zero deaths | zero serious injuries
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Montana Department of Transportation

PO Box 201001
Helena, MT 59620-1001

Memorandum

To: Paul Jagoda, PE
CES Bureau Chief

From: Fred Beal
CES Construction Reviewer

Date: March 30, 2017

Subject: Unmanned Aerial Vehicle (UAV) Mapping Demonstration

Overview

In February 2017 MDT CES Bureau acquired a UAV at no cost from URC Ventures (d.b.a. Stockpile Reports). This memo describes the equipment and workflows used to collect imagery of the Lincoln Rd. MDT Section yard and process it with Pix4D software to create a rectified orthomosaic map, point cloud (LAS file), a Digital Surface Model (DSM), measure a stockpile volume, and create a visualization video clip.

FAA regulations are also discussed in this report. It is also noted that the MDT CES Bureau has created Standard Operating Procedures for UAV use.

Equipment

The Unmanned Aerial System (UAS) is made up of the UAV, a remote controller, a mobile device and two software applications (apps) installed on the mobile device: DJI Go and Map Pilot. Descriptions are provided below.

UAV: DJI Phantom 4 Pro.

The UAV is equipped with a gimbal stabilized 4k/12MP camera as well as multiple sensors used for navigation control and obstacle avoidance. Sensors include barometer, compass, GPS/GLONASS receiver, and optical sensors used for obstacle avoidance and aircraft hover positioning.

Obstacle avoidance system range: 2 – 49 feet (aircraft will automatically avoid collision)

Hover Position Accuracy: (vision positioