using a 2.5D DSM because a DSM is generated by interpolating 3D points of a point cloud. The interpolation process affects the reconstruction of complex structures that contain overhanging elements. We need to calculate the volume of such objects using filtered and cleaned point cloud or 3D mesh; therefore, it is necessary to evaluate the accuracy of the UAS-SfM point cloud in calculating the volume of objects that cannot be achieved using DSM. Images were taken manually using DJI Phantom 4 Professional UAS from an average height of 16 m AGL with oblique (45°) viewing direction. Since the UAV was flown very close to the building, the automatic flight option was not used, it was controlled manually to fly safely and achieve the desired image coverage. A total of 80

images with ~80% overlap were collected. Once the image acquisition was completed, a quality inspection was performed to remove photos with low quality.

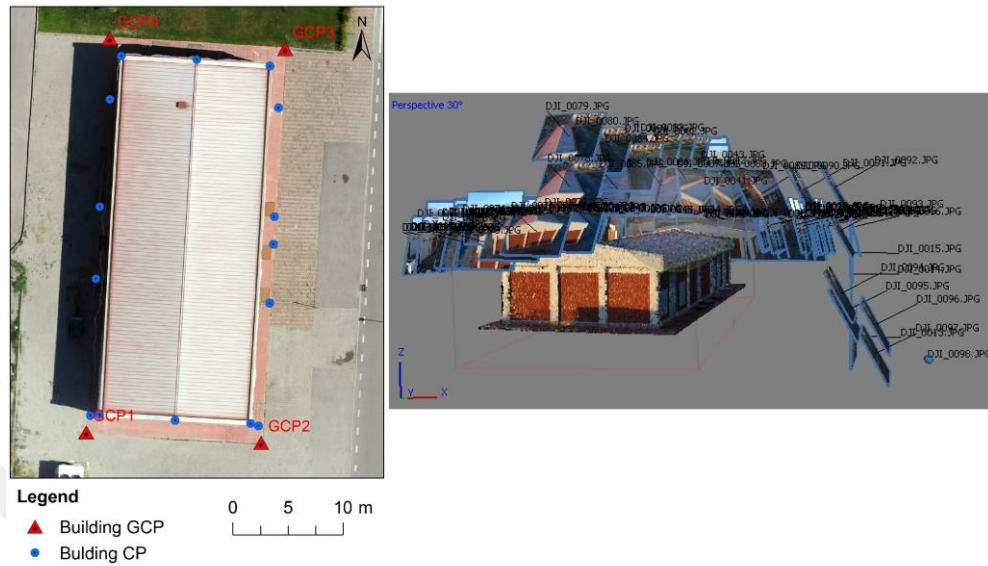


Figure 4.18. Building GCPs and CPs (left), and oblique image acquisition (right).

4.2. SfM Photogrammetry-Based Image Processing

In order to generate photogrammetric products from images UAS images, image processing was carried out in three photogrammetric software packages, which are developed based on computer vision and structure from motion algorithms. The process of image matching, aligning, and bundle block adjustment, which is quite complex, is fully automated. Exterior orientation parameters were determined by software in the process of aerial triangulation, which is based on least square accurate mathematical models; as a result, three-dimensional structures were obtained from two-dimensional image sequences using the SfM-MVS method. By performing computations in software packages, the following products were generated from images of UAS: 3D dense point clouds, triangulated mesh surface, orthomosaics, and digital elevation models (DSMs and DTMs).

A total of 22 photogrammetric projects were processed using three software packages. The projects processed using each software are as follows:

1. Nadir images of 170 m AGL processed without GCP.
2. Nadir images of 170 m AGL processed with 5 GCP layout.
3. Nadir images of 170 m AGL processed with 10 GCP layout.
4. Nadir images of 100 m AGL processed with 5 GCP layout.

5. Nadir images of 100 m AGL processed with 10 GCP layout.
6. Merged process of 100 m and 170 m AGL nadir image blocks with 5 GCPs (only PhotoScan).
7. Oblique images of the building at 16 m AGL processed without GCP.
8. Oblique images of the building at 16 m AGL processed with 4 GCPs.

Photogrammetric image processing was performed using three different commercial photogrammetric 3D reconstruction software packages, namely Agisoft PhotoScan Professional version 1.4.3 (Agisoft, 2018), Pix4Dmapper version 4.3.31 (Pix4D, 2017), and 3Dsurvey version 2.7.0 (3Dsurvey, 2018). The purpose of processing in different software packages was to analyze, compare, and evaluate the influence of computer applications on the accuracy of products. The typical SfM-MVS procedure incorporated in SfM-based photogrammetric software is described in Section 3.2.1. In order to obtain similar products, in the workflow of all the three software packages, full keypoint extraction and optimal processing options were adopted; Although extremely high processing options are available, they are not recommended for mapping purposes of large data. In this section, the workflow implemented by computer vision photogrammetry software (Agisoft PhotoScan) is summarized and illustrated; however, the specifics of this workflow slightly vary in Pix4Dmapper and 3Dsurvey, but a clear commonality exists. The workflow of Agisoft PhotoScan is shown in Figure 4.1. Image processing was performed in the following steps.

In the first step, the project was created, the reference coordinate system was chosen, and the images along with their EXIF metadata, including intrinsic camera parameters, were imported in the project workspace. In the next step, the images were aligned by identifying and matching features between overlapping images. The alignment step in PhotoScan comprises three phases (see Section 3.2.1). First, features (keypoints) are detected by applying a feature detection algorithm. After locating keypoints in neighboring images, matching keypoints are identified, and inconsistent matches are removed. In the third stage, 3D geometry of the scene and camera parameters (focal length, radial lens distortions, and positions of the principal point) are solved simultaneously using a bundle-adjustment algorithm. In the alignment step, the accuracy was set to “high”, and limits were not specified for the key point and tie point parameters because defining an upper limit for these parameters may cause missing in some parts of the point cloud model and affect the comparison with the other software. At this stage,

which is the crucial step in the SfM workflow, the camera position and orientation corresponding to each photo were estimated, and a sparse point cloud model was generated (Figure 4.19).



Figure 4.19. *Sparse point cloud generated using PhotoScan.*

After generating the sparse point cloud, the points with the highest reprojection error were removed using the gradual selection option. For generating accurately georeferenced products, 3D coordinates of GCPs were imported, and each was marked manually on visible photos. At least 3 GCPs are needed for bundle adjustment. Subsequently, the camera alignment was optimized using the GCPs. In order to achieve higher accuracy, optimization procedure should be performed; this process calculates camera external and internal parameters and corrects the probable image distortions like bowl effect (Agisoft 2018). The RMSE of bundle adjustment for all the three software was under 2.5 cm.

Once the camera parameters and the geometry of the output sparse point cloud were optimized, a dense point cloud was generated by applying MVS image matching algorithms, which are based on the estimated camera positions and the calculated depth information (Agisoft, 2018). In this step, several reconstruction parameters such as reconstruction quality (“ultra-high”, “high”, “medium”, and “low”) and depth filtering (“aggressive”, “mild”, and “moderate”) are available, which can be set as per the project requirement. The point cloud quality parameters affect point cloud density and level of detail in the reconstructed scene, while depth filtering parameters control the degree to which outliers are removed from the point cloud. For the aerial mapping, the recommended parameters which are “high” and “aggressive”, were set for quality and depth filtering algorithm, respectively. The depth filtering algorithm was used to filter out

the erroneous points in the process of dense point cloud generation. This stage, which requires a longer time for processing (depends on the computer's processor and RAM), resulted in a highly detailed 3D point cloud (Figure 4.20). The dense point cloud can be modified and classified prior to exporting or proceeding to the next step.



Figure 4.20. 3D view of dense point cloud generated using PhotoScan.

Following the above step, a 3D polygonal mesh model was generated based on the dense point cloud data and interpolation between points. Subsequently, the texture was built and applied to the mesh model. Polygonal mesh models can be exported in many formats with significantly less data size compared to point clouds, which are useful in 3D graphics and solid modeling; in addition, exporting a mesh model as 3D faces or polylines is quite beneficial for surface creation and volume calculation in CAD applications. However, generating mesh models are optional and can be skipped, and the digital surface model (DSM) can be produced directly following dense cloud generation.

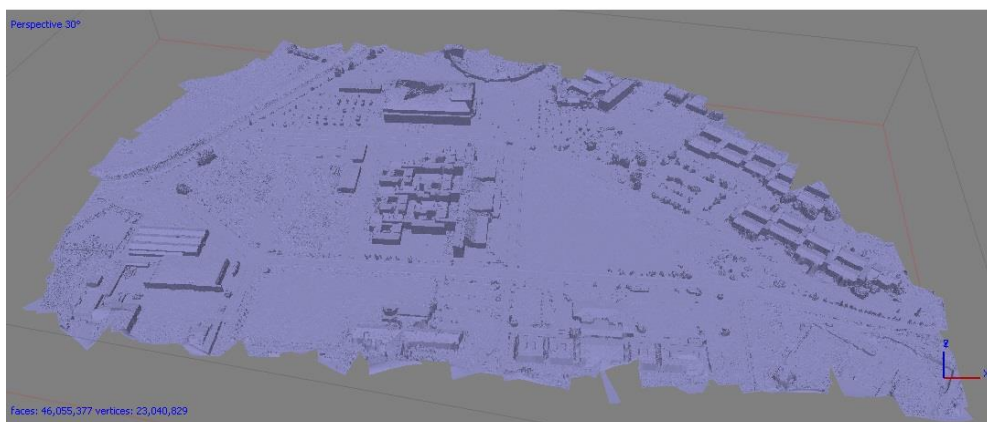


Figure 4.21. 3D view of the solid mesh model generated using PhotoScan.



Figure 4.22. 3D view of the textured mesh model generated using PhotoScan.

Subsequently, the digital surface model (DSM) was generated using the software interpolation algorithm (inverse distance weighting). DSM can be generated and rasterized from a sparse point cloud, dense point cloud, or mesh model in geographic or planar projection. Since the dense point cloud yields more accurate results, the digital surface model was generated based on the whole dense point cloud data. Figure 4.23 shows the DSM created by PhotoScan. The three used software packages use noise filtering algorithms for DSM generation.

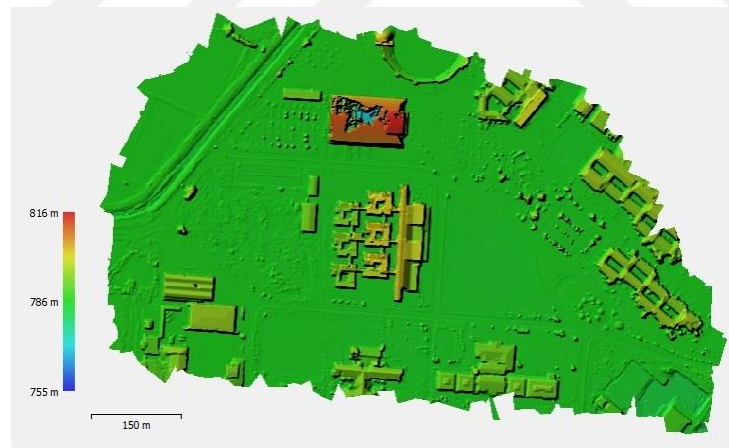


Figure 4.23. DSM generated from the point cloud in PhotoScan.

Digital terrain model (DTM) generation is a semi-automatic process in PhotoScan. In order to be able to generate a DTM, first, the dense point cloud must be classified into at least two classes (i.e., ground points, and others); then the DTM can be produced based on the classified ground point cloud. Agisoft PhotoScan allows manual or automatic classification of the dense cloud (Agisoft, 2018). Although manual classification is a time-taking process, this provides the possibility to classify and export 3D points to

certain standard classes (e.g., ground, buildings, vegetation, etc.). The automatic algorithm was used to detect and classify ground points. The automatic point cloud classification procedure consists of two steps, which classify the point cloud according to three parameters: maximum angle, maximum distance, and the cell size (Agisoft, 2018). In the first step, the software divides the dense point cloud into cells of a specific size and detects the lowest points. The first estimate of the terrain model is given by the triangulation of the detected points. The second step is an iterative process that until the conditions given in the parameters are satisfied, the procedure is repeated. When the conditions are met, the detected points are added to the ground class.

The three parameters determine the conditions to be checked during the test, whether to classify the examined point as ground or a non-ground. The maximum angle parameter sets the angle limitation between the estimated terrain model and the examined point. In the software manual, the recommended angle for nearly flat terrain is 15, and for terrain with steep slopes, higher values are recommended. The maximum distance parameter determines the maximum ground elevation variation at a time. The cell size parameter determines the size of the largest non-ground feature within the scene.

In order to generate the DTM of the study area, the dense point cloud was first classified into ground and non-ground classes using the automatic classification algorithm. In this study, different parameters were tested; as a result, the satisfactory point cloud classification was obtained using the following parameters: 15° for maximum angle, 0.2 m for maximum distance, and 150 m for cell size. After the dense point cloud was classified, the DTM was generated based on the ground class. DTM generation in 3Dsurvey is similar to PhotoScan, but in Pix4Dmapper, the process is fully automatic, which the user cannot interfere with the process. Figure 4.24 shows the DTM generated in PhotoScan using the semi-automatic point cloud classification algorithm.

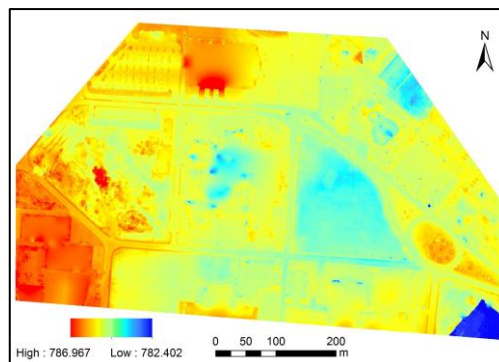


Figure 4.24. DTM generated using semi-automatic algorithm in PhotoScan.

For generating high-resolution orthorectified images of the study area, orthomosaics were generated based on the input photos and constructed digital surface model at 4.0 cm and 2.5 cm resolutions for the flights at 170 m and 100 m AGL, respectively. Orthorectification can be done based on the DSM or mesh model. As described in Section 3.2.5, the orthorectification process removes the image perspective effects (i.e., tilt, terrain distortions) and creates orthomosaic, which is planimetrically correct. Figure 4.25 illustrates the orthomosaic of the study area generated using PhotoScan.

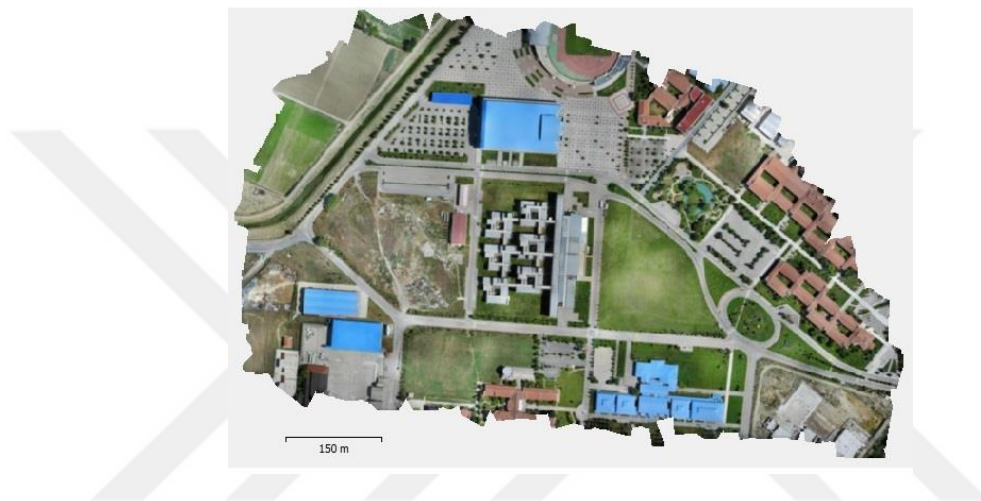


Figure 4.25. *Orthomosaic generated using PhotoScan.*

PhotoScan allows several blending options for the user to modify the visual quality of the orthomosaic. Moving objects can cause artifacts, which in some projects might affect the visual quality of the orthomosaic; similarly, this problem may occur if the source photos were collected from oblique aerial imagery with higher angles. PhotoScan offers an effective editing tool to eliminate the mentioned artifacts manually. Finally, all generated models were exported for further analysis. Similar operations were performed on all eight projects in each software, with the exception that the 3D modeling option was chosen for the processing of the building oblique images in Pix4D.

The processing was performed using a workstation computer with Windows 10 Professional 64-bit operating system, 3.4 GHz Intel processor, and 128 GB RAM. The total processing time for 255 images was about 2 hours for PhotoScan and Pix4Dmapper, and approximately 10 hours for 3Dsurvey. For comparing the processing time, the same number of images were processed using a PC with a 3.6 GHz processor and 32 GB RAM. The processing time for PhotoScan and Pix4Dmapper was about 6 hours, and for 3Dsurvey, it took about 20 hours.

4.3. Accuracy Assessment

The main objective of this study was to analyze and evaluate the accuracy of orthomosaics, DSMs, and point clouds derived from UAS-SfM using different SfM software packages. To achieve the objective of the research, comparative absolute and relative accuracy assessment between the derived data and the accurate field measurements was performed. The absolute accuracy assessment in this research is based on CPs that had been accurately measured using ground-based survey methods and had not been involved in the least-squares bundle adjustment and orientation calculation process. The relative accuracy assessment deals with the inter-relational performance of different methods. The main comparative assessments in this study include (i) virtual model versus CPs, (ii) virtual model versus actual object, and (iii) virtual model versus virtual model. The first comparison is based on point to surface, which is the most common comparison in which the elevation of the virtual model (i.e., DSM) is compared with the CP. The second comparison is based on measurements performed on the actual object and on the virtual model (the building case). In the third comparison, different models generated using various methods are compared.

Accuracy evaluation was performed based on Root Mean Square Error (RMSE) because this is the most common metric used in geospatial accuracy analysis, and the new ASPRS standard was also presented in this metric. The errors in RMSE are squared before averaging; therefore, it gives relatively higher weights to large errors. With this in mind, it is better to use the RMSE rather than the mean absolute error (MAE) in such studies. In surveying, RMSE is often preferred to avoid undesirable large errors (Agüera-Vega et al., 2016; Jaud et al., 2016; Martínez-Carricondo et al., 2018).

Since errors in UAS-SfM-based surveying usually occur in elevations and vertical uncertainty is the primary concern in the literature, this research mainly focuses on vertical accuracy. For vertical accuracy assessment, two sets of CPs (vegetated and non-vegetated) were measured directly on the ground without marking them. For accuracy assessment of the entire study area, a total of 200 CPs (which are located within and outside of GCP polygons) were surveyed, 100 of which are located in vegetated and 100 in non-vegetated terrain. From the 100 CPs located on the bare surface, 7 of them were marked on the ground and used for horizontal and vertical accuracy assessment, and the rest (unmarked) were used for only vertical accuracy assessment. Accuracy analysis was performed separately on three main landcover in the study area (bare surface, vegetated,

and a building; see Figure 4.8). A total of 16 CPs (10 on the building sidewalk, and 6 on the roof) were accurately measured by integration of TS and GNSS to assess the accuracy of the selected building and compare results of different flight heights. All 16 points were contributed to the vertical accuracy assessment; from these points, 10 of them were used for horizontal accuracy assessment. Although photogrammetric software packages calculate and provide the horizontal and vertical accuracy assessment report based on the identified GCPs and CPs, the reports cannot satisfy the user. Therefore, the accuracy analysis and evaluation of the products were performed from the end user's point of view.

Linear RMSE of each coordinate, Easting (X), Northing (Y), and elevation (Z), as well as the horizontal (XY), was calculated for each marked checkpoint. Horizontal accuracy assessment was performed on orthomosaics, and then by comparing the coordinates to the actual surveyed (GNSS) coordinates, RMS errors ($RMSE_X$, $RMSE_Y$, and $RMSE_{XY}$) were calculated using the following equations (Agüera-Vega et al., 2016; ASPRS, 2014; Martínez-Carricondo et al., 2018):

$$RMSE_X = \sqrt{\frac{\sum_{i=1}^n (X_{Oi} - X_{GNSSi})^2}{n}} \quad (4.1)$$

$$RMSE_Y = \sqrt{\frac{\sum_{i=1}^n (Y_{Oi} - Y_{GNSSi})^2}{n}} \quad (4.2)$$

where n is the number of tested CPs; X_{Oi} and Y_{Oi} are X and Y coordinates measured in the orthomosaic for the i th CP; X_{GNSSi} and Y_{GNSSi} are X and Y coordinates measured with the use of RTK GNSS for the i th CP.

$$RMSE_{XY} = \sqrt{RMSE_X^2 + RMSE_Y^2} \quad (4.3)$$

For the seven check points, vertical accuracy was calculated in two methods. In the first method, the horizontal positions of CPs were considered from the orthomosaic, and the height value was derived from the grid DSM, and by comparing to the GNSS measurements, $RMSE_{ZO}$ was calculated.

$$RMSE_{ZO} = \sqrt{\frac{\sum_{i=1}^n (Z_{Oi} - Z_{GNSSi})^2}{n}} \quad (4.4)$$

where Z_{Di} is the elevation in the i th CP obtained from the DSM, considering its X and Y coordinates, measured on the orthomosaic; Z_{GNSSi} is the Z coordinate of the i th CP measured with the GNSS.

This approach was adopted as it would be the process that a user would determine the elevation of a point identified on the orthomosaic. However, as a result of the horizontal error, to some extent, the above method eliminates the effect of the horizontal error from the process. Therefore, the second method that adopted to assess the vertical accuracy was to calculate the elevation difference between DSM and GNSS measurements, while the horizontal positions of CPs were considered directly from the GNSS measurements. In the second method, the $RMSE_{ZD}$ was calculated as follows, which the errors of all vegetated and non-vegetated unmarked CPs were also calculated using this method:

$$RMSE_{ZD} = \sqrt{\frac{\sum_{i=1}^n (Z_{Di} - Z_{GNSSi})^2}{n}} \quad (4.5)$$

where Z_{Di} is the elevation in the i th CP, derived from the DSM, while its X and Y coordinates, measured with the GNSS; and Z_{GNSSi} is the Z coordinate of the i th CP surveyed with the GNSS.

The vertical RMS errors of all vegetated and non-vegetated unmarked CPs were calculated using the second method. Following the calculations, accuracy tables were prepared, and relative frequency histograms of error distribution and scatter plots of elevations were plotted to analyze the correlation and linear association between different survey methods. The R Statistics programming language software's environment was used to plot not only the histograms and linear regression models but also to plot the correlation matrices including distribution histograms along with the fitted normal density curves, bivariate scatter plots containing a fitted regression model, correlation ellipses, and correlation coefficient values to provide a statistical presentation of data. The charts plotted in R, significantly facilitate to pairwise comparisons. In Section 5, the obtained accuracies of the results will be discussed and compared to ASPRS (2014) positional accuracy standard for digital geospatial data.

5. RESULTS AND DISCUSSION

The objective of this thesis was to evaluate the accuracy of the UAS-based survey and structure from motion as an alternative to conventional methods. For achieving the aim of the research, nadir images of the study area were acquired by conducting two flights at 100 and 170 m AGL using the senseFly fixed-wing UAS. For 3D modeling and volumetric accuracy assessment, oblique images of a building were obtained using the DJI Phantom 4 Pro Quadcopter UAV. For validation of the UAS-SfM products, field measurements were conducted using TLS, RTK GNSS, and TS. After data collection, all the required steps of the structure from motion were accomplished, dense point clouds were generated and using the dense point cloud, 2.5 cm and 4.0 cm resolution orthomosaics, and DSMs were produced using the three software packages (Agisoft PhotoScan, Pix4Dmapper, and 3Dsury). In order to assess the effect of the number and distribution of GCP on the accuracy of products, the images of both flights were processed using two GCP schemes (5 GCPs and 10 GCPs). Finally, using validation data, absolute and relative accuracy evaluations were performed on the results, as well as visual assessments were carried out, and comparisons were made. This chapter presents, analyzes, interprets, and compares the results in terms of absolute and relative accuracy assessment. In the first section, absolute accuracy analysis is performed, and the results are evaluated. Then, 3D modeling and volume calculation are presented and discussed. Subsequently, profile and cross-sectional analysis are provided. Finally, visual inspections and quality assessments are presented.

5.1. Absolute Accuracy Analysis and Evaluation of Results

Several factors influence the accuracy of a DSM derived from UAS images, such as flight height AGL, distance to the nearest GCP, image overlap, topography, surface structure, and varying contrast in images (Agüera-Vega et al., 2016; Avanzi et al., 2018; Gindraux et al., 2017; Nesbit & Hugenholtz, 2019; Ruiz et al., 2013; T. Tonkin & Midgley, 2016). In this study, the first two factors were investigated. The following sections present the results of horizontal and vertical accuracy assessment of CPs calculated based on RMSE equations discussed in Section 04.3.

5.1.1. Horizontal and vertical accuracy assessment based on 7 marked CPs

Horizontal errors of orthomosaics in the X direction, Y direction, and in the radial direction (XY) were calculated for all projects based on 7 marked CPs. The error statistics (minimum error, maximum error, mean error, MAE, and RMSE) are given in the following tables (see Table 5.1 to Table 5.5).

Table 5.1. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 100 m AGL nadir images, processed with 5 GCPs and assessed with 7 GNSS CPs. All values are in meters.

100 m AGL (5 GCP)												
	PhotoScan				Pix4Dmapper				3Dsurvey			
	X	Y	Z _o	Z _D	X	Y	Z _o	Z _D	X	Y	Z _o	Z _D
Min	-0.018	0.006	-0.216	-0.222	-0.018	0.009	-0.151	-0.151	-0.053	0.023	-0.088	-0.108
Max	0.030	0.052	0.157	0.157	0.037	0.051	0.100	0.099	0.052	0.166	0.123	0.123
Mean	0.005	0.018	-0.023	-0.024	0.004	0.024	-0.003	-0.004	0.012	0.078	-0.014	-0.025
MAE	0.017	0.018	0.098	0.097	0.014	0.024	0.083	0.081	0.040	0.078	0.075	0.070
RMSE	0.018	0.023	0.125	0.125	0.018	0.028	0.096	0.095	0.042	0.093	0.079	0.076
RMSE_{XY}	0.029				0.033				0.102			
RMSE_{XYZ}	0.128				0.101				0.129			

Table 5.2. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 100 m AGL nadir images, processed with 10 GCPs and assessed with 7 GNSS CPs. All values are in meters.

100 m AGL (10 GCP)												
	PhotoScan				Pix4Dmapper				3Dsurvey			
	X	Y	Z _o	Z _D	X	Y	Z _o	Z _D	X	Y	Z _o	Z _D
Min	-0.008	-0.015	-0.151	-0.146	-0.013	-0.029	-0.024	-0.024	-0.038	-0.027	-0.139	-0.139
Max	0.038	0.087	0.008	0.003	0.034	0.056	0.076	0.075	0.016	0.060	0.190	0.190
Mean	0.007	0.022	-0.053	-0.056	0.006	0.016	0.020	0.019	-0.005	0.025	-0.018	-0.018
MAE	0.011	0.027	0.055	0.056	0.012	0.032	0.038	0.037	0.014	0.033	0.086	0.086
RMSE	0.016	0.036	0.073	0.073	0.016	0.036	0.046	0.045	0.019	0.040	0.104	0.104
RMSE_{XY}	0.040				0.039				0.044			
RMSE_{XYZ}	0.083				0.060				0.113			

Table 5.3. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 170 m AGL nadir images, processed with 5 GCPs and assessed with 7 GNSS CPs. All values are in meters.

170 m AGL (5 GCP)												
	PhotoScan				Pix4Dmapper				3Dsurvey			
	X	Y	Z _o	Z _D	X	Y	Z _o	Z _D	X	Y	Z _o	Z _D
Min	-0.020	-0.014	-0.138	-0.138	-0.036	-0.017	-0.172	-0.175	-0.036	0.003	-0.268	-0.268
Max	0.030	0.013	0.027	0.027	0.070	0.093	0.071	0.071	0.137	0.099	0.055	0.055
Mean	0.005	0.002	-0.055	-0.055	0.008	0.035	-0.017	-0.019	0.017	0.052	-0.083	-0.081
MAE	0.015	0.011	0.063	0.063	0.021	0.040	0.070	0.071	0.047	0.052	0.105	0.102
RMSE	0.017	0.011	0.074	0.075	0.032	0.048	0.085	0.087	0.062	0.064	0.139	0.138
RMSE_{XY}	0.020				0.058				0.089			
RMSE_{XYZ}	0.077				0.103				0.165			

Table 5.4. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 170 m AGL nadir images, processed with 10 GCPs and assessed with 7 GNSS CPs. All values are in meters.

170 m AGL (10 GCP)												
	PhotoScan				Pix4Dmapper				3Dsurvey			
	X	Y	Z _O	Z _D	X	Y	Z _O	Z _D	X	Y	Z _O	Z _D
Min	-0.007	-0.029	-0.016	-0.016	-0.043	-0.014	-0.033	-0.034	-0.029	-0.015	-0.134	-0.134
Max	0.053	0.021	0.108	0.108	0.048	0.068	0.068	0.068	0.018	0.074	0.107	0.107
Mean	0.010	-0.005	0.040	0.040	0.011	0.014	0.027	0.026	0.004	0.025	-0.055	-0.055
MAE	0.014	0.018	0.045	0.044	0.027	0.020	0.036	0.036	0.012	0.032	0.086	0.085
RMSE	0.022	0.020	0.054	0.053	0.031	0.030	0.040	0.040	0.015	0.042	0.092	0.092
RMSE_{XY}	0.029				0.044				0.045			
RMSE_{XYZ}	0.061				0.059				0.102			

Table 5.5. Horizontal and vertical error statistics of orthomosaics and DSMs derived from the merged process of 100 and 170 m AGL nadir images and assessed with 7 GNSS CPs. All values are in meters.

Merged process of 100 and 170 m AGL data (5 GCP)				
	PhotoScan			
	X	Y	Z _O	Z _D
Min	-0.013	-0.006	-0.086	-0.086
Max	0.037	0.054	0.029	0.029
Mean	0.002	0.019	-0.025	-0.025
MAE	0.013	0.021	0.037	0.036
RMSE	0.016	0.027	0.047	0.047
RMSE_{XY}	0.032			
RMSE_{XYZ}	0.057			

Before discussing the results, it is again worth noting that the images taken from 100 m height AGL have relatively lower overlap. The results of PhotoScan showed that horizontal accuracy was not affected by flight height, but the overlap is crucial because the horizontal accuracy in higher flight height with more overlap showed 1 cm higher accuracy. The horizontal accuracy was significantly affected by the number and distribution of GCPs. The results of Pix4D and 3Dsurvey showed that accuracy was improved by increasing the number of GCPs. However, results of PhotoScan indicated that as the number of GCP increased, the horizontal accuracy decreased. The results highlighted that a higher number of GCP can have a negative impact on horizontal accuracy. The maximum horizontal and vertical errors in the above tables indicate the error of points outside of GCP polygon. Since the horizontal errors are in the level of $1-1.5 \times \text{GSD}$, the values of Z_O and Z_D in the above tables show that vertical accuracy was not affected by the horizontal error.

To summarize the horizontal accuracy of PhotoScan, from both flight heights, orthomosaics were produced with RMSE_X and RMSE_Y of ~2 cm, and horizontal accuracy

($RMSE_{XY}$) of ~ 3 cm. According to the American Society for Photogrammetry and Remote Sensing (ASPRS) positional accuracy standards for digital geospatial data (ASPRS, 2014), the horizontal accuracy obtained from the images of 100 m AGL with 2.5 cm GSD, meets the ASPRS 2014 standard horizontal accuracy class $RMSE_x$ and $RMSE_y$ of 2.5 cm and $RMSE_r$ (the horizontal linear RMSE) of 3.5 cm for normal error distribution. The $RMSE_{XY}$ matches 6.1 cm accuracy at 95% confidence level. According to Class 1 of the legacy ASPRS map standard 1990 (ASPRS, 1990), the equivalent map scale for the achieved horizontal accuracy is 1:100. Similarly, the horizontal accuracy achieved from the images of 170 m AGL with 4.0 cm GSD, meets the ASPRS 2014 standard horizontal accuracy class $RMSE_x$ and $RMSE_y$ of 5.0 cm and $RMSE_r$ of 7.1 cm, for normal error distribution, and the horizontal accuracy at 95% confidence level is 12.2 cm. Referring to Class 1 of ASPRS 1990, the corresponding map scale for the achieved horizontal accuracy is 1:200. The achieved horizontal accuracy agrees with the findings of Agüera-Vega et al. (2016); Bennassi et al. (2017); Cryderman et al. (2014); Fernández et al. (2016); Gerke & Przybilla (2016); Gindraux (2017); Gonçalves & Henriques (2015); Jaud et al. (2016); Martínez-Carricondo et al. (2018); Rehak & Skaloud (2015); Reshetyuk & Mårtensson (2016); Whitehead & Hugenholtz, (2015); and Wierzbicki et al. (2015). However, some studies achieved lower accuracy from closer ranges. For instance, from a flight height of about 50 m AGL, Pérez et al. (2013) and Lucieer et al. (2014), achieved $RMSE_{XY}$ of 7.2 cm and 7.0 cm, respectively. Similarly, Coveney and Roberts (2017) obtained $RMSE_{XY}$ of 7.6 cm from 90 m height AGL. Sanz-Ablanedo et al. (2018) and Hill (2019) achieved horizontal accuracy of 8.6 and 10 cm, respectively. Despite the fact that the number of GCPs used in the literature vary, the results from the literature indicate that the horizontal accuracy reliability is at the level of 10 cm.

As shown in Table 5.5, the double block merged process of the images taken from 100, and 170 m heights AGL (processed with 5 GCP) showed remarkable 3D accuracy improvement (~ 2 cm). Nevertheless, horizontal accuracy was not improved significantly. PhotoScan outperformed both Pix4D and 3Dsurvey in horizontal accuracy. However, based on the 7 CPs evaluation, Pix4D results show higher Z accuracy in the processing of images with lower overlap. However, vertical accuracy evaluation based on the 7 CPs were performed only to find the effect of the horizontal error on the vertical accuracy. Vertical accuracy ($RMSE_{ZD}$) is evaluated separately based on 200 CPs.

5.1.2. Vertical accuracy assessment based on 200 unmarked CPs

As discussed in Chapter 2, horizontal accuracy is not the main concern in UAS-SfM-based surveying. In SfM-derived DSMs, the major errors usually occur in Z values. With this in mind, horizontal accuracy was assessed based on 7 CPs, and given the importance of elevation in topographic mapping, vertical accuracy assessment was performed based on 200 CPs in vegetated and non-vegetated areas. The vertical accuracy of non-vegetated and vegetated land cover was evaluated separately. The statistical results of the accuracy assessment are presented in the following sections.

5.1.2.1. Non-vegetated land cover

Table 5.6. Vertical error statistics of DSMs derived from 100 m AGL nadir images, processed with 5 & 10 GCPs and assessed with 100 GNSS CPs. All values are in meters.

100 m AGL (non-vegetated 100 CP)						
	PhotoScan		Pix4Dmapper		3Dsurvey	
	5 GCP	10 GCP	5 GCP	10 GCP	5 GCP	10 GCP
Min	-0.344	-0.165	-0.245	-0.104	-0.190	-0.270
Max	0.163	0.030	0.123	0.101	0.123	0.222
Mean	-0.004	-0.051	0.011	0.002	-0.059	-0.059
MAE	0.075	0.053	0.068	0.031	0.076	0.118
RMSE	0.102	0.066	0.085	0.039	0.091	0.137

Table 5.7. Vertical error statistics of DSMs derived from 170 m AGL nadir images, processed with 5, 10, and without GCPs and assessed with 100 GNSS CPs. All values are in meters.

170 m AGL (non-vegetated 100 CP)									
	PhotoScan			Pix4Dmapper			3Dsurvey		
	5 GCP	10 GCP	without GCP	5 GCP	10 GCP	without GCP	5 GCP	10 GCP	without GCP
Min	-0.324	-0.080	-1.633	-0.375	-0.302	-1.264	-0.481	-0.190	-1.034
Max	0.091	0.203	-0.577	0.394	0.330	0.320	0.266	0.107	0.463
Mean	-0.044	0.031	-0.974	0.016	0.031	-0.320	-0.080	-0.042	-0.008
MAE	0.055	0.048	0.974	0.077	0.050	0.398	0.100	0.071	0.293
RMSE	0.076	0.059	1.015	0.103	0.071	0.514	0.133	0.084	0.356

For the ease of interpretation, comparison, and correlation analysis, relative frequency histograms of errors were plotted in classes of 2 cm interval to compare each class to the total number of errors. In order to measure the linear dependence between SfM DSM elevations and the validation data of DGNSS, correlation analysis was performed based on the Pearson correlation method, which is the most common technique

for measuring the strength of the association between two variables. Pairwise matrices were prepared, and correlation coefficients were computed. Relative frequency histograms of elevation difference between UAS-SfM and DGNSS elevation data, as well as scatter plots of correlation between UAS-SfM and TLS elevations along with the fitted linear regression models for the projects 100 m AGL with 5 GCPs and 100 m AGL with 10 GCPs are given in Figures 5.1 and 5.3, respectively. Figures 5.5 and 5.7 show relative frequency histograms and scatter plots of projects 170 m AGL with 5 GCPs and 170 m AGL with 10 GCPs, respectively.

Moreover, for more detailed graphical accuracy analysis of SfM DSMs generated using three different software packages, correlation matrices were plotted using R statistical programming language to investigate the relationship between multiple variables (DGNSS validation elevations, Agisoft PhotoScan DSM elevations, Pix4D DSM elevations, and 3Dsurvey DSM elevations) simultaneously. A chart of the correlation matrix was plotted for each project. In the correlation matrix diagram, the distribution histogram of each variable (elevation) along with a fitted normal density curve is shown on the diagonal, the bivariate scatter plots including a fitted line and correlation ellipses are displayed at the bottom of the diagonal, and correlation coefficient values are given above the diagonal. The chart combines the statistical presentation of data, which facilitates pairwise comparison and measuring the linear association between two variables as well as the visual test for bivariate normality. Pairwise elevation correlation matrices for projects at 100 m AGL processed with 5 GCPs and 10 GCPs are given in Figures 5.2 and 5.4; and for 170 m AGL with 5 GCPs and 10 GCPs are given in Figures 5.6 and 5.8, respectively.

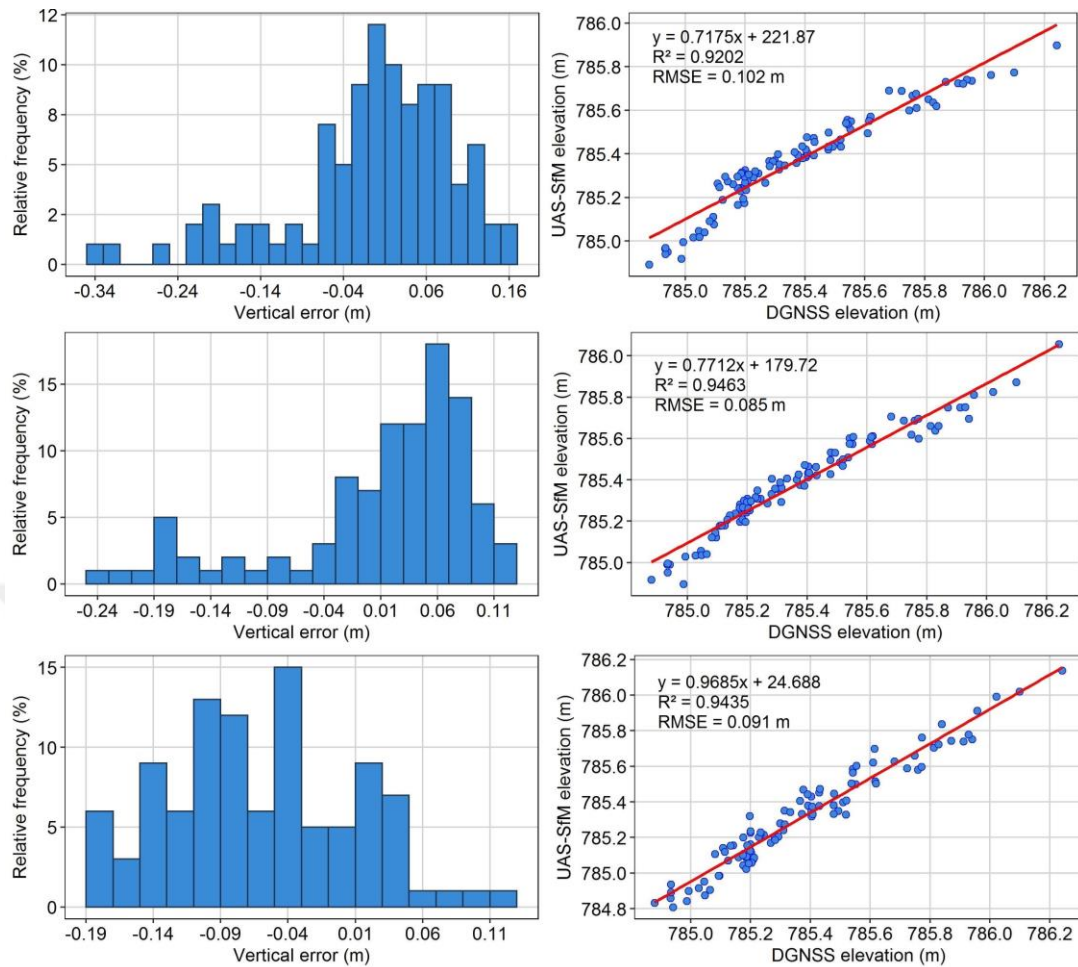


Figure 5.1. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 100 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

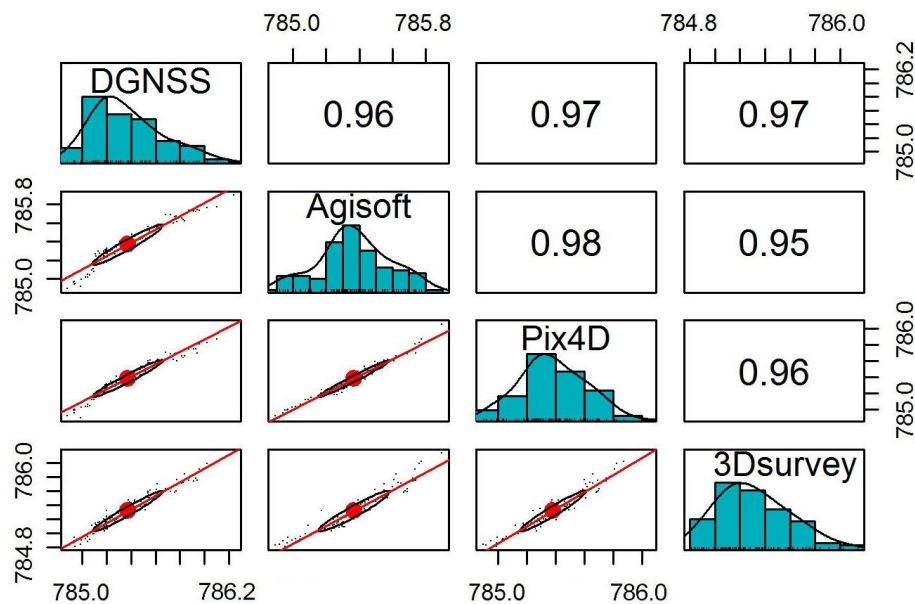


Figure 5.2. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 100 m AGL nadir images, processed with 5 GCPs.

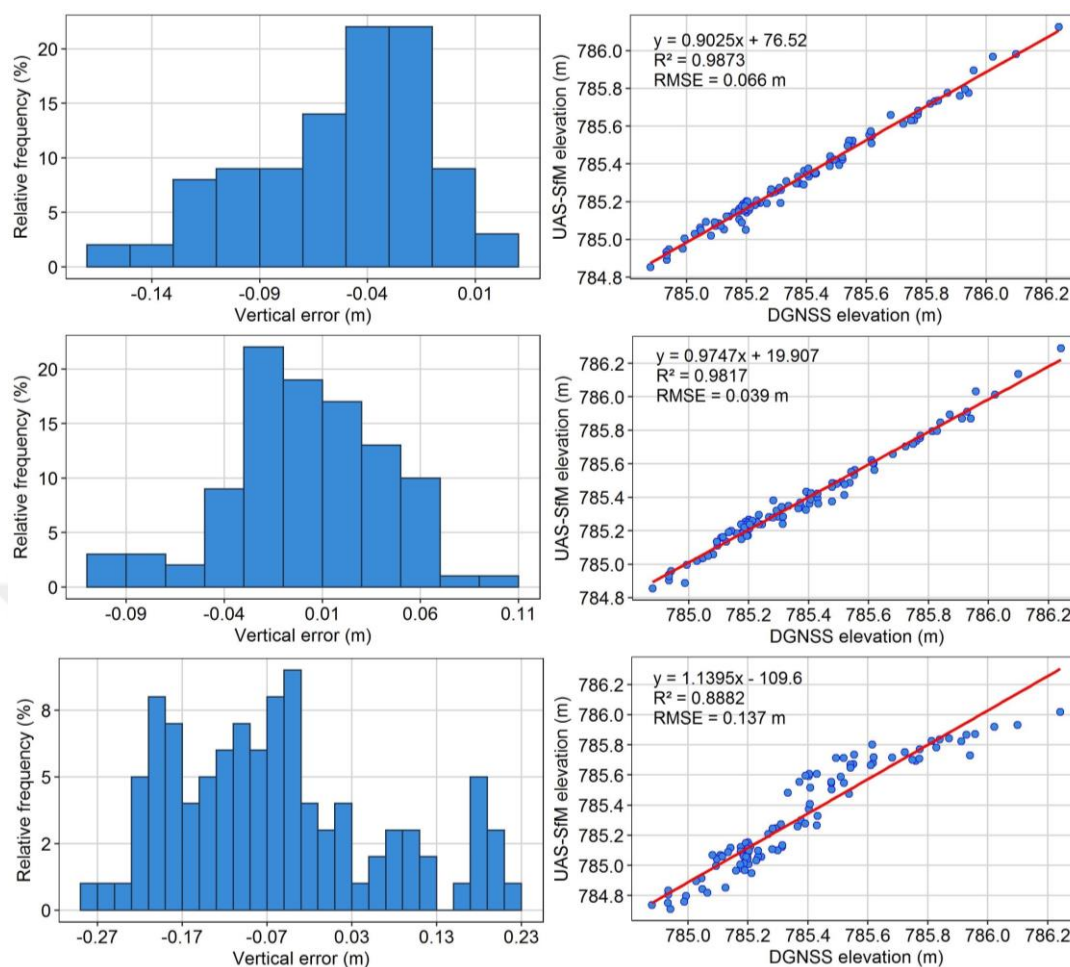


Figure 5.3. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 100 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

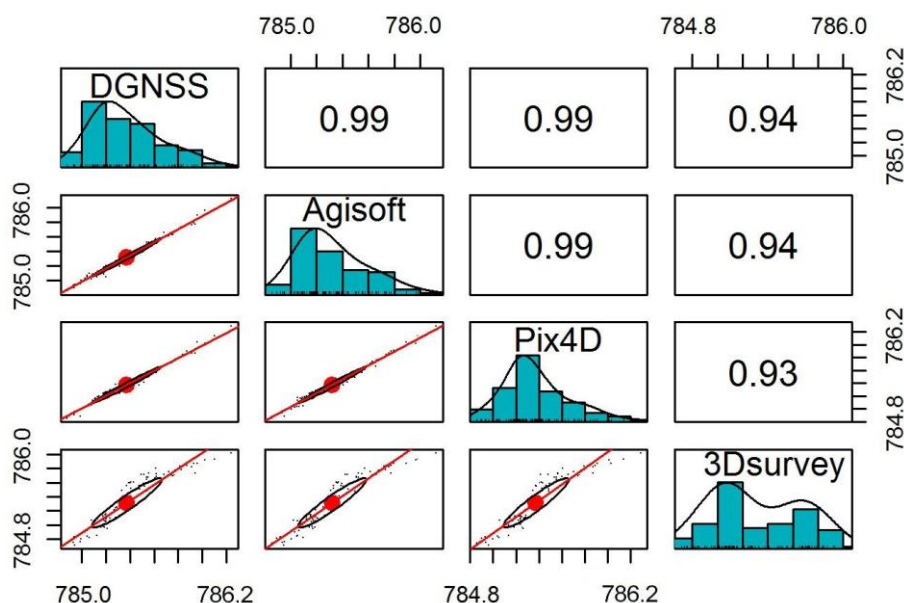


Figure 5.4. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 100 m AGL nadir images, processed with 10 GCPs.

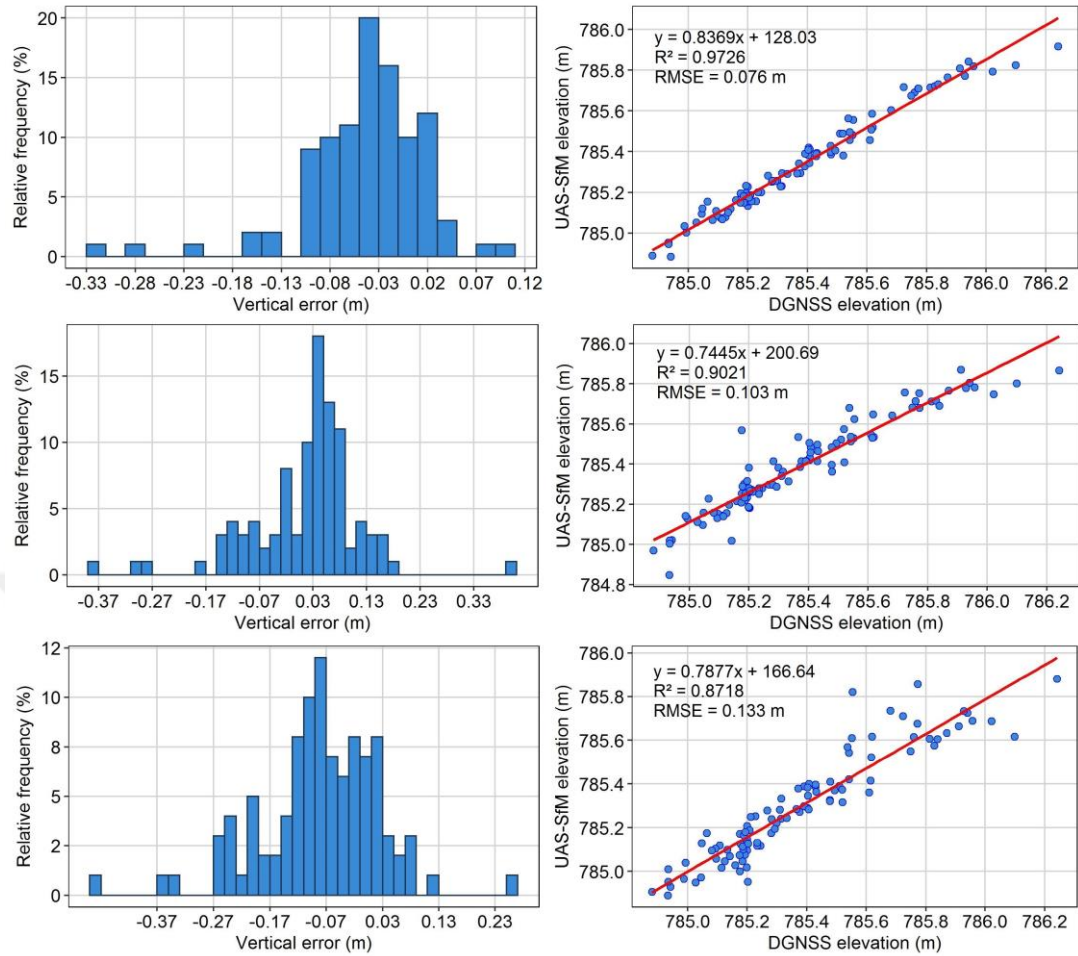


Figure 5.5. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 170 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

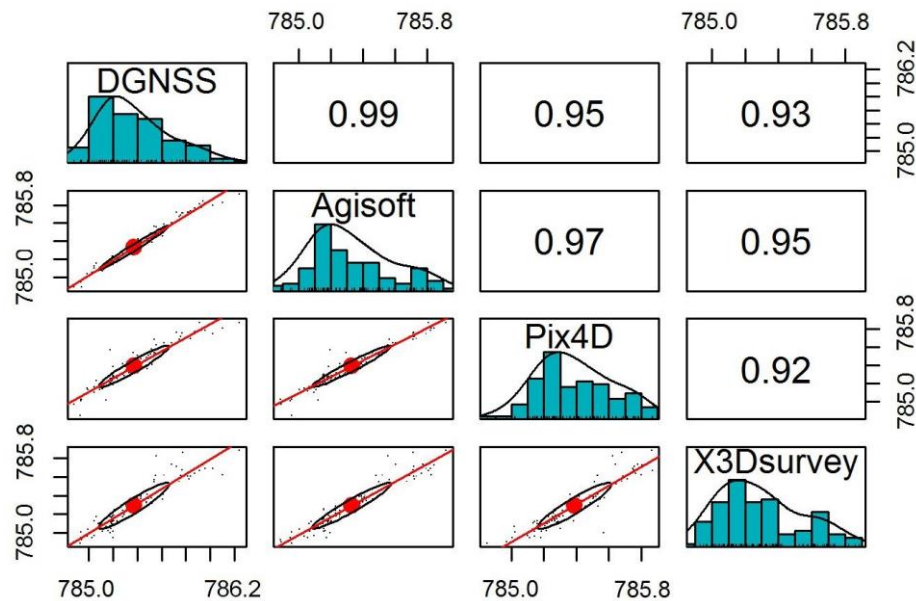


Figure 5.6. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 170 m AGL nadir images, processed with 5 GCPs.

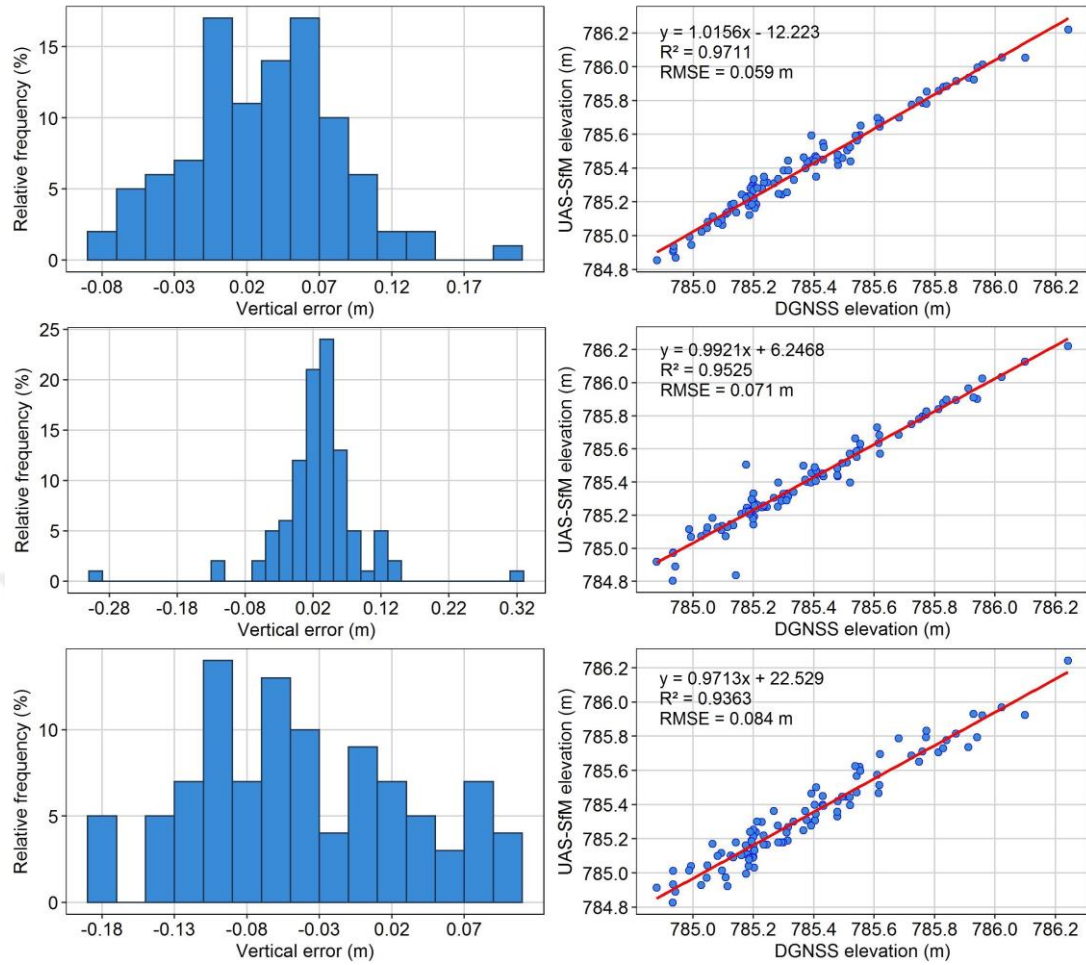


Figure 5.7. Relative frequency histogram of non-vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DSM derived from 170 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

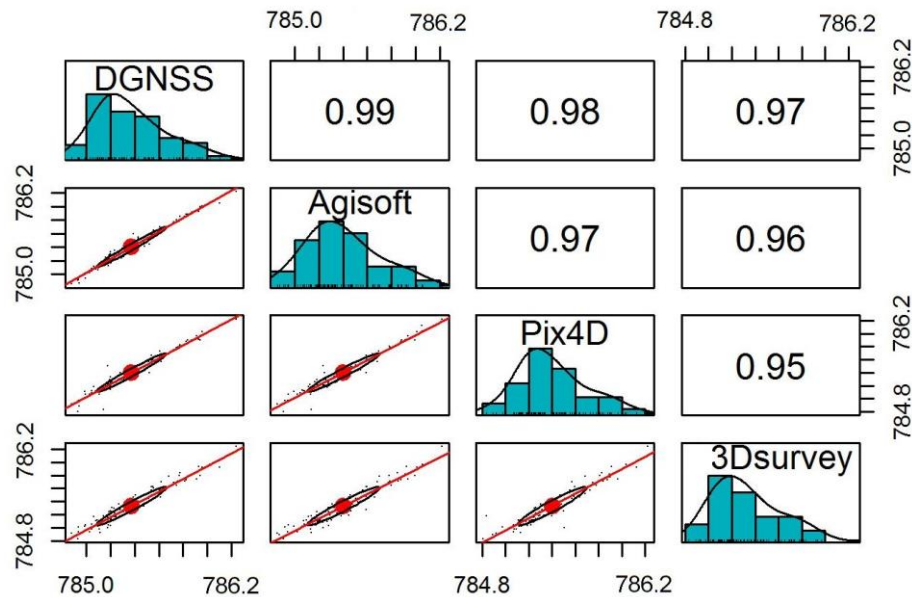


Figure 5.8. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 170 m AGL nadir images, processed with 10 GCPs.

Table 5.6 compares the elevation error statistics of SfM DSMs derived from 100 m AGL nadir images processed with 5 and 10 GCPs using the three software. The results of PhotoScan and Pix4D clearly show the impact of GCP on the accuracy, where the highest elevation accuracy achieved by Pix4D (3.9 cm) and PhotoScan (6.6 cm) using 10 GCPs; georeferencing using 10 GCPs shows 3.6 and 4.6 cm improvement in accuracy comparing to 5 GCPs. On the contrary, in 3Dsurvey, the RMS error increased by increasing the number of GCPs. Figures 5.1 to 5.4 illustrate the relative frequency histograms of vertical error and pairwise correlation of elevations. The figures indicate that there is a high positive linear correlation between DGNSS and SfM DSM elevations. For the 5 GCP scheme, as RMSE values for PhotoScan, Pix4D, and 3Dsurvey are very close (0.102, 0.085, and 0.091 m, respectively), they show almost the same trend, and there is no significant difference in correlation. However, histograms show a high similarity in error distribution between PhotoScan and Pix4D. On the other hand, 3Dsurvey shows quite different error distribution and fewer outliers. The results of the 10 GCP scheme (see Figures 5.3 and 5.4) show that vertical accuracy dramatically increased in Pix4D and PhotoScan. Scatter plots also show a high correlation ($R^2 = 0.99$) between the elevations of PhotoScan, Pix4D, and DGNSS. The minimum and maximum error values decreased, and outliers are significantly reduced. However, the result of 3Dsurvey shows higher error values and a relatively weak correlation.

As Table 5.7 demonstrates, the errors in DSMs derived from images of 170 m show the same trend for PhotoScan and Pix4D, where vertical accuracy increased by doubling the GCP numbers. However, PhotoScan shows higher accuracy than Pix4D. Contrary to 3Dsurvey's results at 100 m AGL, accuracy was increased in the 10 GCP schemes of 170 m AGL; however, it is still lower than PhotoScan and Pix4D. Relative frequency histograms and correlation scatter plots and correlation matrices of 5 and 10 GCP schemes are shown in Figures 5.5, 5.6, 5.7, and 5.8. The statistics illustrate that in 5 GCP scheme, the correlation is weaker, and the number of outliers is higher than the 10 GCP scheme. In the 10 GCP scheme, the error distribution for PhotoScan is almost normal, ranging from -8.0 cm to 20.3 cm with only one outlier. Similarly, Pix4D shows a nearly normal distribution ranging from -30.2 cm to 33.0 cm with three outliers. The error distribution in 3Dsurvey ranges from -19.0 cm to 10.7 cm.

PhotoScan outperformed the other two software packages in generating higher accuracy DSM from higher overlap images. It can be clearly seen in the figures that

PhotoScan shows a very high correlation in both GCP schemes. This means that PhotoScan is capable of producing high-accuracy DSMs if images have higher overlaps. Pix4Dmapper can produce DSMs with good accuracy not only from high overlap images but also from lower overlap images. 3Dsurvey yielded average accuracy with a relatively weak correlation.

To sum up, in the non-vegetated area, the highest vertical accuracy of 3.9 cm was achieved from the images of 100 m AGL (~60% overlap) using 10 GCPs by Pix4Dmapper. This accuracy meets Class 3 (RMSE 5 cm) of ASPRS 2014 absolute accuracy, which the equivalent Class 1 contour interval as per ASPRS 1990 is 15 cm. Since PhotoScan achieved 6.6 cm accuracy, based on the ASPRS standard, this is equivalent to 9.8 cm absolute accuracy at 95% confidence level. From the images of 170 m AGL (~75% overlap), the highest achieved accuracy was 5.9 cm by PhotoScan, which this agrees with Class 4 (RMSE 10 cm) of ASPRS 2014, which accordingly 95% confidence level is 19.6 cm. The equivalent Class 1 contour interval as per ASPRS 1990 is 30 cm. The achieved vertical results are also consistent with the literature mentioned in the above section.

5.1.2.2. Merged project

In order to check the accuracy of the project combined from different flight heights, a merge process was performed by combining images of both flights. Merged blocks of 100 m and 170 m AGL nadir images were processed using PhotoScan with 5 GCPs. Figure 5.9 and Figure 5.10 demonstrate the histogram and correlation matrix of this project. By comparing the DSM accuracy of this project with that of projects that were processed individually with 5 GCPs, we can see that in flight 1, the error range is from -0.34-0.16 m, in flight 2 with the same GCP number, errors ranging from -0.32-0.09 m, while in the merged project, errors ranging from -0.15 m to 0.07 m. The error histogram of the DSM derived from the merged project shows a significant improvement in the elevation accuracy. Although the scatter plots of both separately processed projects show high correlation coefficient values, the error distribution histograms show large outliers in both projects. The relative frequency histogram of errors in the merged project shows that outliers were removed, and the errors have a nearly normal distribution. Moreover, considering the correlation coefficient and the confidence ellipses, the correlation of the merged project is comparable with that of projects that were separately processed using

10 GCPs. Figure 5.10 shows that a high correlation exists between the elevations of the DSM derived from the merged process and other DSMs that were generated from single flight height images. Merging nadir images taken from two different flight heights not only improves accuracy but also results in more detail and better 3D models.

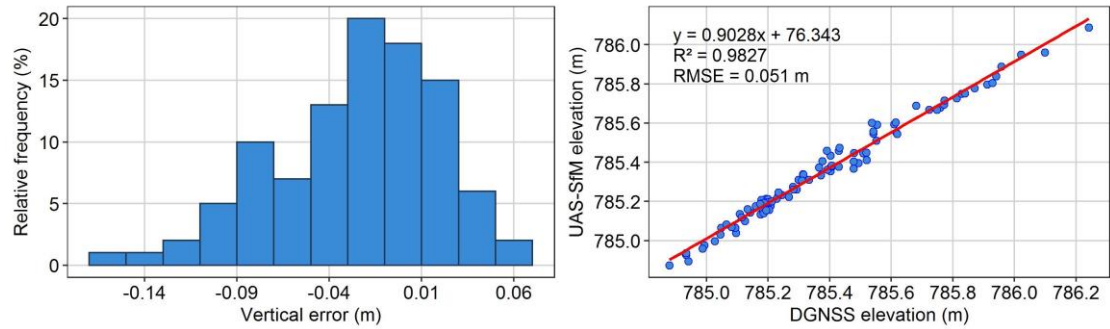


Figure 5.9. Relative frequency histogram of vertical errors and scatter plot of correlation between UAS-SfM and DGNSS non-vegetated elevations. UAS-SfM DSM derived from merged process of 100 and 170 m AGL nadir images, processed with 10 GCPs using.

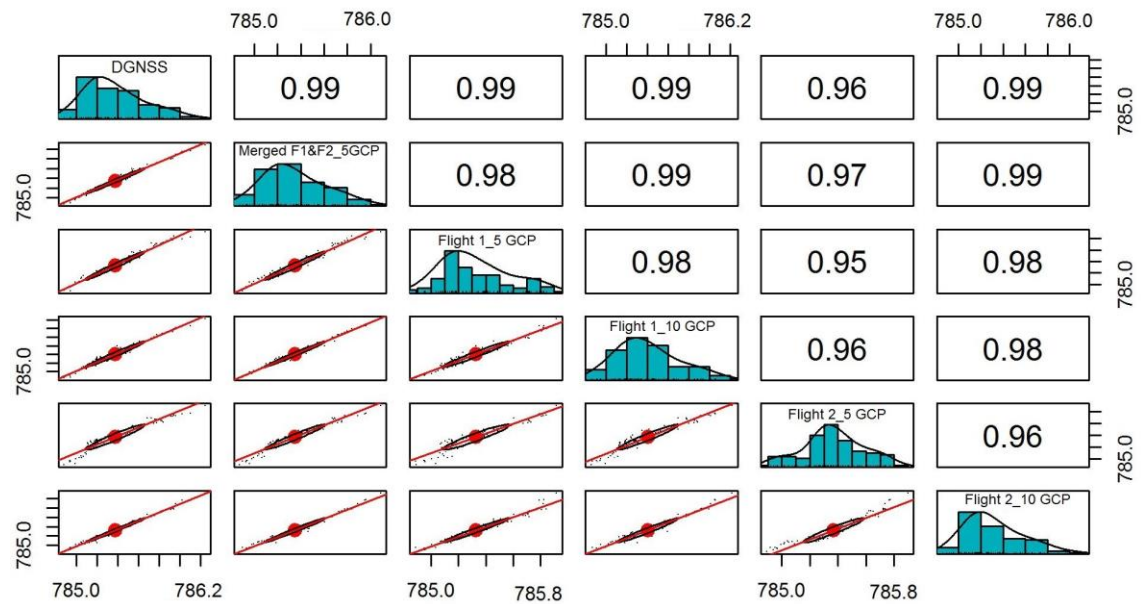


Figure 5.10. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from merged process of 170 m (Flight 1) and 100 m (Flight 2) AGL nadir images, processed with 10 GCPs using PhotoScan.

5.1.2.3. Relative accuracy of UAS images processed without GCP

Images of 170 m AGL were processed using the three software without using GCP to evaluate the relative accuracy. The images were aligned and georeferenced using the EXIF geotags. Figure 5.11 illustrates the correlation scatter plot matrix of DGNSS elevations and SfM elevation processed without GCP.

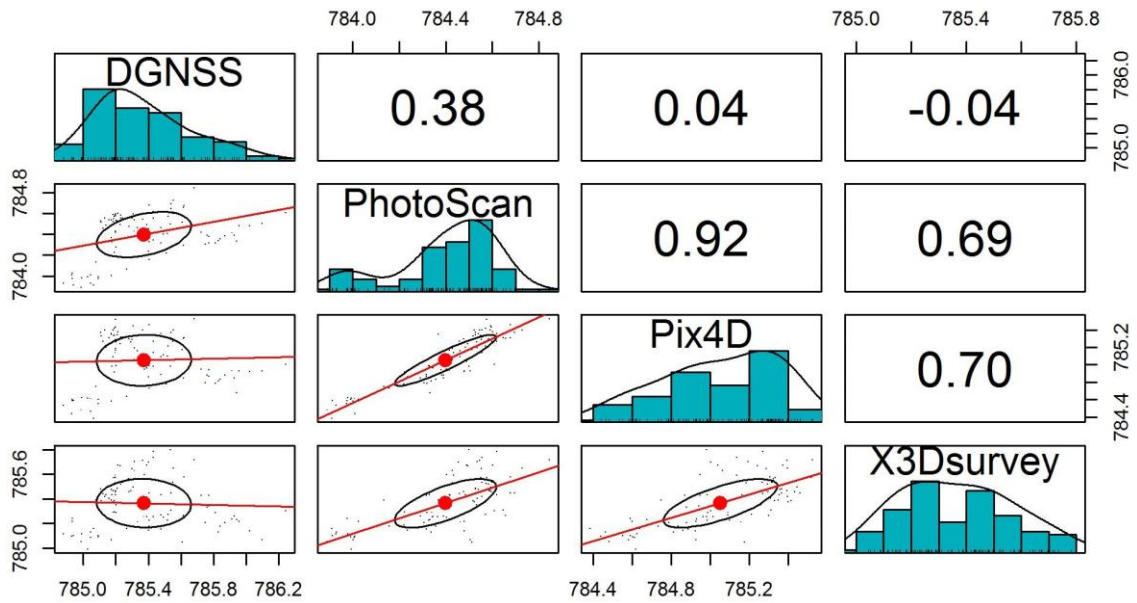


Figure 5.11. Correlation scatter plot matrix of DGNSS non-vegetated elevations and UAS-SfM DSM elevations derived from 170 m AGL nadir images, processed using the three software without GCP.

As the diagram shows, it is not possible to get a strong correlation between the SfM elevation and the DGNSS elevation because the UAS internal GPS is not accurate enough to match the DGNSS. Nevertheless, the matrix shows a strong elevation correlation between PhotoScan and Pix4D DSMs. 3Dsurvey also shows a positive correlation with both PhotoScan and Pix4D, but the correlation is weak. Considering the relative accuracy of PhotoScan and Pix4D, if they are scaled with simple measurements instead of georeferencing with GCPs, the DSMs produced using these software packages can be used for many applications, especially when time is critical. However, for obtaining high-accuracy 3D models, georeferencing using GCPs is inevitable.

5.1.2.4. Vegetated land cover

modeling of densely vegetated areas. Bearing this in mind, the accuracy assessment of the DTMs was performed on areas covered with grasses and sparse trees. The vertical error distribution histograms, scatter plot of correlations, and matrices are given in the below figures. According to ASPRS, vegetated vertical accuracy is an estimate of the vertical accuracy based on the 95% confidence level in vegetated terrain, where vertical errors do not necessarily approximate a normal distribution.

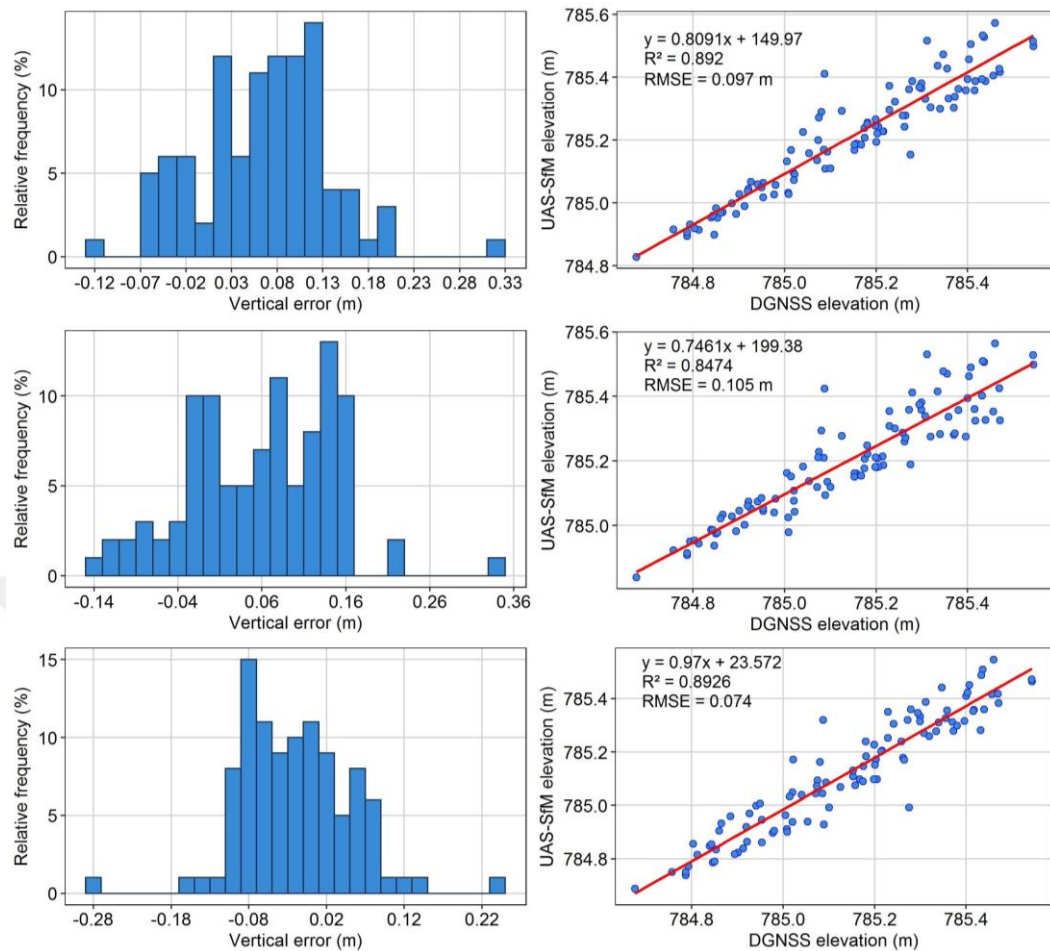


Figure 5.12. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 100 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

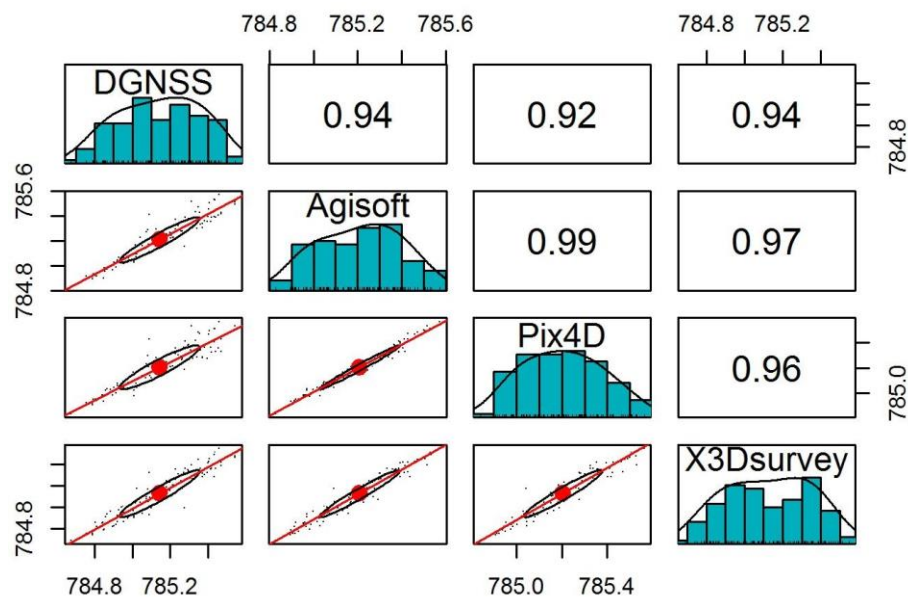


Figure 5.13. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 100 m AGL nadir images, processed with 5 GCPs.

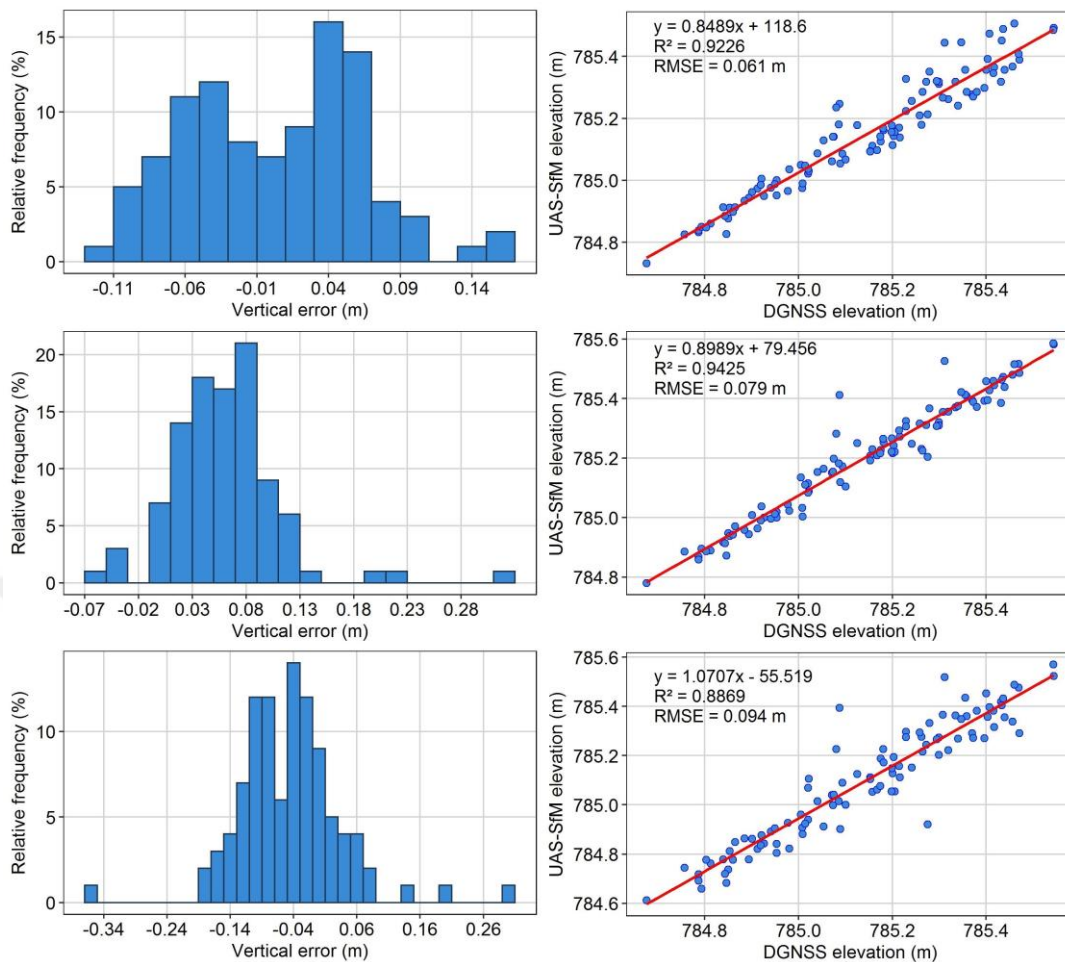


Figure 5.14. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 100 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

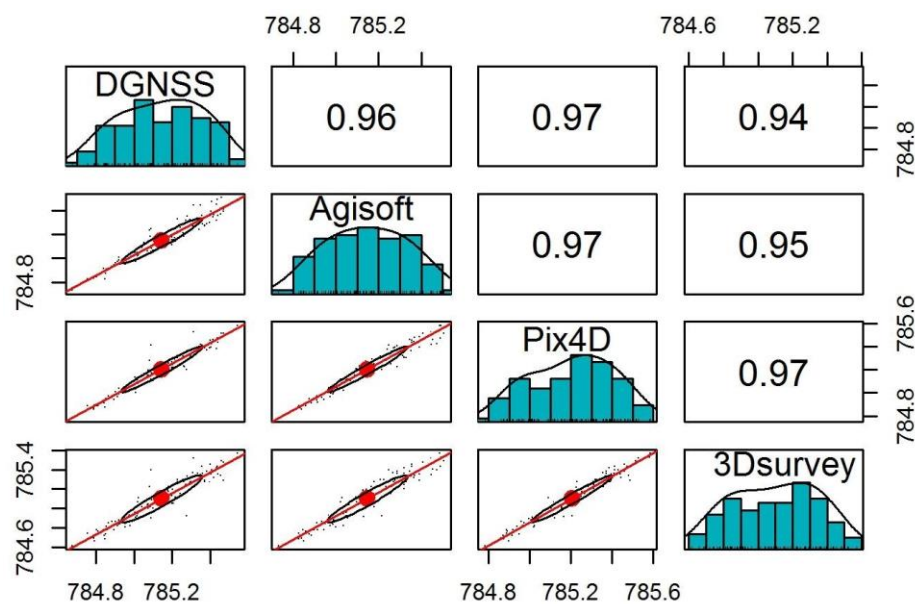


Figure 5.15. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 100 m AGL nadir images, processed with 10 GCPs.

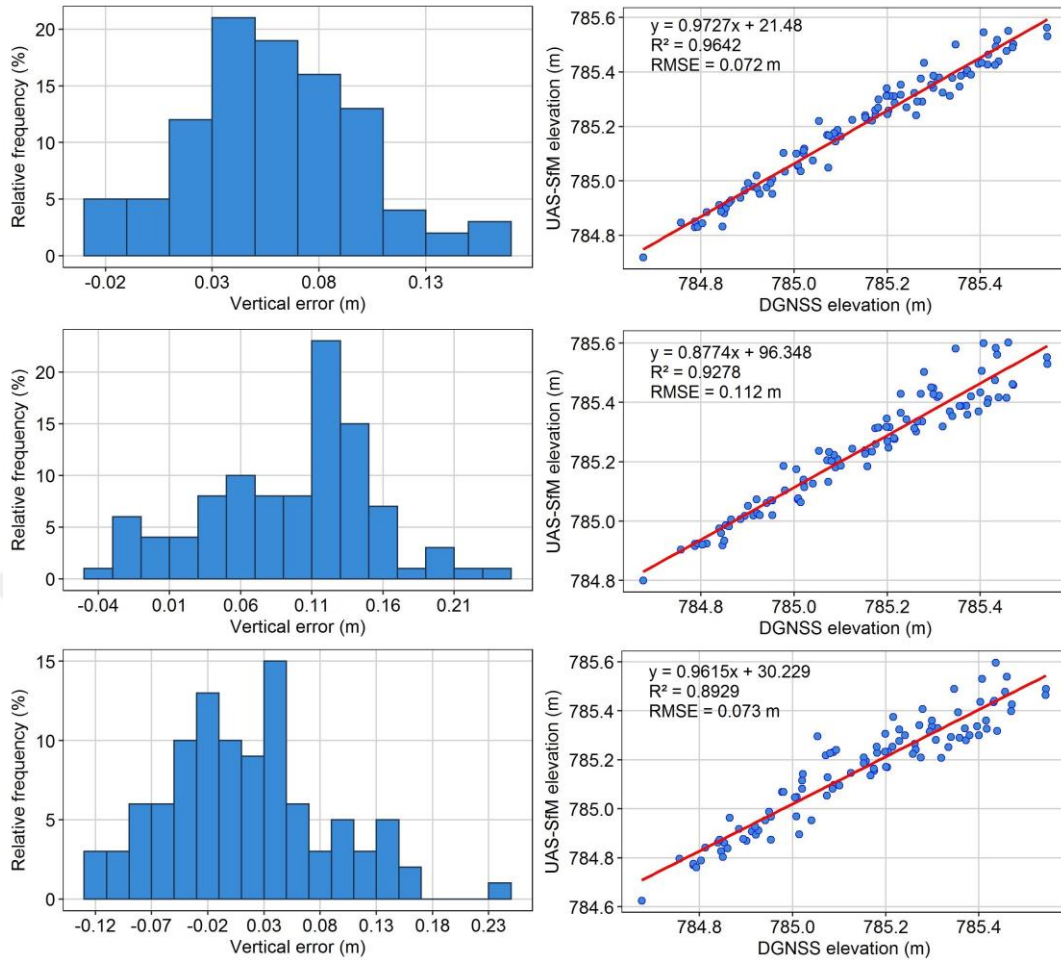


Figure 5.16. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 170 m AGL nadir images, processed with 5 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsury (bottom).

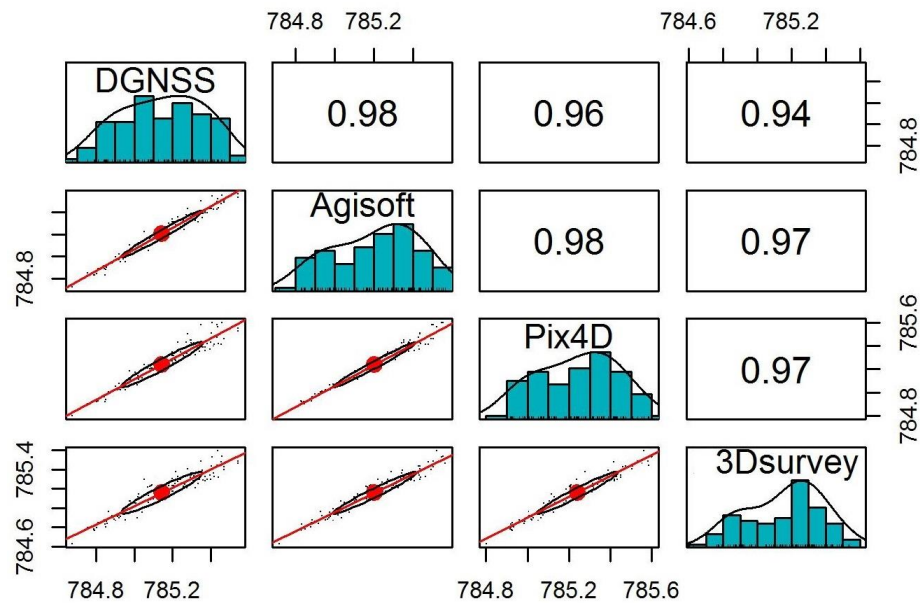


Figure 5.17. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 170 m AGL nadir images, processed with 5 GCPs.

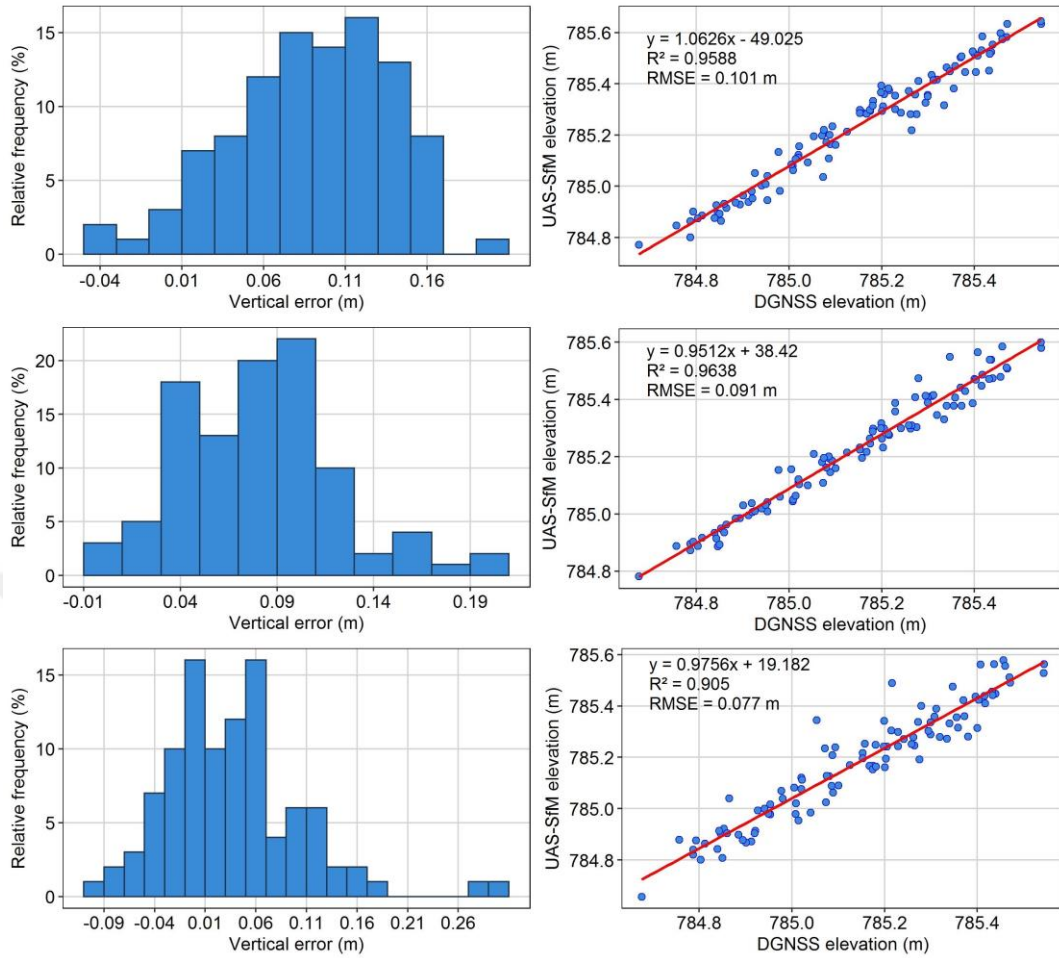


Figure 5.18. Relative frequency histogram of vegetated vertical errors and scatter plot of correlation between UAS-SfM and DGNSS elevations. UAS-SfM DTM derived from 170 m AGL nadir images, processed with 10 GCPs using PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

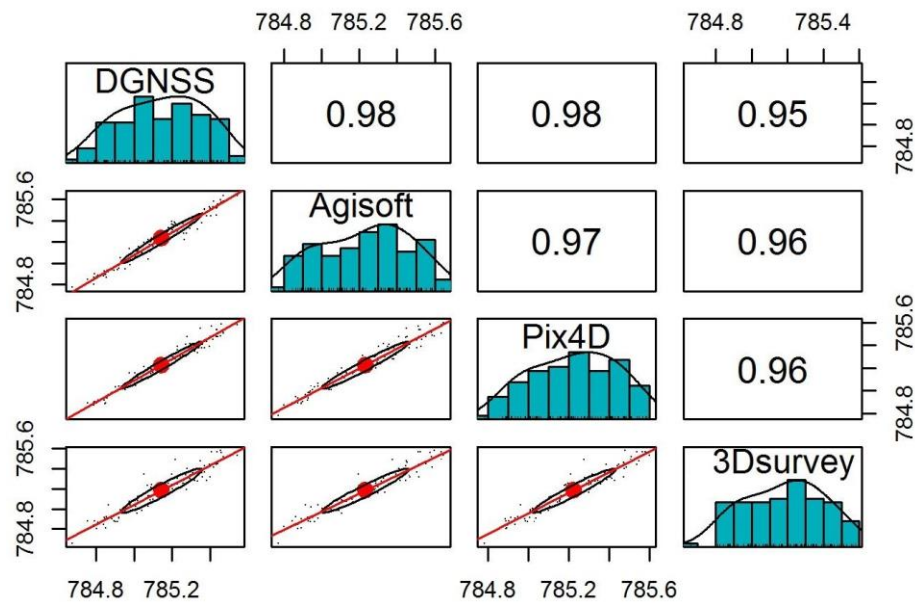


Figure 5.19. Correlation scatter plot matrix of DGNSS vegetated elevations and UAS-SfM DTM elevations derived from 170 m AGL nadir images, processed with 10 GCPs.

The above figures show that as expected, the vegetated vertical error is not too much; this is due to the flat area with sparse and low-height vegetation. The results showed that by increasing the GCP numbers, the vegetated accuracy also increased to some extent. The correlation was also improved using 10 GCPs. The results derived from images of flight 1, where images have more overlap, show stronger correlation than that of flight 2; however, some outliers remain, which is typical for vegetated areas.

5.1.2.5. Influence of GCP distribution on vertical accuracy

Images of both flights were georeferenced using 5 and 10 GCPs. The location of 5 GCPs was intentionally selected in the middle of the study area to leave some areas outside of the GCP polygon to analyze the relationship between errors and their distance to the nearest GCP. In Figure 5.20, the farthest point from the nearest GCP is 267 m; it shows that error increases with distance from GCP. Polynomial regression of 100 samples of difference between SfM DSM elevations and DGNSS in non-vegetated terrain highlights the influence of GCP distribution on vertical error. The figure illustrates that up to a distance of 170 m, almost all of the errors are under 20 cm. As the distance increases, the error also increases gradually, where after 170 m, a 100 m increase in distance indicates about 1 dm increase in error (in both 100 and 170 m AGL). Figure 5.21 shows a similar correlation.

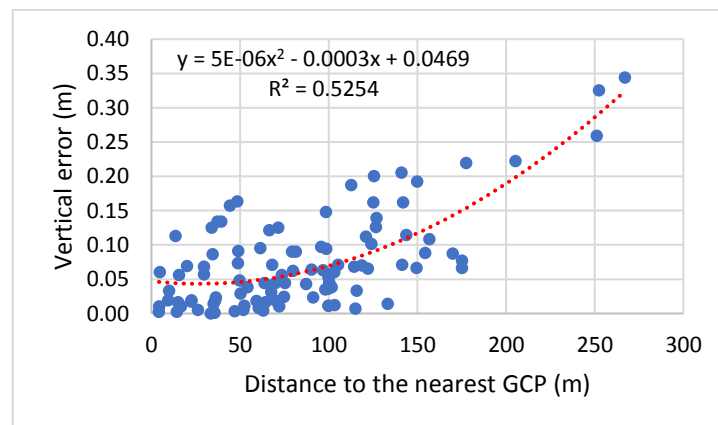


Figure 5.20. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 100 m AGL nadir images, georeferenced with 5 GCPs using PhotoScan.

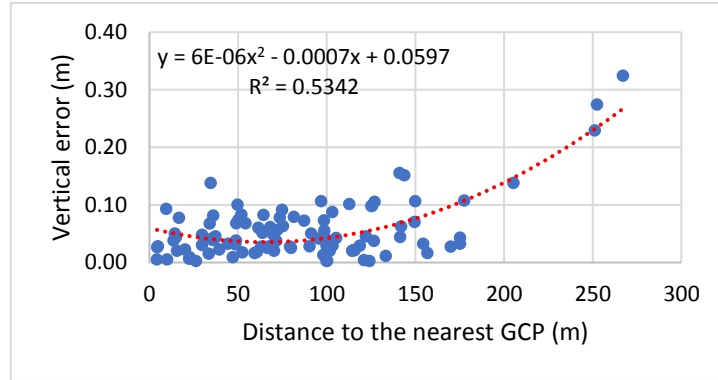


Figure 5.21. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 170 m AGL nadir images, georeferenced with 5 GCPs using PhotoScan.

For an in-depth investigation of the relationship, images of both flights were georeferenced using 10 GCPs and distributed in a way that most of the validation points fall within the GCP polygon, and the maximum distance of validation points from the GCP cluster is 125 m. Figure 5.22 and Figure 5.23 indicate that using 10 GCPs closer to CPs, the correlation between the distance to GCP and the error is weakened, where up to a distance of 100 m, the majority of errors are below 15 cm, most of which range from 0-10 cm.

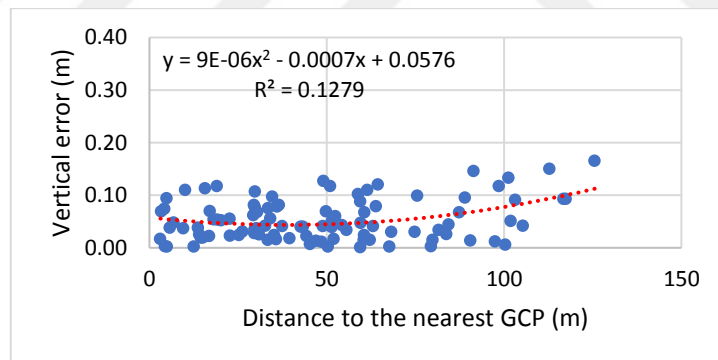


Figure 5.22. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 100 m AGL nadir images, georeferenced with 10 GCPs using PhotoScan.

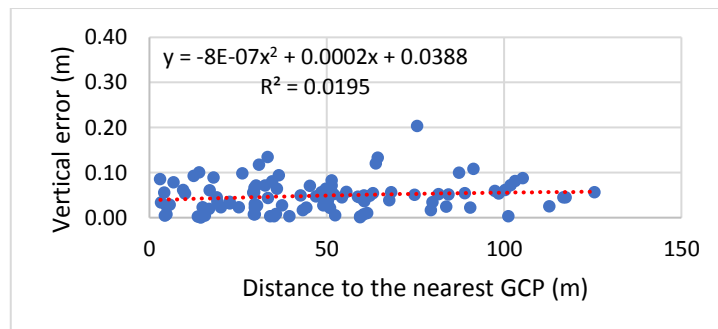


Figure 5.23. Scatter plot of correlation between distance to the nearest GCP and vertical error. Derived from DSM of 170 m AGL nadir images, georeferenced with 10 GCPs using PhotoScan.

From the above figures, we conclude that up to a distance of 100 m, the correlation between distance to the nearest GCP and vertical error is almost zero in both flights, and positive correlation starts from 100 m, where after 150 m, the vertical error increases dramatically. The results of Pix4Dmapper showed the same trend.

5.1.2.6. Accuracy assessment of oblique and nadir photogrammetry in the survey of the selected building at different flight heights

For horizontal and vertical accuracy assessment of the surveyed building, 16 CPs were marked and measured accurately, where 10 of them were selected around the building, and the other 6 CPs were marked on the roof. The 10 CPs were used for horizontal accuracy assessment of the orthomosaics derived from close-range oblique survey data, and also to assess the influence of the horizontal error on the vertical accuracy of DSMs. In addition, horizontal and vertical accuracy comparisons were made between the results of the three software in oblique image processing.

Table 5.8. Horizontal and vertical error statistics of orthomosaics and DSMs derived from 16 m AGL oblique images, processed with 4 GCPs and assessed with 10 GNSS-TS CPs. All values are in meters.

Oblique 16 m AGL (4 GCP)												
	PhotoScan				Pix4Dmapper				3Dsurvey			
	X	Y	Z _O	Z _D	X	Y	Z _O	Z _D	X	Y	Z _O	Z _D
Min	-0.020	-0.005	-0.004	-0.003	-0.060	-0.002	0.004	0.006	-0.022	-0.002	-0.007	-0.007
Max	0.023	0.030	0.040	0.040	0.030	0.077	0.086	0.071	0.099	0.014	0.009	0.009
Mean	0.007	0.008	0.009	0.012	-0.013	0.025	0.031	0.028	0.015	0.003	-0.001	-0.001
MAE	0.017	0.010	0.013	0.013	0.030	0.026	0.031	0.028	0.035	0.005	0.006	0.006
RMSE	0.018	0.015	0.020	0.020	0.036	0.039	0.045	0.038	0.051	0.007	0.006	0.006
RMSE_{XY}	0.024				0.053				0.052			
RMSE_{XYZ}	0.031				0.070				0.052			

Table 5.8 summarizes the horizontal and vertical accuracy assessment of orthomosaics and DSMs derived from oblique images of the building using the three software. The accuracy assessment results based on the 10 CPs given in the table show the best performance of PhotoScan, which resulted in 1.8 cm RSME_X, 1.5 cm RMSE_Y, 2.4 cm RMSE_{XY}, 2.0 cm RMSE_Z, and 3.1 cm 3D RMSE. Pix4Dmapper and 3Dsurvey yielded relatively lower horizontal accuracy (RMSE_{XY} = 5.3 cm and RMSE_{XY} = 5.1 cm, respectively). For the flat area around the building, 3Dsurvey showed higher vertical accuracy than the other two software. The results of PhotoScan and 3Dsurvey demonstrate that the vertical accuracy was not affected by the horizontal error; however,

the results of Pix4D show a 7 mm elevation difference between Z_O and Z_D due to the horizontal displacement.

For vertical accuracy evaluation and comparison of building point clouds derived from the nadir and oblique images, 16 CPs were used. The results of horizontal and vertical accuracy assessment are given in the following tables.

Table 5.9. Vertical error statistics of the building point clouds derived from oblique and nadir images of different flight heights using PhotoScan and assessed with 16 GNSS-TS CPs. All values are in meters.

	Oblique 16 m AGL	Nadir 100 m AGL		Nadir 170 m AGL		Nadir merged of 100 and 170 m
	4 GCP	5 GCP	10 GCP	5 GCP	10 GCP	5 GCP
Min	-0.035	-0.093	-0.106	-0.141	-0.080	-0.086
Max	0.031	-0.003	0.020	0.022	0.116	0.060
Mean	0.002	-0.044	-0.056	-0.068	-0.003	-0.042
MAE	0.015	0.044	0.058	0.072	0.041	0.050
RMSE	0.019	0.049	0.063	0.082	0.051	0.055

Table 5.10. Vertical error statistics of the building point clouds derived from oblique and nadir images of different flight heights using Pix4D and assessed with 16 GNSS-TS CPs. All values are in meters.

	Oblique 16 m AGL	Nadir 100 m AGL		Nadir 170 m AGL	
	4 GCP	5 GCP	10 GCP	5 GCP	10 GCP
Min	-0.045	-0.056	-0.120	-0.101	-0.086
Max	0.092	0.037	-0.002	0.071	0.078
Mean	0.018	-0.004	-0.052	-0.043	-0.017
MAE	0.035	0.025	0.052	0.057	0.046
RMSE	0.044	0.030	0.060	0.064	0.051

Table 5.11. Vertical error statistics of the building point clouds derived from oblique and nadir images of different flight heights using 3Dsurvey and assessed with 16 GNSS-TS CPs. All values are in meters.

	Oblique 16 m AGL	Nadir 100 m AGL		Nadir 170 m AGL	
	4 GCP	5 GCP	10 GCP	5 GCP	10 GCP
Min	-0.043	-0.142	-0.046	-0.229	-0.184
Max	0.121	0.045	0.137	0.115	0.139
Mean	0.028	-0.067	0.059	-0.041	-0.023
MAE	0.041	0.077	0.070	0.079	0.085
RMSE	0.052	0.085	0.078	0.099	0.099

The vertical accuracy assessment results of building point clouds derived from the nadir and oblique images using PhotoScan, Pix4D, and 3Dsurvey given in Tables 5.9, 5.10, and 5.11, compare the accuracies obtained from different flight heights. As the

tables show, PhotoScan yielded the highest vertical point cloud accuracy from oblique images (RMSE = 1.9 cm). The results of Pix4D and 3Dsurvey from oblique images show 4.4 cm and 5.2 cm vertical accuracy, respectively. The vertical point cloud accuracy obtained from nadir images of 100 m and 170 m flight heights processed with 5 GCPs and 10 GCPs range from 3-10 cm, where the highest accuracy was obtained by Pix4D and the least by 3Dsurvey. As can be seen in the above tables, increasing the number of GCPs from 5 to 10 resulted in different vertical accuracy, which in some cases contributed to the accuracy and in some cases the accuracy was reduced as the GCP number increased (e.g., images of 100 m AGL processed by PhotoScan and Pix4D).

5.2. 3D modeling and volumetric accuracy assessment

A building with an overhanging eave was surveyed using TLS and UAS to compare models, as well as the accuracy of UAS-SfM in volumetric calculations. 3D models of the building were reconstructed from UAS oblique images acquired from 16 m height AGL and nadir at 100 and 170 m AGL using the three software packages. The volume of the building was calculated from the generated point cloud using AutoCAD Civil 3D. Figure 5.24 shows the 3D dense point cloud model of the building generated from oblique images using Agisoft PhotoScan.

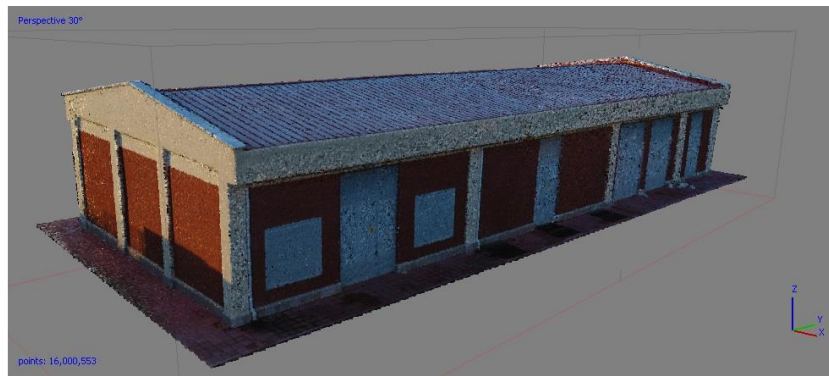


Figure 5.24. 3D dense point cloud of the building generated using PhotoScan from oblique image of DJI Phantom 4 Pro UAS at 16 m AGL.

Figure 5.25 and Figure 5.26 illustrate 3D solid and textured mesh models of the building generated using PhotoScan. Figure 5.27 compares the TLS and UAS-SfM (PhotoScan) point clouds of the building. A comparative figure of the building point clouds generated from oblique and nadir images of different flight heights using the three software is given in Figure 5.28.

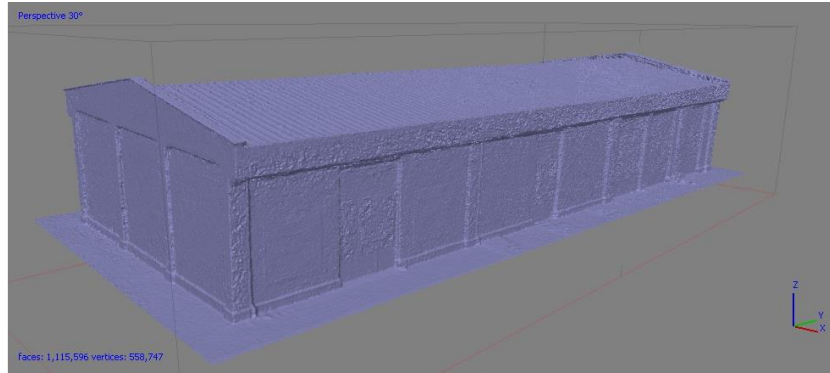


Figure 5.25. 3D solid mesh of the building generated using PhotoScan.



Figure 5.26. 3D textured mesh of the building generated using PhotoScan.

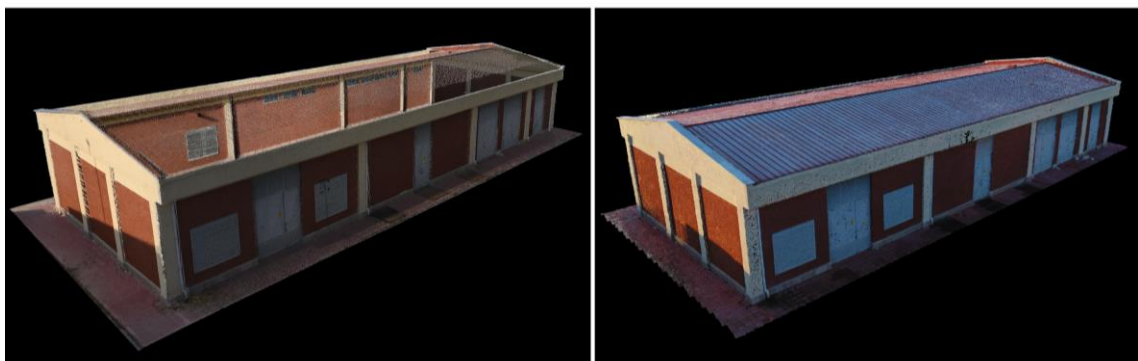


Figure 5.27. Comparison of TLS (left) and SfM-PhotoScan (right) building point clouds.

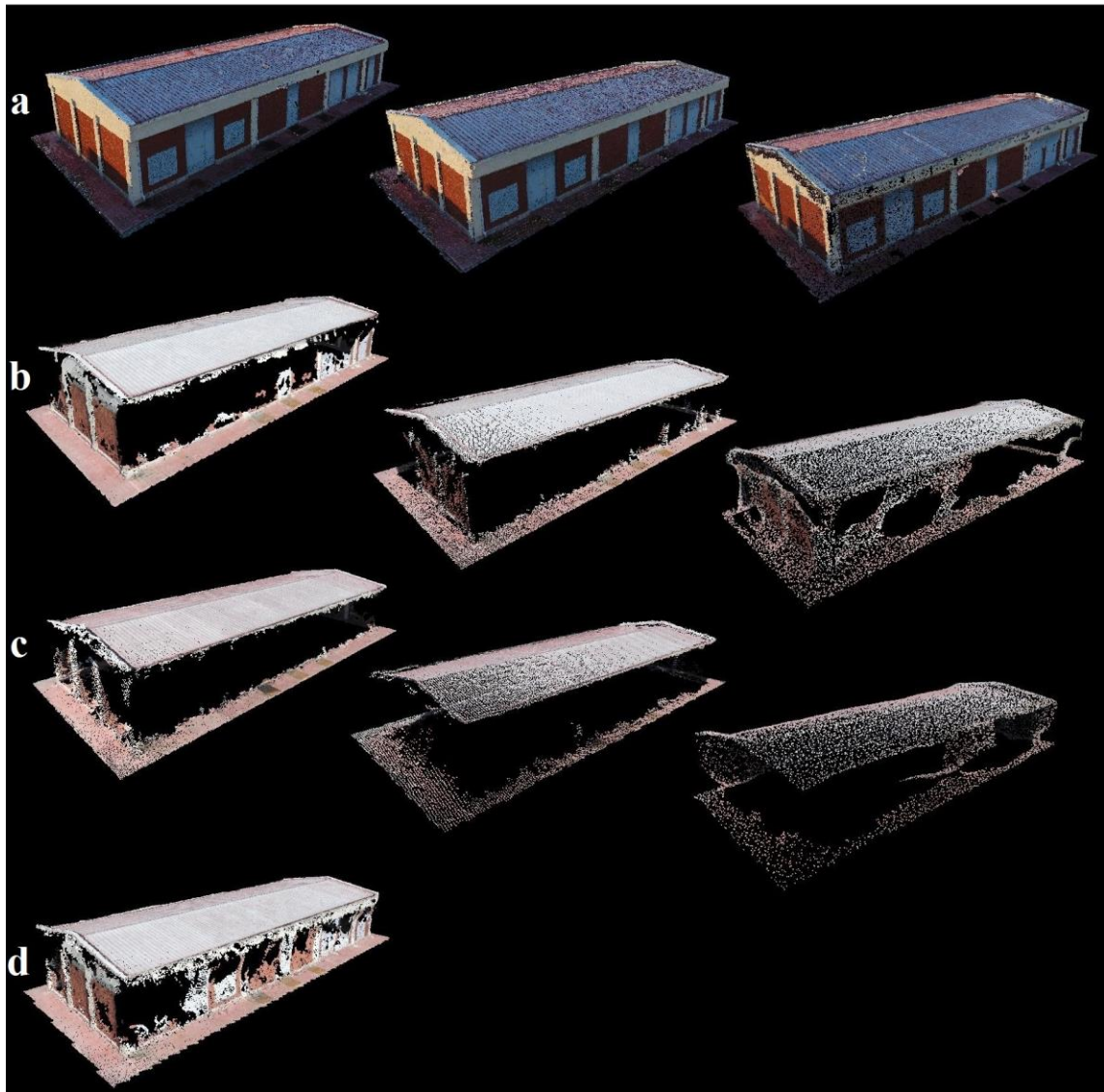


Figure 5.28. Comparison of oblique and nadir point clouds derived from images of DJI oblique 16 m AGL (a), senseFly 100 m (b), 170 m (c), and merged of 100 and 170 m (d) processed using PhotoScan (left), Pix4D (middle), and 3Dsurvey (right) SfM-MVS software packages.

As can be seen in Figure 5.27, the TLS point cloud is very dense, but it shows gaps on the roof because it was surveyed from the ground at about 2.5 m height. On the other hand, the point cloud model of UAS-SfM generated using PhotoScan shows a comparable complete dense point cloud of the building. This shows the advantage of UAS-SfM over the TLS in 3D modeling.

Figure 5.28 illustrates the advantage of close-range oblique image acquisition over nadir. The point cloud models generated from images of DJI Phantom 4 Pro presented almost perfect models of the building, while this is impossible from nadir images. However, merging two nadir blocks of different flight heights (100 and 170 m AGL) highly contribute to the point cloud density, as shown in Figure 5.28d, the gaps at the

sides of the building considerably filled using integrated processing of two photogrammetric blocks. The figure also shows the superiority of PhotoScan in generating dense point clouds over Pix4D and 3Dsurvey. It is worth mentioning that PhotoScan's point cloud required less cleaning (since this software allows the user to perform some filtering on the sparse point cloud). Pix4D and 3Dsurvey produced rather noisy point clouds that required a lot of work and manual cleaning to perform the volumetric calculation.

The building volume was calculated using TLS point cloud as well as from the point clouds derived from oblique and nadir UAS images. For comparing the results of the TLS and the UAS-based survey, the length, width, and height of the building were measured from point clouds. The measurements obtained from TLS was also validated by direct field measurements using a TS and measuring tape. The volumetric calculation results of TLS and SfM derived from oblique images of 16 m AGL are given in Table 5.12.

Table 5.12. Building dimensions and volume measured from 3D point clouds of TLS and SfM (derived from oblique images of 16 m AGL taken using DJI Phantom 4 Pro).

	TLS	PhotoScan with GCP	Pix4D with GCP	3Dsurvey with GCP	PhotoScan without GCP
Length (m)	32.821	32.829	32.846	32.874	32.865
Width (m)	12.945	12.958	12.969	12.952	12.959
Height 1 (m)	5.600	5.595	5.571	5.666	5.610
Height 2 (m)	6.685	6.683	6.699	6.713	6.742
Volume (m³)	2480.770	2481.430	2481.860	2527.09	2526.930
Volume difference (m³)		0.66	1.09	46.32	46.16

The above table shows that there is an insignificant difference between the volume and dimensions of the building measured from the TLS and PhotoScan point clouds. The maximum differences in dimensions are at the level of 0.01 m, and 0.66 m³ in volume. Similarly, the results of Pix4Dmapper show little differences, with maximum dimension and volume differences of about 0.03 m and 1.09 m³, respectively. In contrast, the results from 3Dsurvey show considerable differences, in which the maximum difference in dimensions is approximately 0.06 m and in volume 46.32 m³.

The following tables compare the statistics of the building point clouds and volumes calculated from point clouds of oblique and nadir images. The TLS point cloud statistics show approximately 56 million points in which the point spacing is 2 mm. The results show that PhotoScan produced point cloud of the building with 4 mm point spacing, while

the point spacing in data of Pix4D and 3Dsurvey are 7 mm and 35 mm, respectively. The point count in PhotoScan, Pix4D, and 3Dsurvey are 16,000,553, 4,199,742, and 259,887, respectively. As the statistics show, after TLS, PhotoScan produced point clouds with the highest density. On the other hand, 3Dsurvey generated a sparse point cloud compared to others. Although the processing options were set to optimum in all the three software, the tables show that the point count in the point cloud of the building generated from the nadir images of 100 m AGL using PhotoScan is higher than that of 3Dsurvey from 16 m AGL. This shows that 3Dsurvey is not suitable for 3D modeling.

Table 5.13. Building point cloud statistics and comparison of the building volumes calculated from PhotoScan point clouds.

PhotoScan							
	TLS	Oblique 16 m AGL	Nadir 100 m AGL		Nadir 170 m AGL		Nadir merged of 100 and 170 m
		4 GCP	5 GCP	10 GCP	5 GCP	10 GCP	5 GCP
Volume (m³)	2480.77	2481.430	2484.980	2487.290	2492.030	2465.180	2490.370
Volume difference (m³; SfM-TLS)		0.660	4.210	6.520	11.260	-15.590	9.600
Point count	56,655,406	16,000,553	325,612	321,088	122,334	121,326	213,991
Point density (samples×m²)	246031	52937	667	687	255	257	478
Point spacing (m)	0.002	0.004	0.038	0.038	0.063	0.062	0.046
Min elevation	785.32	785.318	785.282	785.125	785.051	785.307	785.355
Max elevation	792.414	792.392	792.465	792.328	792.420	792.235	792.318

Table 5.14. Building point cloud statistics and comparison of the building volumes calculated from Pix4Dmapper point clouds.

	TLS	Pix4Dmapper				
		Oblique 16 m AGL	Nadir 100 m AGL		Nadir 170 m AGL	
		4 GCP	5 GCP	10 GCP	5 GCP	10 GCP
Volume (m ³)	2480.77	2481.860	2602.830	2638.420	2648.640	2639.250
Volume difference (m ³ ; SfM-TLS)		1.090	122.060	157.650	167.870	158.480
Point count	56,655,406	4,199,742	69,984	70,645	26,525	26,005
Point density (samples × m ⁻²)	246031	17946	138	140	51	51
Point spacing (m)	0.002	0.007	0.085	0.085	0.140	0.140
Min elevation	785.32	785.472	785.205	785.239	785.280	785.380
Max elevation	792.414	792.418	792.422	792.343	792.380	792.370

Table 5.15. Building point cloud statistics and comparison of the building volumes calculated from 3Dsurvey point clouds.

	TLS	3Dsurvey				
		Oblique 16 m AGL	Nadir 100 m AGL		Nadir 170 m AGL	
		4 GCP	5 GCP	10 GCP	5 GCP	10 GCP
Volume (m³)	2480.77	2527.090	2766.010	2790.980	2863.570	2883.570
Volume difference (m³; SfM-TLS)		46.320	285.240	310.210	382.800	402.800
Point count	56,655,406	259,887	43,297	30,972	13,322	11,447
Point density (samples × m⁻²)	246031	837	151	114	46	33
Point spacing (m)	0.002	0.035	0.081	0.094	0.148	0.175
Min elevation	785.32	785.390	785.214	785.323	785.080	785.190
Max elevation	792.414	792.463	792.387	792.453	792.180	792.180

The volume and measurements obtained from PhotoScan point cloud processed without GCP yielded better results than the results from 3Dsurvey processed with GCP. The results showed that 3Dsurvey is not suitable for accurate 3D modeling and volumetric calculations. PhotoScan can be used for urgent volumetric works without the need for GCPs. It gives excellent results for imprecise estimates, for example, for stockpile measurement or other volumetric survey works. It should be noted that Pix4dmapper and 3D survey failed to reconstruct the building without GCP. In summary, the volumes calculated from the results of PhotoScan are considerably more accurate than that of Pix4D and 3Dsurvey. By producing very dense point clouds of the building with 2 cm horizontal and vertical accuracy from oblique images, and 5 cm from nadir images of 100 and 170 m AGL, PhotoScan demonstrated its superiority over Pix4Dmapper and 3Dsurvey.

The exact volume of vertical objects with overhanging elements can only be calculated using a point cloud or triangulated model, DSM overestimates the volume due to its 2.5D nature. Figure 5.29 shows that in DSM, the building overhanging eave interpolated from top to bottom vertically, while in the point cloud model, every detail can be measured. Since the digital surface model is 2.5D model with a single attribute (Z) for each planar (X, Y) location, which is generated using interpolation (Nesbit & Hugenholtz, 2019), it is impossible to obtain detailed 3D information on flat vertical objects. For example, details of building walls cannot be extracted from DSM, but only the ground and rooftop can be represented.

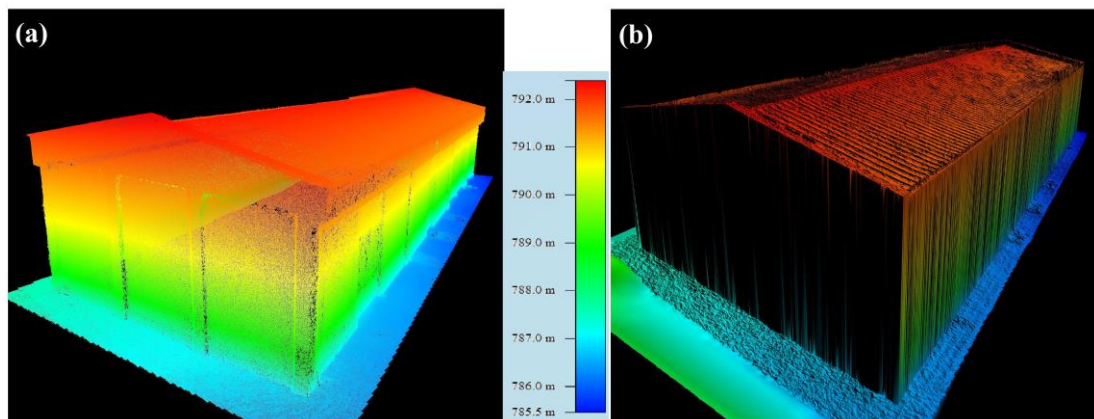


Figure 5.29. Comparison of the 3D point cloud (a) and 2.5D DSM (b) of the building with the overhanging element.

5.3. Profile and cross-sectional analysis

For a comprehensive evaluation from the user's point of view, profile and cross-sectional analysis are essential because these are the indispensable part of terrain analysis. The cross-profile analysis allows us to better describe the vertical quality and the level of detail of the reconstruction.

Profiles and cross-sections of the selected part of the road (see Figure 5.30) were created using AutoCAD Civil 3D from TS survey data, TLS point cloud, and UAS-SfM DSMs of 170 m AGL (flight 1) and 100 m AGL (flight 2) generated using the three software. The following figures show profiles and cross-sections of the selected road extracted from field measurements and DSMs of UAS-SfM. Profile details were extracted at the DSM resolution level.

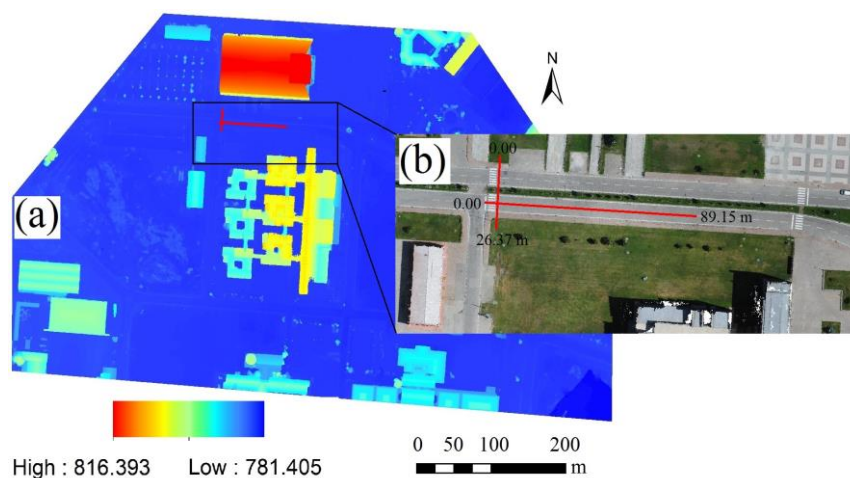


Figure 5.30. Location of the selected road profile and cross-section on the DSM (a) and point cloud (b) of the study area.

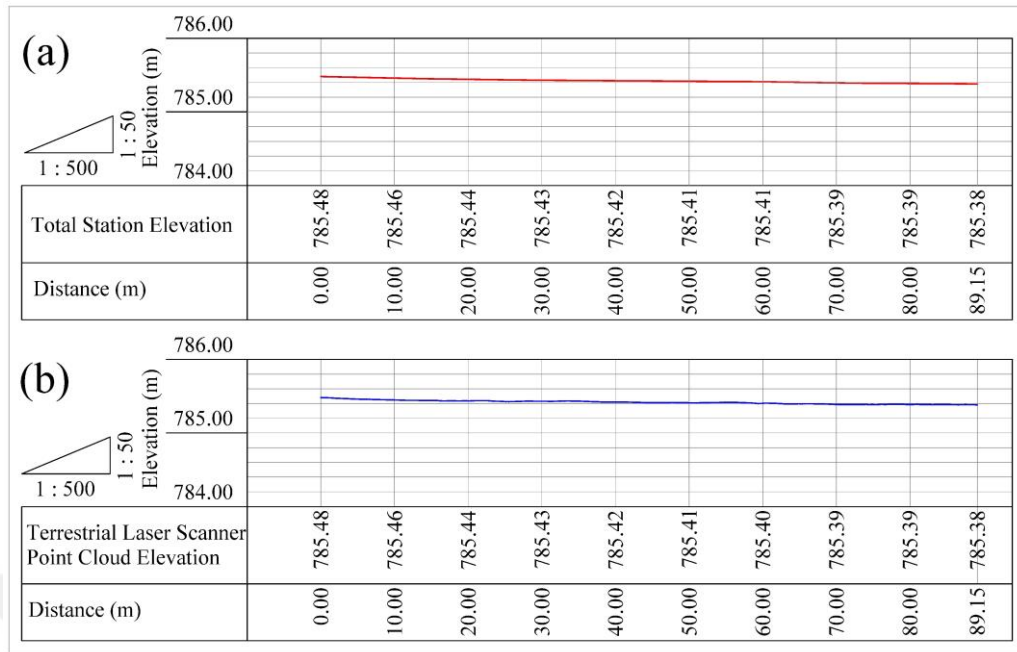


Figure 5.31. Road longitudinal profiles created from TS (a) and TLS (b) data.

The above figure shows profiles of the road surveyed using the total station and terrestrial laser scanner. A comparison was made, and the result showed that the elevation differences were in millimeters.

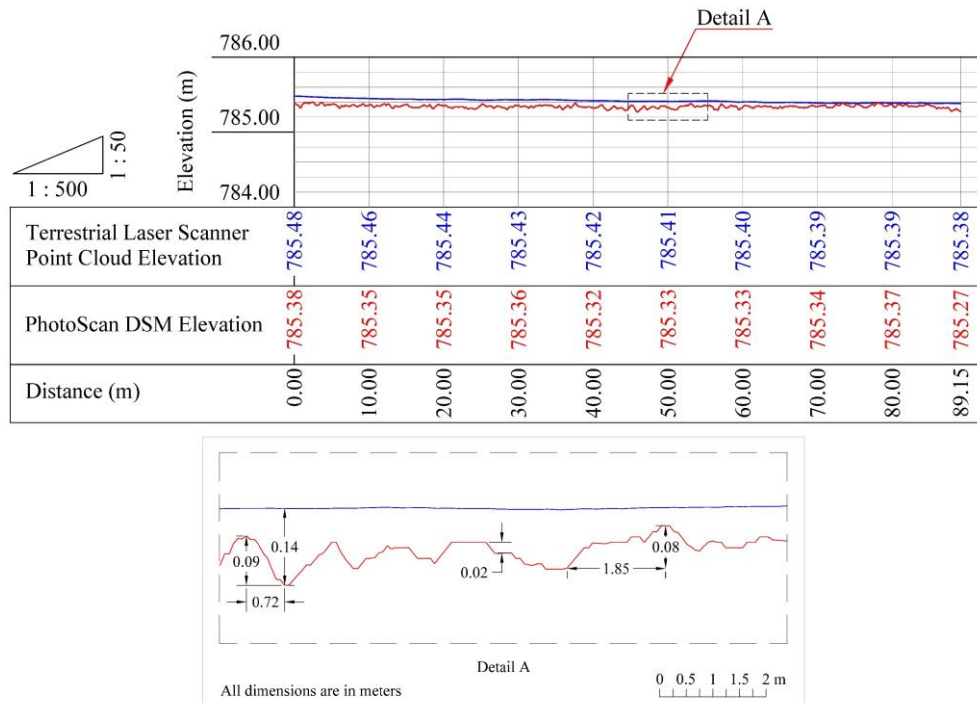


Figure 5.32. Vertical differences between TLS point cloud profile and PhotoScan DSM extracted profile (flight 1; 5 GCP).

Figure 5.32 illustrates the profile elevation differences between TLS point cloud and PhotoScan DSM of flight 1 processed with 5 GCPs. Detail A shows the reconstructed surface undulation; the dimensions of the major surface undulations are shown.

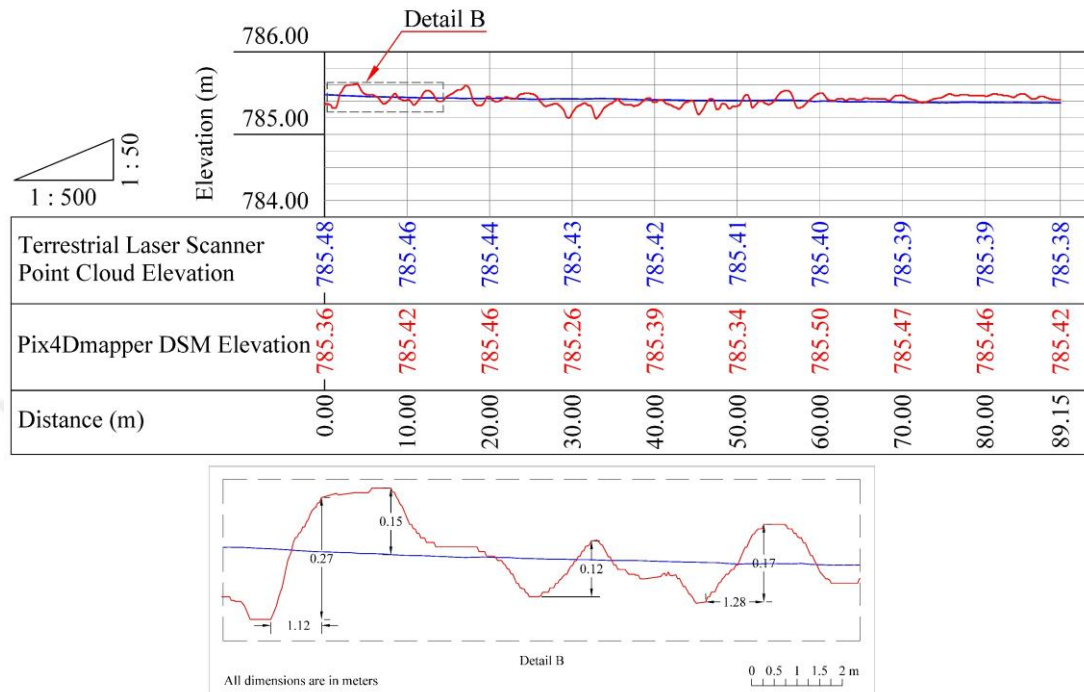


Figure 5.33. Vertical differences between TLS point cloud profile and Pix4D DSM extracted profile (flight 1; 5 GCP).

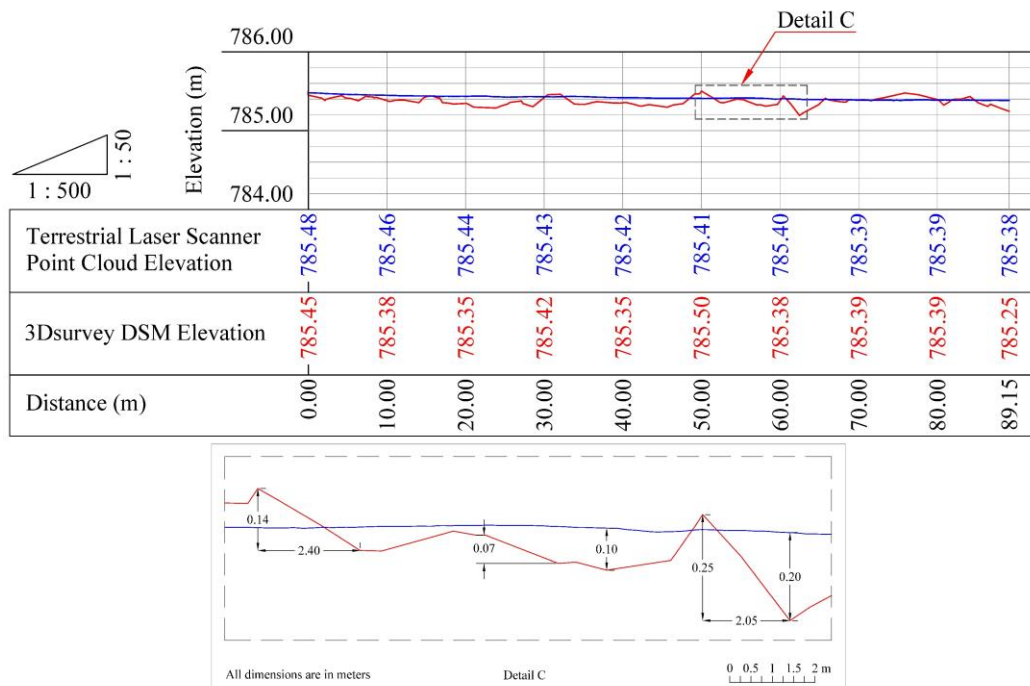


Figure 5.34. Vertical differences between TLS point cloud profile and Pix4D DSM extracted profile (flight 1; 5 GCP).

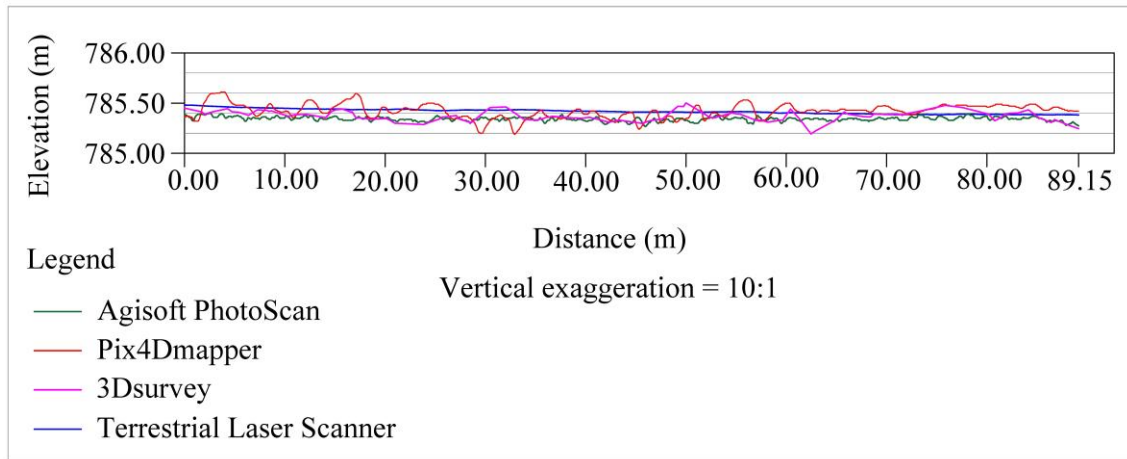


Figure 5.35. Comparison of vertical profiles extracted from TLS point cloud and UAS-SfM based DSMs (flight 1; 5 GCP).

Figure 5.35 compares the profiles of flight 1 extracted from DSMs of the three software. As can be seen, the profile created from PhotoScan's DSM is smoother and more accurate than Pix4D and 3Dsurvey.

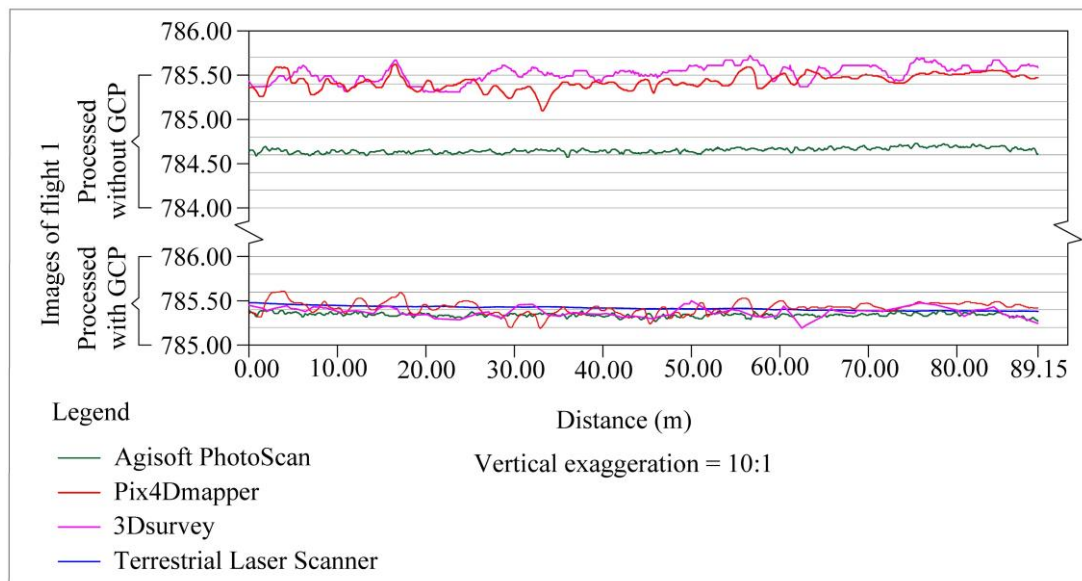


Figure 5.36. Comparison of UAS-SfM based profiles processed with and without GCPs (flight 1; 5 GCP).

In order to evaluate the relative accuracy of the DSMs generated without georeferencing, the profiles were created from both DSMs generated from point clouds processed with GCPs and without GCP (see Figure 5.36). The above figure shows the importance of GCP; in addition to high fluctuations, the profiles of DSMs without GCP show inverse slopes. Nevertheless, the relative accuracy of PhotoScan is also much better than that of Pix4D and 3Dsurvey.

The following figures compare the road cross-sections created from the SfM DSMs and the TLS point cloud.



Figure 5.37. Cross-section of the road extracted from the TLS point cloud.

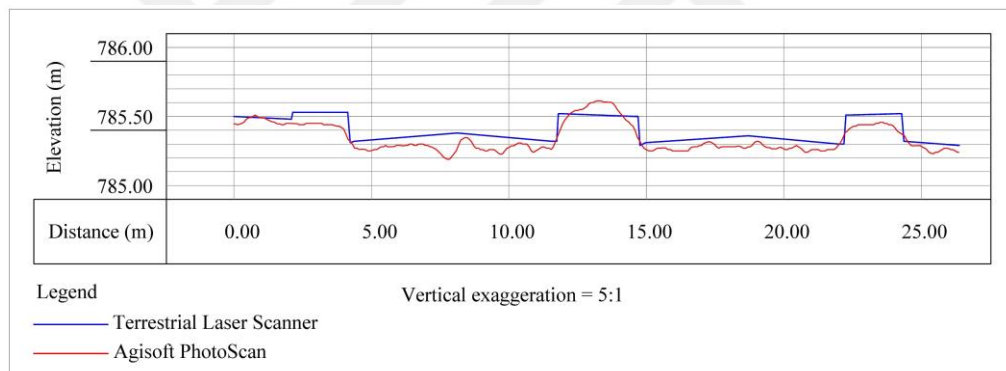


Figure 5.38. Vertical differences between TLS point cloud and PhotoScan DSM cross-sections (flight 1; 5 GCP).

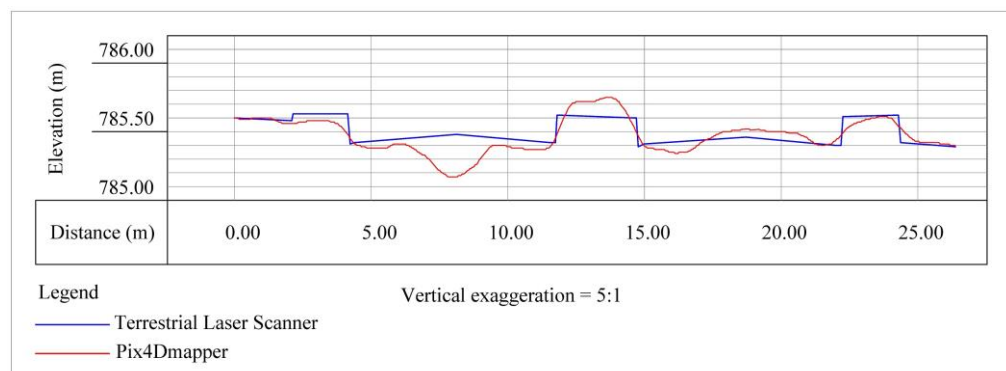


Figure 5.39. Vertical differences between TLS point cloud and Pix4D DSM cross-sections (flight 1; 5 GCP).

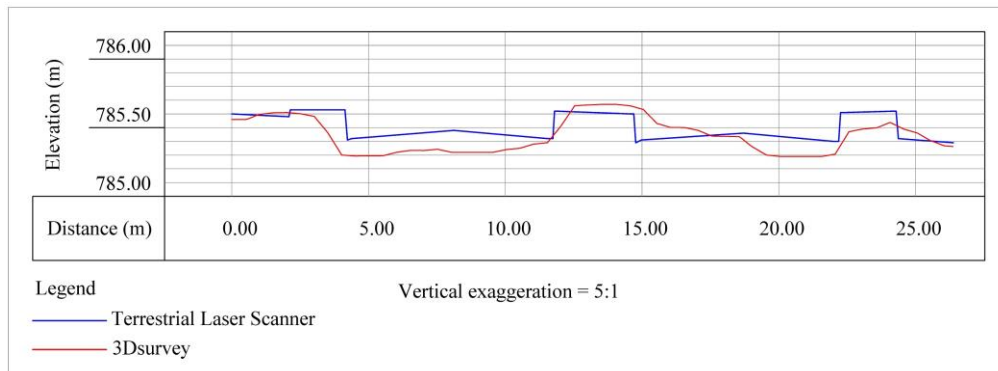


Figure 5.40. Vertical differences between TLS point cloud and 3Dsurvey DSM cross-sections (flight 1; 5 GCP).

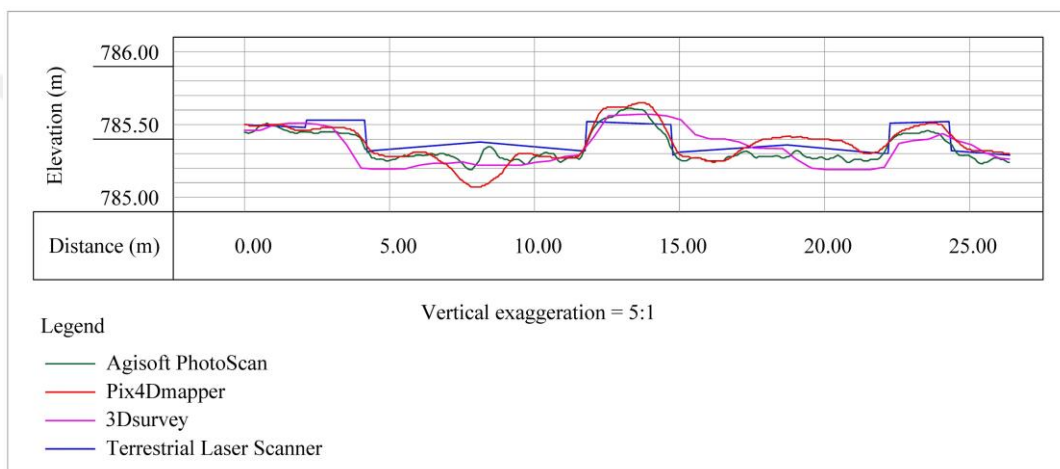


Figure 5.41. Comparison of road cross-sections extracted from TLS point cloud and UAS-SfM DSMs (flight 1; 5 GCP).

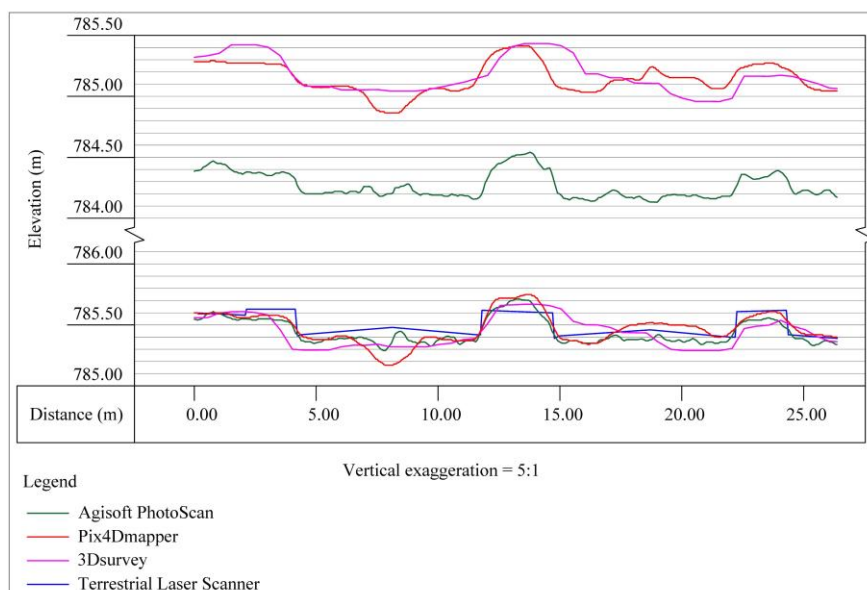


Figure 5.42. Comparison of UAS-SfM based road cross sections processed with and without GCPs

The following figures show the profiles and cross-sections created from flight 2 DSMs.

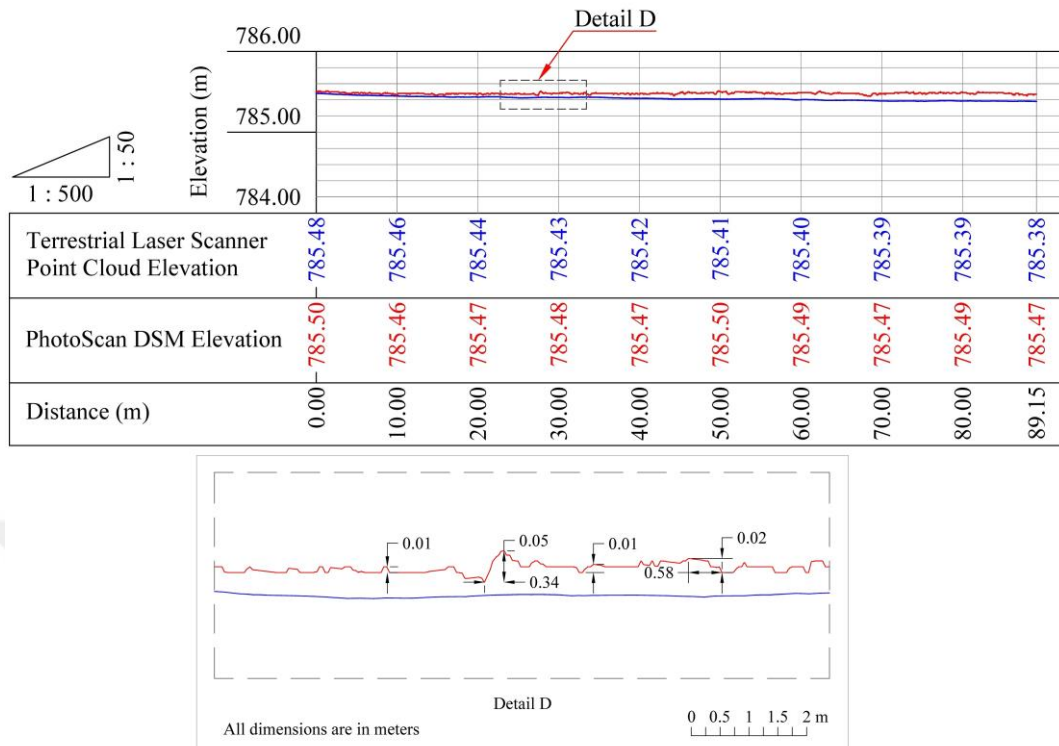


Figure 5.43. Vertical differences between TLS point cloud profile and PhotoScan DSM extracted profile (flight 2; 5 GCP).

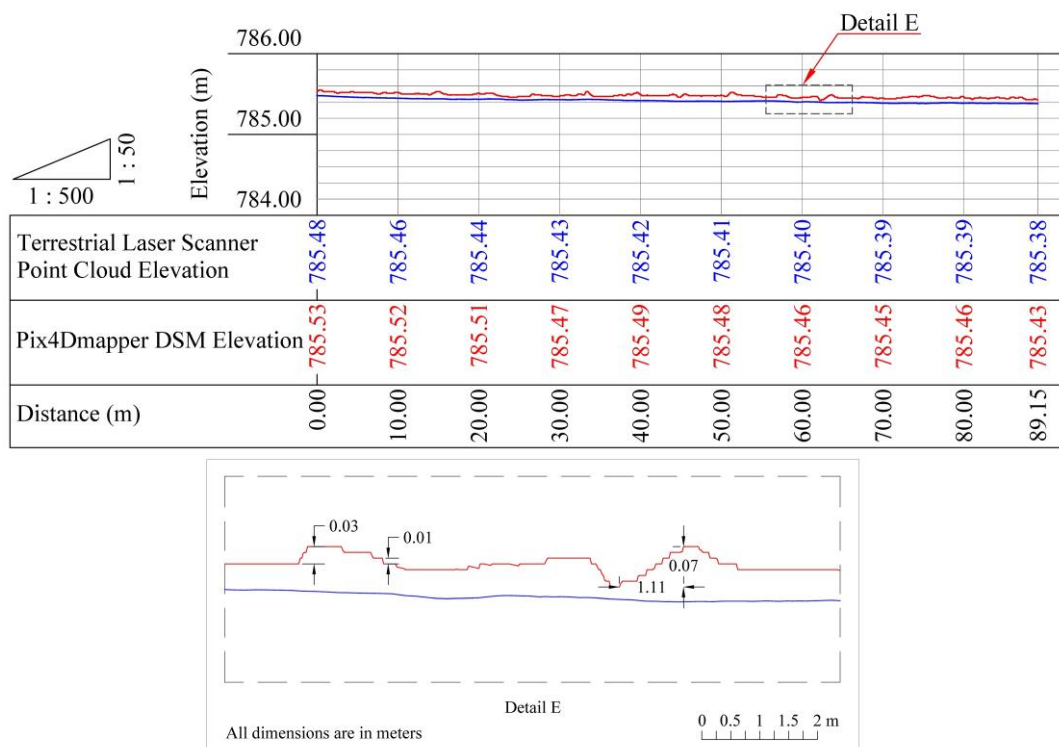


Figure 5.44. Vertical differences between TLS point cloud profile and Pix4D DSM extracted profile (flight 2; 5 GCP).

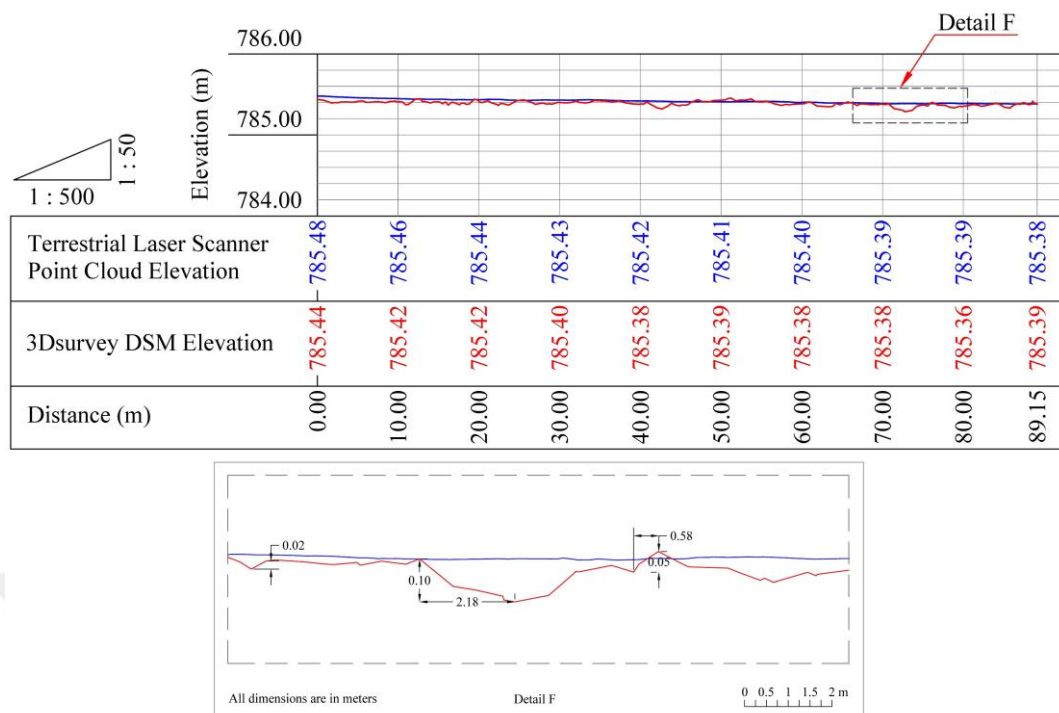


Figure 5.45. Vertical differences between TLS point cloud profile and 3Dsurvey DSM extracted profile (flight 2; 5 GCP).

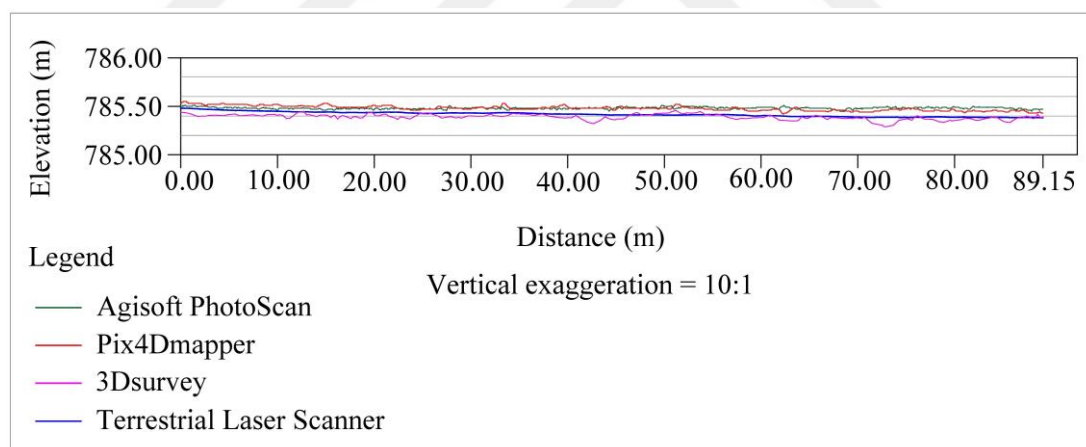


Figure 5.46. Comparison of vertical profiles extracted from TLS point cloud and UAS-SfM based DSMs (flight 2; 5 GCP).

The above figures show that profiles created from the DSMs of flight 2 have higher accuracy and smoother lines.

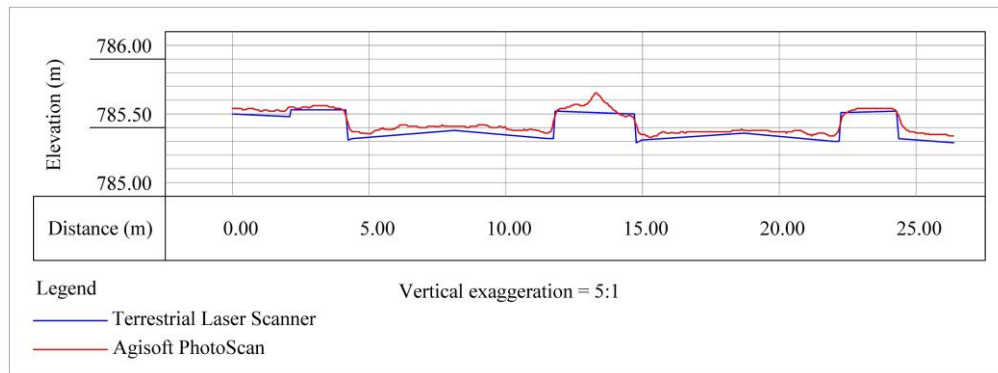


Figure 5.47. Vertical differences between TLS point cloud and PhotoScan DSM cross-sections (flight 2; 5 GCP).

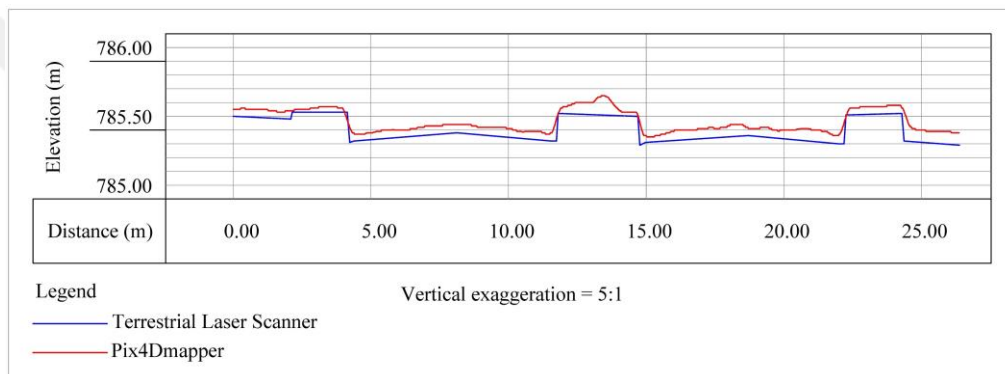


Figure 5.48. Vertical differences between TLS point cloud and Pix4D DSM cross-sections (flight 2; 5 GCP).

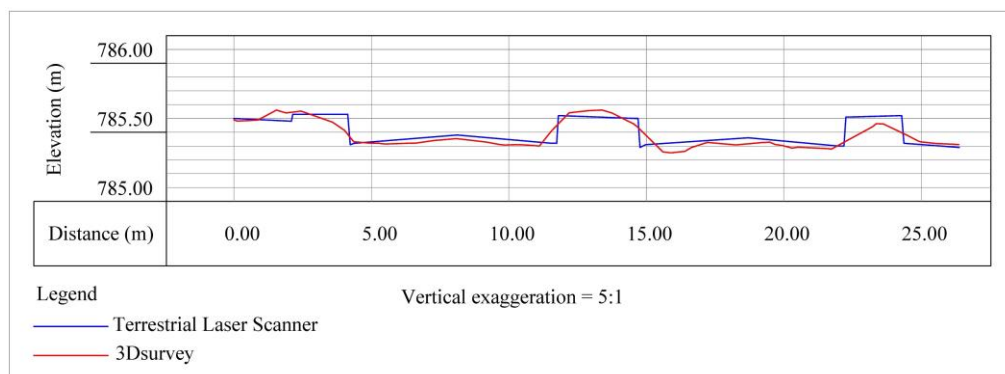


Figure 5.49. Vertical differences between TLS point cloud and 3Dsury DSM cross-sections (flight 2; 5 GCP).

Similarly, the cross-sections created from the DSMs of flight 2 with lower altitude, show higher accuracy and visual quality.

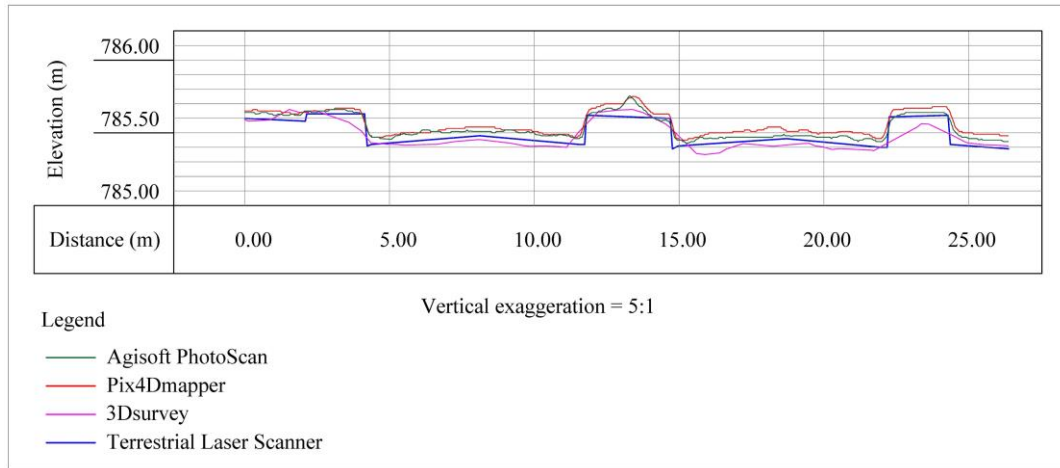


Figure 5.50. Comparison of road cross-sections extracted from TLS point cloud and UAS-SfM DSMs (flight 2; 5 GCP).

The above figures clearly show the effect of flight altitude. The results from flight 1 and flight 2 indicate that flight altitude is more important than the image overlap. Although the image overlaps are higher in flight 1, the reconstructed surfaces have high fluctuation due to high altitude. The following tables show the results of profiles and cross-sectional accuracy analysis.

Table 5.16. Profile statistics of elevation difference between UAS-SfM (100m AGL) and TLS.

100 m AGL						
5 GCP				10 GCP		
	PhotoScan	Pix4D	3Dsurvey	PhotoScan	Pix4D	3Dsurvey
Min (m)	-0.002	0.014	-0.098	-0.067	-0.026	-0.066
Max (m)	0.115	0.105	0.046	-0.002	0.063	0.068
Mean (m)	0.060	0.058	-0.026	-0.027	0.007	0.019
MAE (m)	0.060	0.058	0.031	0.027	0.014	0.026
RMSE (m)	0.066	0.059	0.038	0.029	0.017	0.032

Table 5.17. Profile statistics of elevation difference between UAS-SfM (170 m AGL) and TLS.

170 m AGL						
5 GCP				10 GCP		
	PhotoScan	Pix4D	3Dsurvey	PhotoScan	Pix4D	3Dsurvey
Min (m)	-0.152	-0.238	-0.217	-0.102	-0.253	-0.173
Max (m)	0.003	0.150	0.086	0.031	0.162	0.112
Mean (m)	-0.078	0.000	-0.055	-0.034	-0.025	-0.049
MAE (m)	0.078	0.061	0.069	0.036	0.058	0.068
RMSE (m)	0.083	0.075	0.081	0.042	0.073	0.083

Tables 5.16 and 5.17 show the influence of flight height as well as the GCP number on the DSM accuracy analyzed by profile differences. The tables show the considerable contribution of 10 GCPs to the vertical accuracy. By adding five more GCPs, the accuracy was improved about 4 cm. The figures below compare the profiles and cross-sections derived from flight 1 and flight 2 data (processed using 5 GCPs).

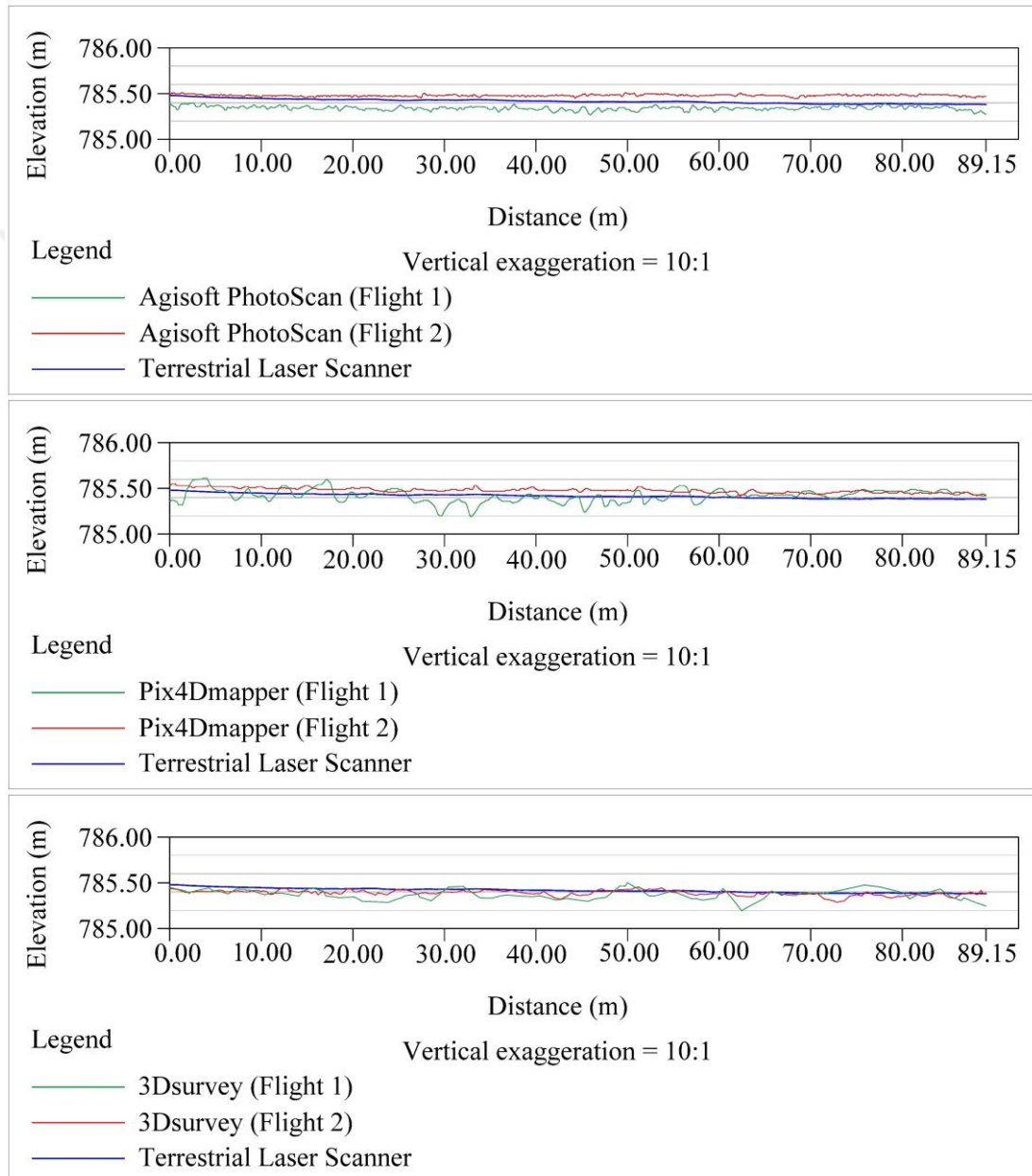


Figure 5.51. Comparison of road profiles extracted from TLS point cloud and SfM DSMs of flight 1 and 2.

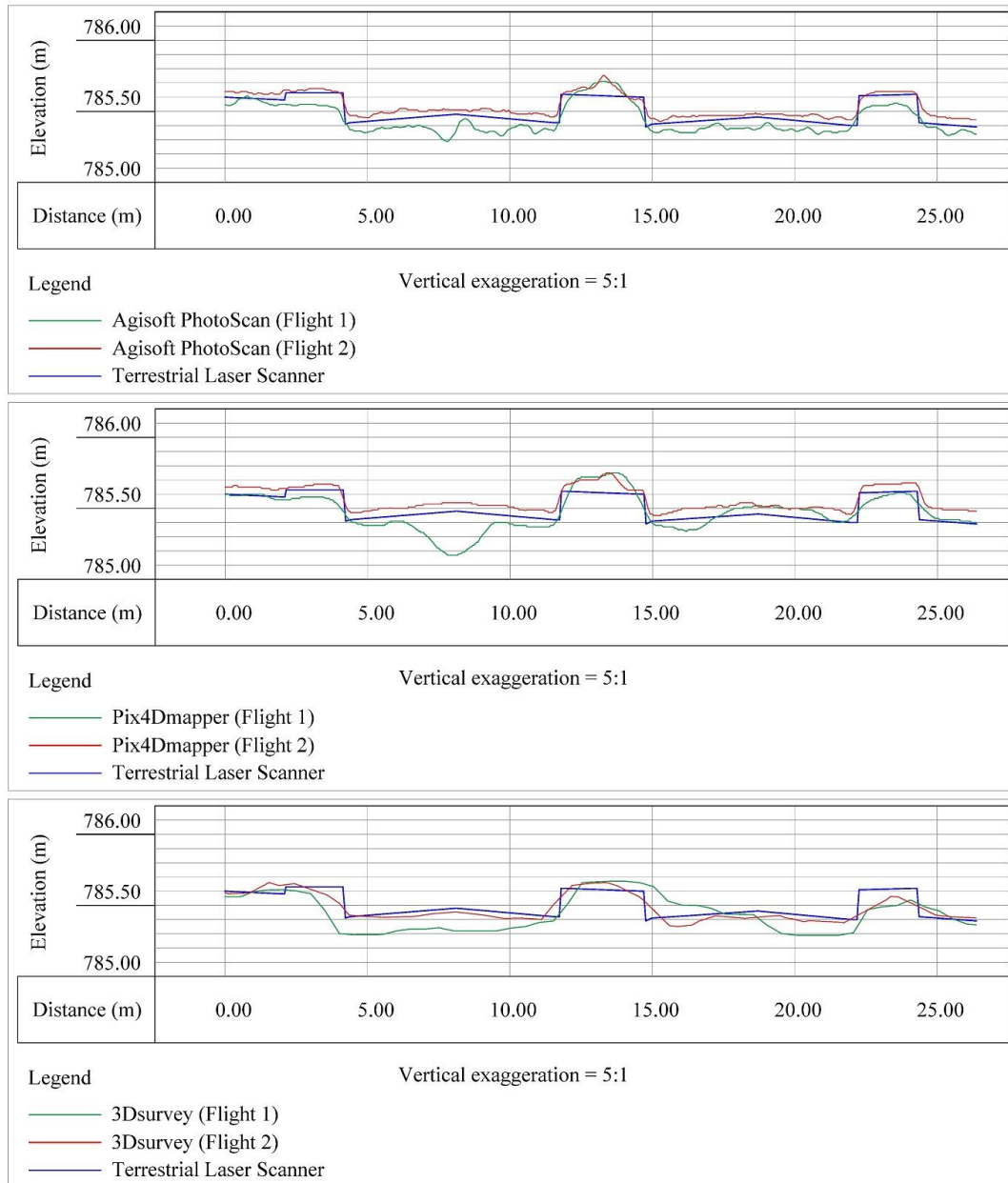
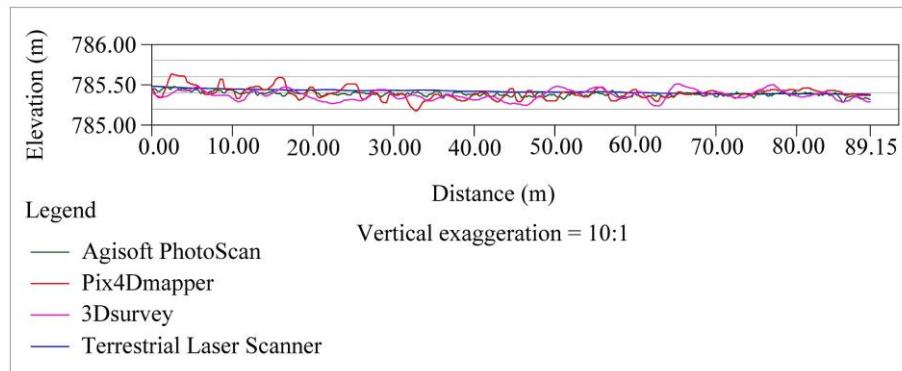
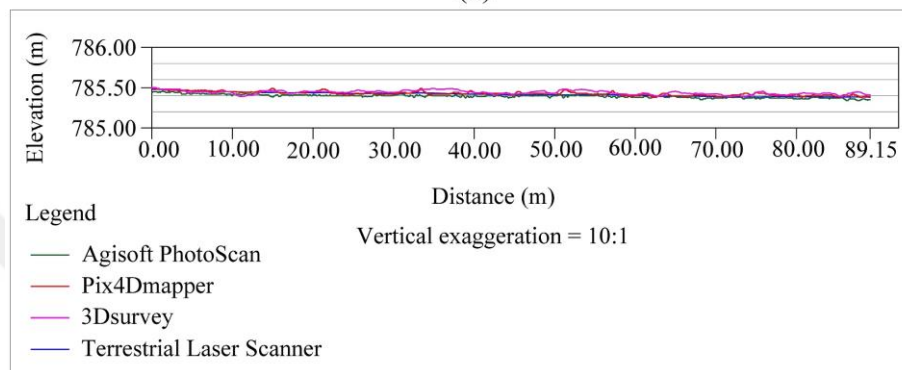


Figure 5.52. Comparison of road cross-sections extracted from TLS point cloud and SfM DSMs of flight 1 and 2.

Figure 5.53 and Figure 5.54 show the profiles and cross-sections extracted from data of flight 1 and flight 2 processed with 10 GCPs. The profiles and cross-sections of flight 2 show significant improvements. However, in flight 2, only profile and cross-section of PhotoScan show better accuracy.

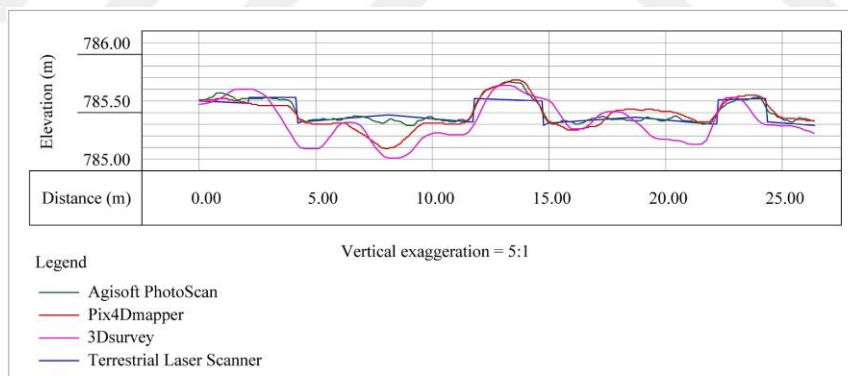


(a)

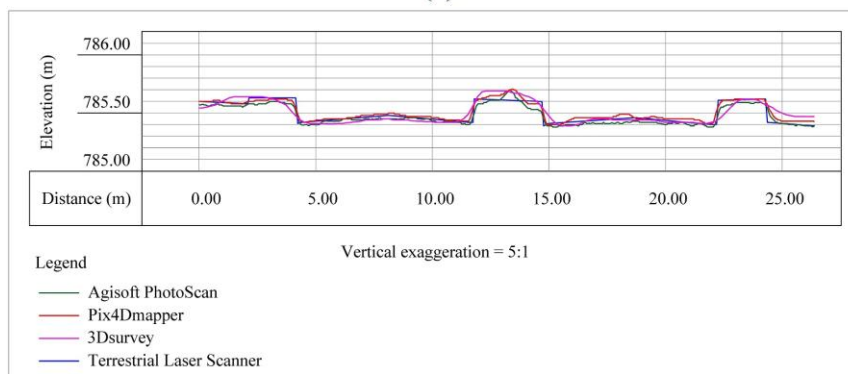


(b)

Figure 5.53. Comparison of profiles of flight 1 (a) and 2 (b) processed using 10 GCPs.



(a)



(b)

Figure 5.54. Comparison of cross-sections of flight 1(a) and 2 (b) processed using 10 GCPs.

Even though the image overlaps in flight 2 was lower than that of flight 1, the results of flight 2 showed higher accuracy. PhotoScan yielded more noise-free, smooth, and realistic results than Pix4D and 3Dsurvey (see Figure 5.55). Pix4D produced relatively coarse DSM from images of 170 m AGL. Although Pix4D produced more accurate DSM from data of 100m AGL, still the surface is not as smooth as PhotoScan. As shown in Tables 5.13, 5.14, and 5.15, PhotoScan produced very dense point cloud compared to Pix4D and 3Dsurvey. However, 3Dsurvey produced sparse point clouds; therefore, small details cannot be extracted. Nevertheless, 3Dsurvey showed higher consistency and smoother surface at both flight heights compared to Pix4D.

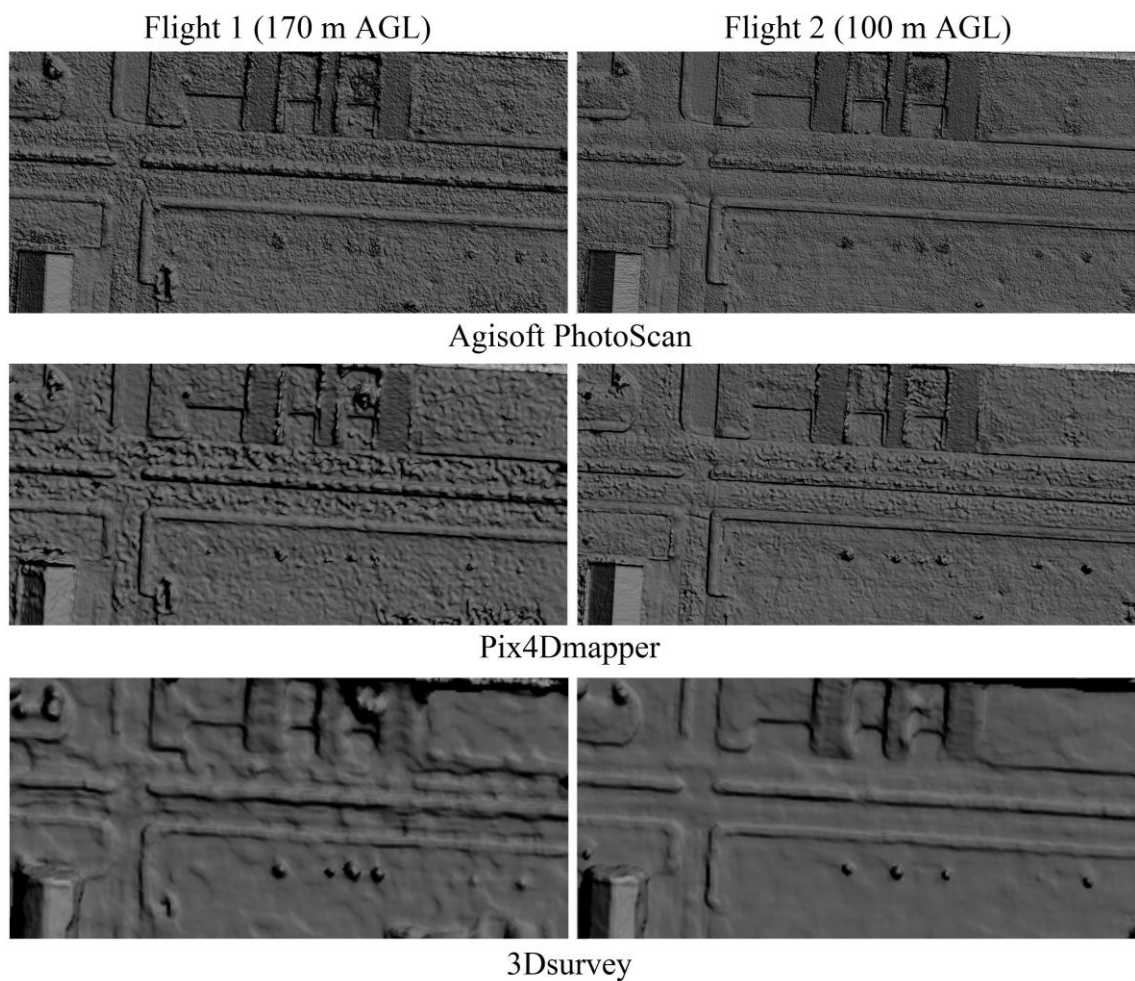


Figure 5.55. Comparison of DSM surface quality generated by PhotoScan, Pix4D, and 3Dsurvey from images of two flights.

The results indicate that at lower flight heights with higher overlap (i.e., at 30-50 m AGL and overlap > 80%), PhotoScan is capable of producing elevation models comparable to TLS models. Results of profile and cross-sectional analysis revealed that for evaluating the accuracy of UAS-SfM digital elevation models, only point-based

analysis is not sufficient, in addition to CP-based assessments, more in-depth examinations are also needed to validate this approach for use in engineering mapping activities.

Figure 5.56 and Figure 5.57 show road profiles and cross-sections extracted from SfM point clouds of different flight heights processed using the three software packages. The figures illustrate the point cloud density and the level of noise in elevation across the profile. It should be noted that the software applies noise filtering during the DSM generation to remove outliers as much as possible. Therefore, creating DSM from the generated point cloud using another software before filtering is not recommended, as this will result in an erroneous elevation model.

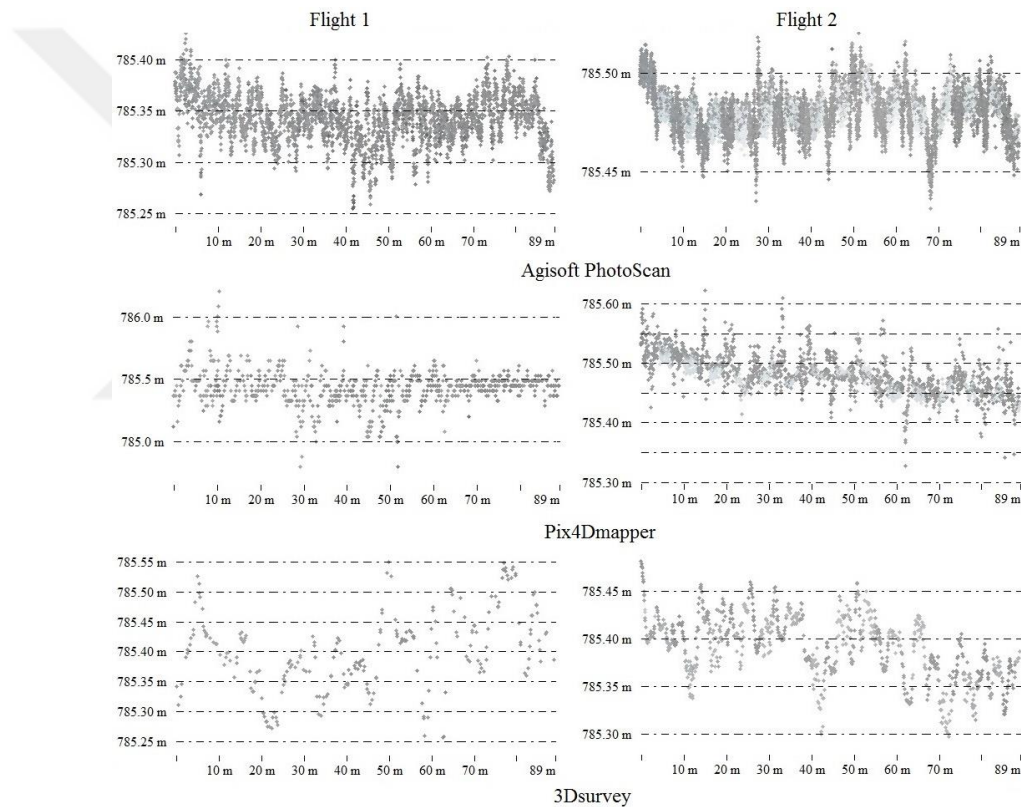


Figure 5.56. Comparison of point clouds in road profiles extracted from SfM point clouds generated by PhotoScan, Pix4D, and 3Dsurvey.

Figure 5.58 compares the building cross-sections extracted from point clouds of TLS and SfM. The SfM-MVS point clouds were generated using PhotoScan from oblique images of 16 m AGL, nadir images of 100 m AGL, and nadir images of 170 m AGL.

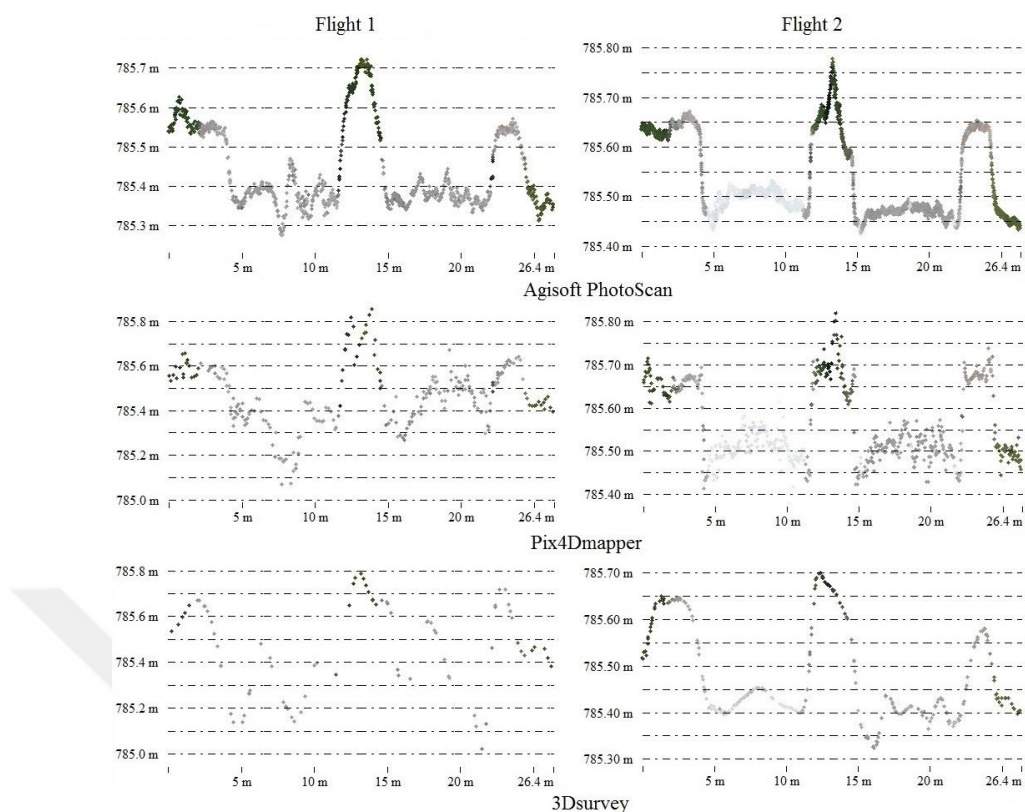


Figure 5.57. Comparison of point clouds in road cross-sections extracted from SfM point clouds generated by PhotoScan, Pix4D, and 3Dsurvey.

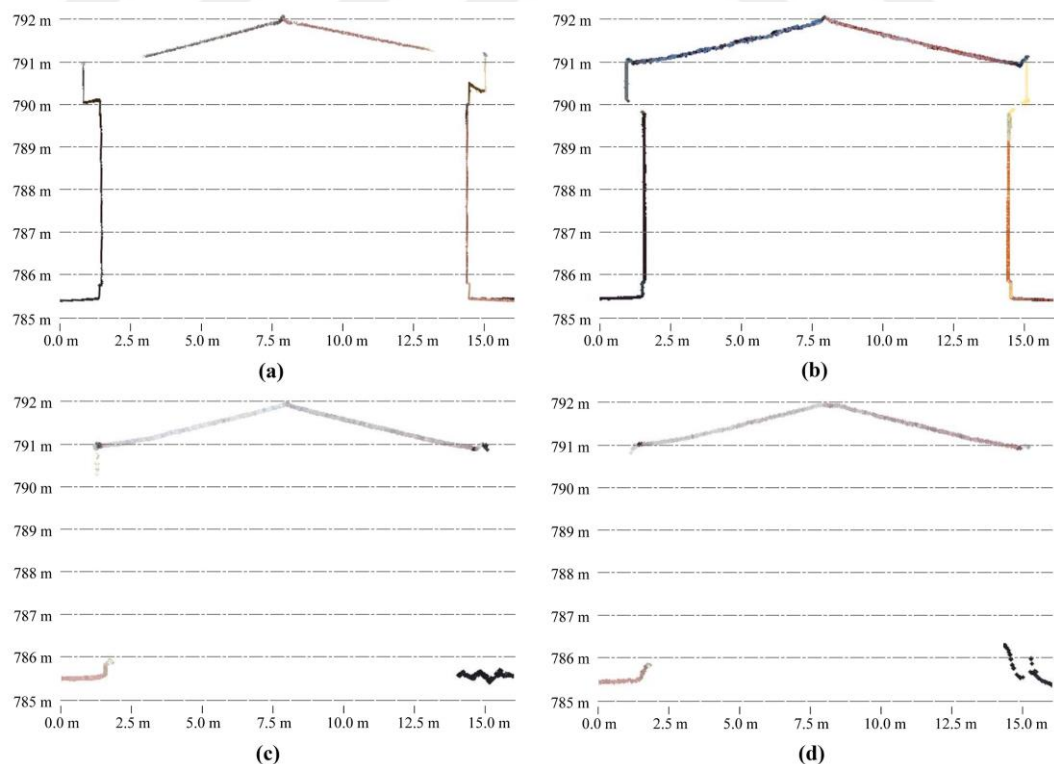


Figure 5.58. Comparison of building cross-sections extracted from point clouds of TLS (a), oblique images of 16 m AGL (b), nadir images of 100 m AGL (c), and nadir images of 170 m AGL (d). SfM point clouds was processed using PhotoScan.

5.4. Visual inspection and quality assessment

5.4.1. Comparison of Point clouds

Point cloud statistics of the entire study area, including the number of points, density, and spacing, are presented in Table 5.18. The following figures represent the point cloud density in one square meter obtained from the data of TLS, DJI Phantom 4 Pro at a lower height, and senseFly UAS at relatively higher height above ground level. The comparison of true color point clouds of the study area is given in Figure 5.61 and Figure 5.62, in which white areas indicate gaps in the point cloud.

Table 5.18. UAS-SfM point cloud statistics of the study area.

	PhotoScan		Pix4D		3Dsurvey	
	100 m AGL	170 m AGL	100 m AGL	170 m AGL	100 m AGL	170 m AGL
Point count	163,530,714	62,447,182	36,158,386	15,335,369	15,179,890	5,795,771
Point density (samples $\times$ m⁻²)	518	200	121	47	58	19
Point spacing (m)	0.044	0.071	0.091	0.143	0.131	0.227
Min elevation (m)	748.841	741.416	778.175	776.948	780.009	771.779
Max elevation (m)	816.478	816.284	816.396	816.437	813.129	816.517

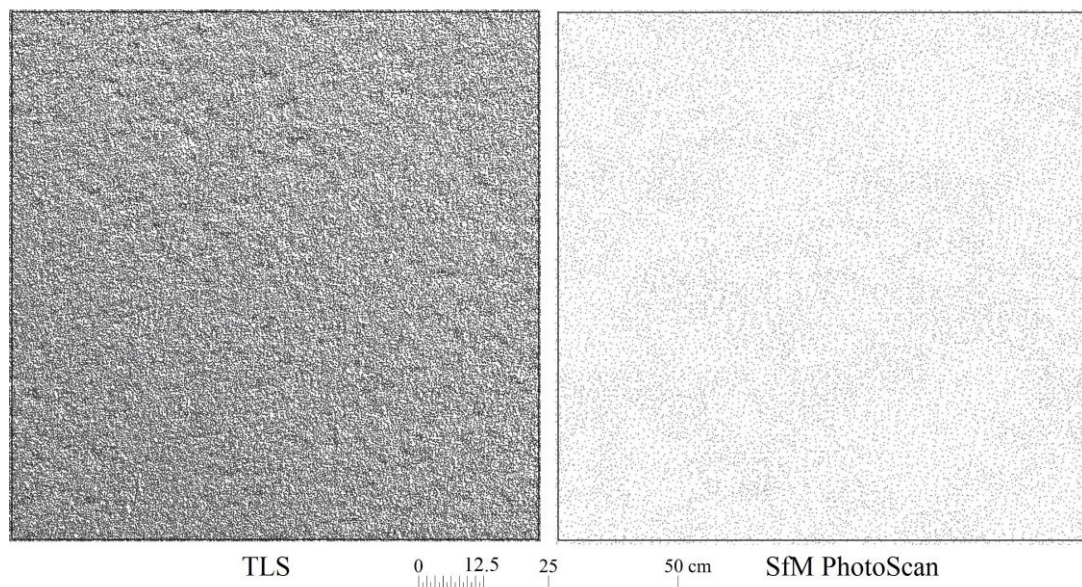


Figure 5.59. Comparison of TLS and UAS-SfM point cloud density. SfM point cloud derived from 16 m AGL oblique images of DJI UAS, processed using PhotoScan.

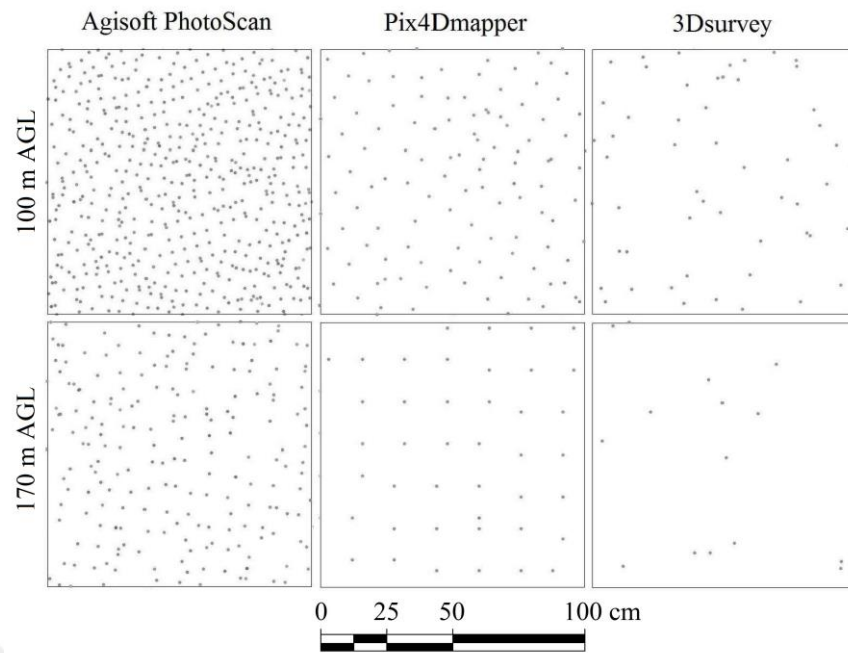


Figure 5.60. Comparison of point cloud density derived using different software packages from UAS images of different flight heights.

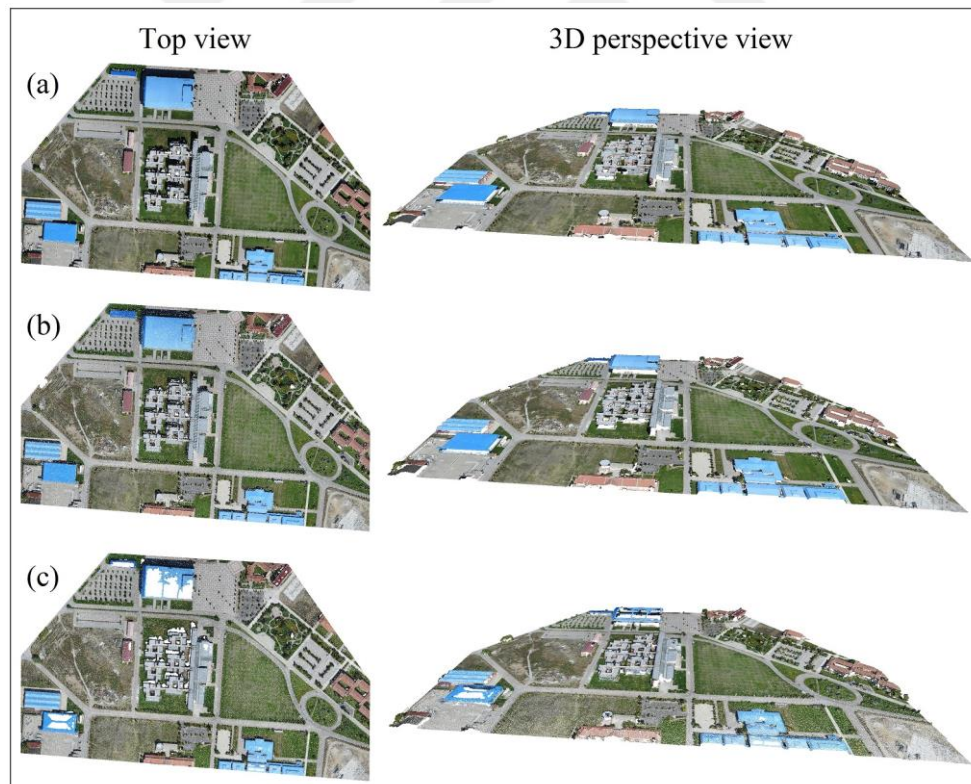


Figure 5.61. Comparison of point clouds produced by PhotoScan (a), Pix4D (b), and 3Dsurvey (c) from images of UAS at 170 m height AGL.

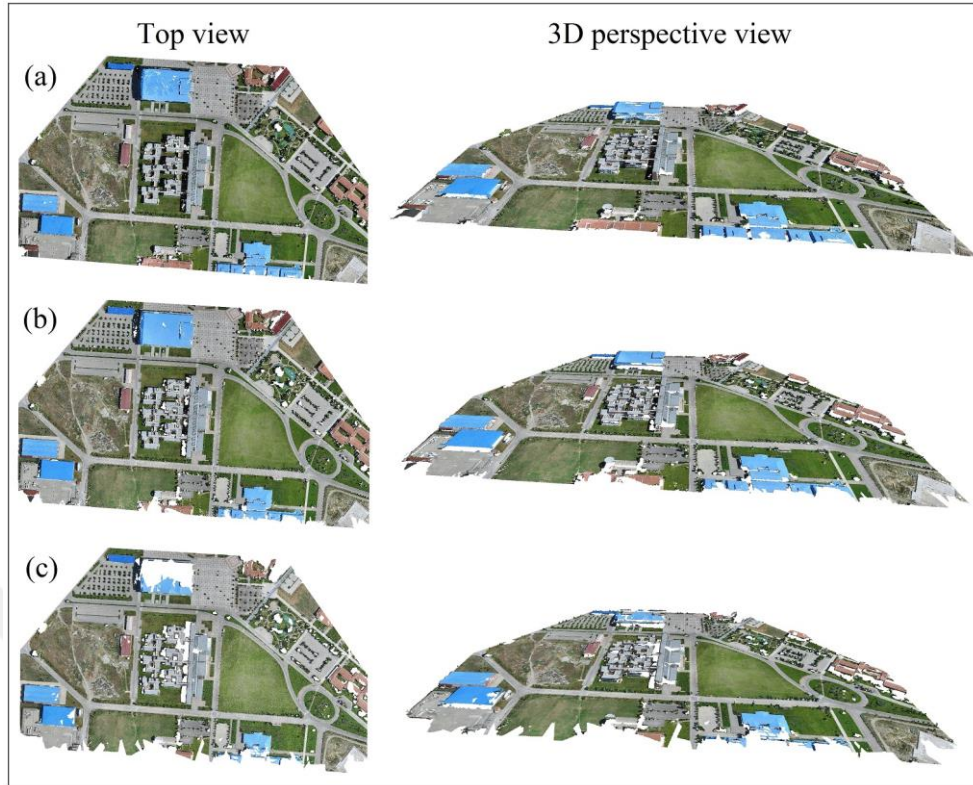


Figure 5.62. Comparison of point clouds produced by PhotoScan (a), Pix4D (b), and 3Dsurvey (c) from images of UAS at 100 m height AGL.

5.4.2. Comparison of DSMs

The DSMs generated using PhotoScan, Pix4D, and 3Dsurvey, are given in Figure 5.63. The figure shows that from the images of flight 1(170 m AGL with 75 and 65% forward and side overlaps), PhotoScan and Pix4D generated faultless DSMs; however, the DSM of 3Dsurvey has some deficiencies. As the figure shows, in generating DSM from the images of flight 2 (100 m AGL with ~60% forward and side overlaps), Pix4Dmapper outperformed all other software packages and provided elevations for all features, including less textured roofs. The result of PhotoScan from the image of flight 2 with lower overlap, shows a defect in the reconstruction of a building's roof (marked with a circle). The same problem can be seen in the DSM of 3Dsurvey. The main reason for the defects is probably the image overlap. Figure 5.64 shows the camera locations of flight 2, where the drone was diverted from its path by the wind, thus affected the image overlap.

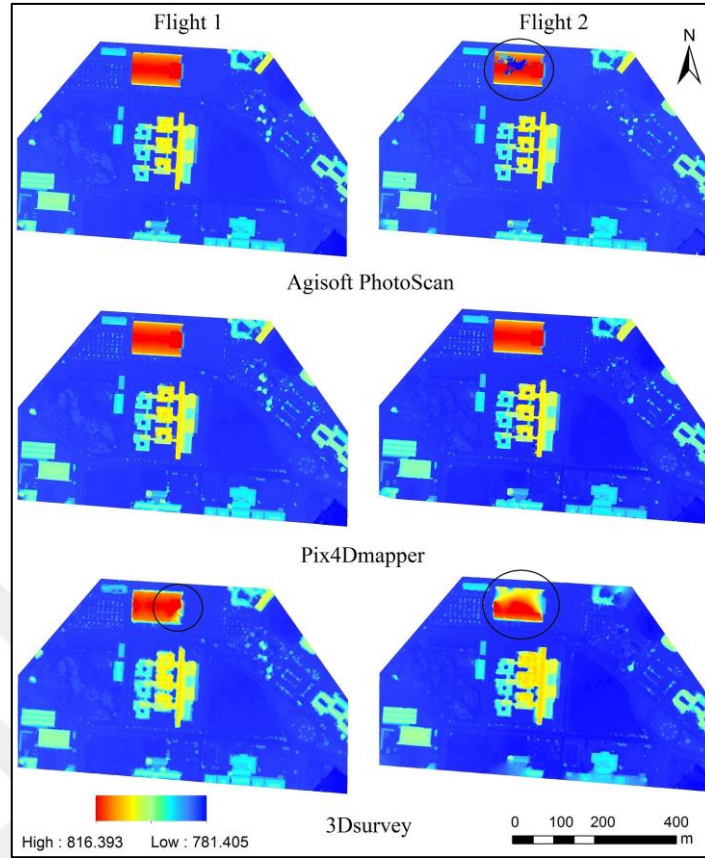


Figure 5.63. Comparison of DSMs produced by different software packages from images of different flight height AGL.

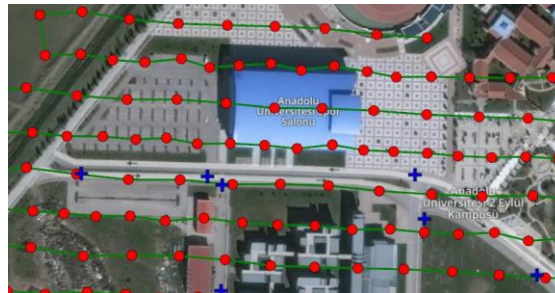


Figure 5.64. Camera locations of flight 2.

Although Pix4D can generate point clouds from lower overlapping images, the critical issue is the level of accuracy; the profiles, cross-sections as well as surface analysis (Figure 5.55) revealed that the DSM obtained from lower overlap images by Pix4D are not accurate. Figure 5.65 shows the DSM of the entire campus generated using PhotoScan from images of flight 1, presented using the atlas shader to illustrate a more realistic terrain representation. The figure shows the high capability of PhotoScan in representing terrain from high overlapping images.

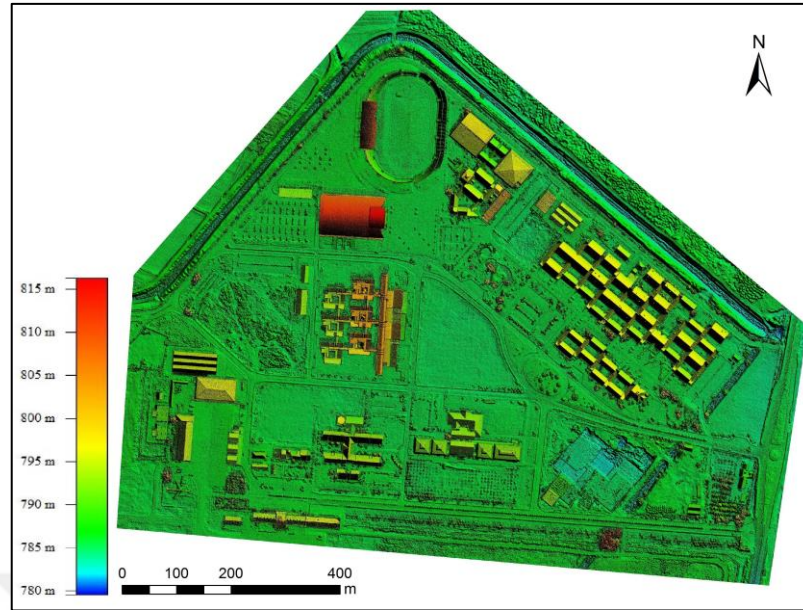


Figure 5.65. DSM of the entire campus derived from 170 m AGL, processed using PhotoScan.

5.4.3. Comparison of DTMs

The digital terrain models (DTMs) of the study area were created using automatic algorithms, as described in Section 4.2. Pix4Dmapper generates DTM with a resolution $5 \times$ DSM resolution, while PhotoScan allows the user to generate a DTM with resolution equal to the resolution of DSM. 3Dsurvey has some difficulties with exporting resolutions higher than 15 cm. The following figures show the DTMs generated using the three software. The resolution of the DTMs is 20 cm.

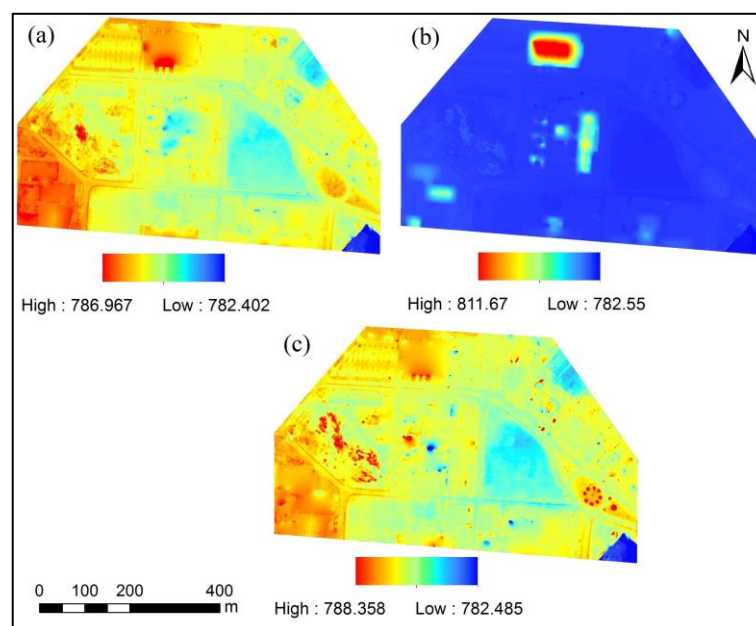


Figure 5.66. Comparison of DTMs generated from UAS images of 170 m AG, (a) PhotoScan, (b) Pix4Dmapper, (c) 3Dsurvey

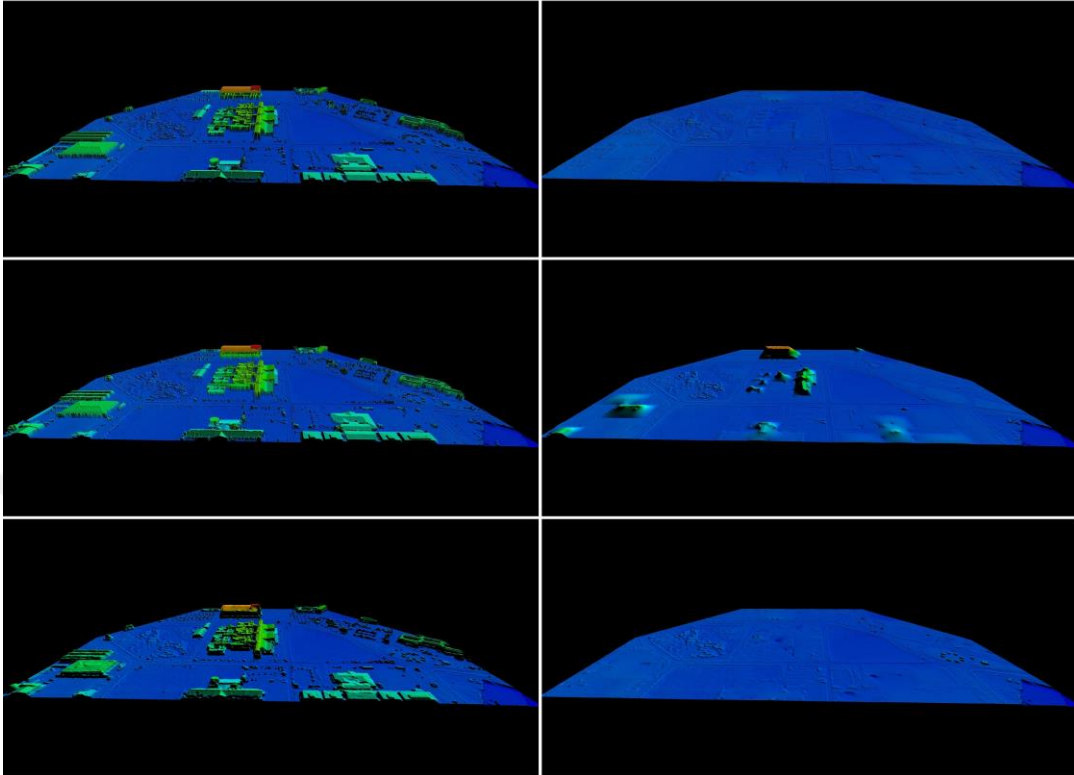


Figure 5.67. 3D comparison of DSM (left) and DTM (right) created using automatic algorithms of PhotoScan (top), Pix4D (middle), and 3Dsurvey (bottom).

The above figure clearly shows that the automatic DTM generation algorithm of Pix4Dmapper failed to filter out some buildings; whereas, PhotoScan and 3Dsurvey removed the features to some extent.

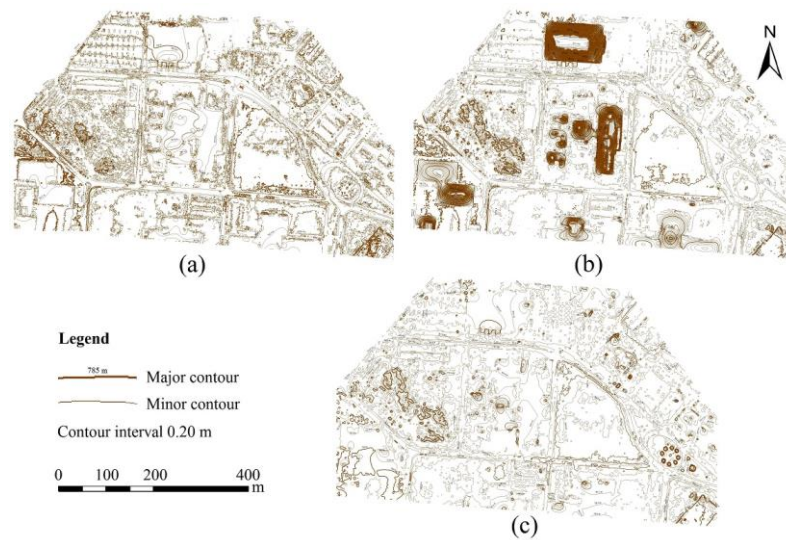


Figure 5.68. Comparison of contours produced using DTMs of PhotoScan (a), Pix4D (b), and 3Dsurvey (c).

Figure 5.68 compares the contours generated from the DTMs produced by the three software. The figure shows that highly detailed contours can be generated using the UAS-SfM survey, which obtaining this level of detail using field measurements is quite cumbersome.

5.4.4. Comparison of orthomosaics

In generating orthomosaics, Pix4Dmapper yielded better visual quality, especially from the images of flight 1. PhotoScan also generated high-quality orthomosaics. However, 3Dsurvey produced low-quality orthomosaics. Figure 5.69 illustrates the orthomosaics produced by the three software; areas marked by circles show the defects of 3Dsurvey in orthorectification.



Figure 5.69. Comparison of orthomosaics generated using PhotoScan (left), Pix4D (middle), and 3Dsurvey (right).

6. CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to evaluate the accuracy of UAS photogrammetry and structure from motion as a low-cost alternative to terrestrial surveys for geomatics engineering applications. In this thesis, a brief introduction to unmanned aerial systems and UAS photogrammetry, including some theoretical background and comprehensive literature review were presented. To achieve the objectives of the study, the entire study area was surveyed by conducting two UAS photogrammetric flights at different flight heights using a survey-grade lightweight fixed-wing UAV and a non-metric digital camera. For 3D modeling and volumetric calculations, a close-range oblique photogrammetric survey of a building was performed using a small multi-rotor UAV. For validating the UAS-SfM products, field measurements were conducted using RTK GNSS, terrestrial laser scanner, and total station. The collected images were processed using three SfM software packages, namely Agisoft PhotoScan, Pix4Dmapper, and 3Dsurvey. Three software packages were used to examine the influence of processing software on the quality and accuracy of the photogrammetric projects. Two GCP schemes (5 GCPs and 10 GCPs) were designed to investigate the influence of GCP number and distribution on accuracy. By applying the SfM-MVS workflow through the use of these software packages, point clouds, mesh models, DSMs, DTMs, and orthomosaics were generated. From the nadir images of 100 and 170 m AGL, 2.5 and 4.0 cm resolution orthomosaics and DSMs were produced. For an in-depth examination of SfM capabilities, one photogrammetric project was processed by combining two sets of nadir images taken from different heights. From the oblique images of 16 m AGL, 0.5 cm resolution orthomosaics and DSMs were generated. To evaluate the accuracy of the products, absolute and relative horizontal and vertical accuracy analysis was performed on orthomosaics, DEMs, and point clouds. In addition, correlation analysis and comparative evaluations, including virtual model versus control points, virtual model against actual object, and virtual model versus virtual model, were conducted. The conclusions that can be drawn from the results of the quality and accuracy analysis include many points, which are outlined below.

6.1. Summary of Findings

The absolute accuracy assessment showed that the best horizontal and vertical accuracy achieved from the images of 100 m AGL with 60% forward and side image overlaps, in which the horizontal RMSE for the orthomosaic was 3 cm, and the vertical RMSE for the DSM was 4 cm. Likewise, orthomosaic with 3 cm horizontal and DSM with 6 cm vertical accuracy were achieved from the images of 170 m AGL with 75% forward and 60% side overlaps. From the oblique images of 16 m AGL, $RMSE_{XY} = 2.4$ cm, and $RMSE_Z = 2$ cm were obtained.

According to the American Society for Photogrammetry and Remote Sensing (ASPRS) positional accuracy standards for digital geospatial data (ASPRS, 2014), the achieved horizontal accuracy of orthomosaics derived from 100 m and 170 m AGL images, meet the ASPRS 2014 horizontal accuracy classes RMSE 2.5 and RMSE 5.0 cm, respectively. These accuracies are equivalent to map scales of 1:100 and 1:200 of ASPRS 1990. Similarly, the obtained vertical accuracy of DSM derived from 100 m AGL images, in non-vegetated areas meets Class 3 (RMSE 5 cm) of ASPRS 2014 absolute accuracy. The equivalent Class 1 contour interval as per ASPRS 1990 for this accuracy is 15 cm. The DSM vertical accuracy derived from the images of 170 m AGL, complies with Class 4 (RMSE 10 cm) of the ASPRS 2014. The equivalent Class 1 contour interval as per ASPRS 1990 for this accuracy is 30 cm. The vertical accuracy achieved from the 100 and 170 m AGL images, meet the ASPRS 2014 95% confidence level vertical accuracy of 9.8 and 19 cm, respectively. The achieved accuracy of orthomosaics and DSMs reconstructed from 16 and 100 m AGL images is sufficient for most terrain analysis applications, including civil engineering projects.

The findings of this study confirm the conclusions in the literature regarding the importance of flight height, image overlap, and GCP number and distribution on the accuracy of SfM-MVS products. The horizontal accuracy was not affected by flight height; however, flight height greatly affected the vertical accuracy, where a 70 m increase in flight height caused a 3 cm decrease in vertical accuracy. This demonstrates the strong influence of flight height on vertical accuracy. Vertical accuracy was significantly improved by increasing the number of GCPs.

The number and distribution of GCP is crucial in horizontal and vertical accuracy. The vertical accuracy of the DSM processed without GCP is not reliable because the results which were processed without GCPs showed vertical discrepancies in meters.

Nevertheless, the results from such image processing showed good precision. The study revealed that there is a high positive linear relationship between the distance to the nearest GCP and the vertical error. This research provided considerable insight into GCP distribution. The results showed that the vertical error significantly increased when the distance to the nearest GCP exceeded 150 m. After 150 m, an increase of 100 m in the distance caused approximately a decimeter error in the Z value. On the one hand, the accuracy of the model is to some extent, directly related to the number of GCPs, but on the other hand, increasing GCP numbers affects the project time and cost. As using 4 GCPs in the processing of oblique images yielded very high accuracy, it can be stated that “more” does not necessarily mean “better”. Therefore, it can be concluded that a well-planned GCP layout requires comparatively few GCPs.

Combining two photogrammetric blocks of nadir images significantly contributed to vertical accuracy and the production of a denser point cloud. The study highlighted that by integrating the images of two different flight heights, outlier values were substantially reduced, and the errors showed a normal distribution. In light of the results, double block image acquisition is highly recommended for 3D city modeling. However, it is recommended that the highest flight height should not exceed two times the lowest flight height.

The results of the building survey showed that UAS-based photogrammetry is comparable to TLS in terms of precision. The comparison of TLS and UAS in the 3D modeling of the building revealed that although TLS produced a high-density point cloud, it required many scan positions to cover the object. UAS-SfM also produced a complete dense point cloud of the building. However, the accuracy of UAS-SfM derived products largely depends on image acquisition, GCP planning, and photogrammetric image processing software. Since both methods have their advantages and limitations, the integration of TLS and UAS-SfM can generate a complete model of the object of interest. Processing software remarkably affects the horizontal and vertical accuracy of SfM-MVS products. The comparison of three software packages in the study showed that accuracy differences emerged in the order of $2\text{--}3 \times \text{GSD}$. The results showed a high correlation between the results of PhotoScan and Pix4D, while 3dsurvey slightly differs from both. This indicates the similarity of algorithms used in PhotoScan and Pix4D. Generally, PhotoScan outperformed both Pix4D and 3Dsurvey in accuracy and quality; however, the results showed that Pix4D performed better in generating DSM from lower overlapping

images. In summary, PhotoScan produces accurate and high-quality 3D models from images with sufficient overlap. A very dense point cloud of the surveyed building with 2 cm horizontal and vertical accuracy was produced using PhotoScan. Pix4Dmapper also generated a relatively dense point cloud of the building. However, 3Dsurvey was not successful in generating 3D point clouds neither from nadir images nor from oblique. In DTM generation using automatic algorithms, PhotoScan and 3Dsurvey performed well by removing features to some extent and generating acceptable DTMs from point clouds; however, Pix4Dmapper failed to filter out some buildings.

In the calculation of the building volume, the differences between the volumes calculated from the TLS point cloud and PhotoScan point cloud was 0.66 m^3 , whereas this difference using Pix4D and 3Dsurvey point clouds were 1.09 m^3 and 46.32 m^3 , respectively. PhotoScan also provided reasonable volumetric accuracy from nadir images taken from relatively higher heights; however, Pix4D and 3Dsurvey overestimated the building volume from those data. It should be noted that the exact volume of vertical objects with overhanging elements can only be calculated using a point cloud or triangulated model, DSM overestimates the volume due to its 2.5D nature. The case study in this research revealed the effectiveness of UAS-SfM in volumetric calculations.

6.2. Advantages and Challenges of UAS Photogrammetry and Structure from Motion

UAS-SfM has effectively revolutionized the acquisition of high-resolution topographic data by reducing the need for technical expertise or expensive surveying equipment. Nevertheless, the need for survey equipment such as TS or DGNSS for accurate georeferencing of point clouds is still a technical and financial limitation. The spatial resolution and point densities that are achievable with UAS-based SfM-MVS are comparable to TLS and considerably higher than those of DGNSS, TS, and ALS. However, the quality and density of SfM-MVS-derived data depend on the image acquisition plan. The significant advantages of UAS-SfM over conventional methods can be summarized as lower price, rapid mapping, higher spatiotemporal resolution, safe observation of hazardous and inaccessible areas, and quick response in emergency situations.

Compared to other digital survey techniques, the main attraction of structure from motion method is its low cost. Specifically, surveys based on UAS and SfM-MVS are

easy and convenient. SfM-MVS needs a camera that can be mounted on many types of platforms. Commercial and open-source software can be used for SfM-MVS processing. SfM-MVS is the only method that can produce a full 3D point cloud that can compete with that of TLS. In contrast, TLS costs much higher, requires licensed commercial software, and field works are relatively cumbersome. In brief, based on the author's experience and literature review, the advantages of SfM-MVS compared to other digital survey methods can be summarized as follows (Carrivick et al., 2016; Greenwood et al., 2019; Mark William Smith & Vericat, 2015; Stöcker et al., 2017):

- SfM-MVS is a cost and time-effective solution.
- Fieldworks and data acquisition, as well as software operation are convenient.
- SfM-MVS generates fully 3D survey data; as otherwise, it is only possible with TLS.
- Since point clouds and textured surfaces derived from the SfM-MVS method are intrinsically multi-dimensional, they can be simply transformed into DEMs and orthoimages.
- SfM-MVS is applicable in surveying with high resolution over a vast range of spatial scales.
- With the careful acquisition of GCPs and correct application, SfM-MVS is able to deliver accuracy comparable to other direct and indirect topographic surveying methods.

In light of the literature review (see Table 2.1 and Section 2.3) and the experiments conducted in this research, SfM-MVS cannot completely replace the other digital surveying methods, especially in cases where highly accurate surveys are required. However, in some circumstances, particularly in large areas where decimeter-scale accuracy is acceptable, SfM-MVS is a rapid and efficient method for producing high-resolution terrain models and planimetric maps. In such conditions, there is no need to use costly survey solutions such as TLS or ALS. TS and DGPS surveys allow the use of point codes to add attributes to the surveyed points. In contrast, during the UAS photogrammetry survey, this information is not included, and the points and attributes are unknown. 3D points are generated in the office, which further works such as noise filtering and point cloud classification are needed to produce topographic maps. A major drawback of the SfM-MVS method is the inability to determine the quality of a particular survey before data collection. Another disadvantage of SfM-MVS is the long

computational run time in large spatial scale and very high-resolution surveys. However, these lengthy processing times are much less than the time that would have been spent on data collection by terrestrial methods.

Although UAVs are very effective for data acquisition; however, with the increase of multi-purpose UAVs, concerns about public safety, data protection, and privacy have forced national and international authorities to introduce regulatory laws on the use of unmanned aircraft systems, which sometimes restrict the use of drones. Depending on the country's regulations, such provisions considerably affect how, where, and when UAV flight operations and data collection can be performed (Stöcker et al., 2017). The major disadvantages of SfM-MVS compared to other digital survey methods can be summarized as follows (Carrivick et al., 2016; Greenwood et al., 2019; Mark William Smith & Vericat, 2015; Stöcker et al., 2017):

- Image-based topographic surveys are not successful in areas with dense vegetation.
- Collecting and processing of large spatial scale data are challenging.
- In the SfM-MVS method, 3D points are derived from images in which the accuracy of data depends on factors that cannot be directly controlled by the surveyor; therefore, repeatability problems may arise.
- Since point clouds are generated using SfM-MVS in the office, during the survey, codes and attributes cannot be recorded to points. In addition, it is difficult to determine whether 3D point clouds will be successfully produced.
- SfM-MVS software cannot analyze point cloud information in an automatic manner.

6.3. Limitations of the Study and Recommendations for Future Research

The author is aware that this research is not exhaustive and has some limitations. A thorough study of the accuracy of UAS-SfM in different study areas, considering terrain, land cover, and texture variability, might help to understand the influence of these factors on accuracy. Future research on different image overlaps at the same flight height will help to find the optimum percentage to achieve the best accuracy. Comparative research on the performance of open-source software packages will contribute to the body of knowledge. Investigating the potential of UAS platforms and multi-spectral, thermal, and LiDAR sensors are interesting topics for future works.

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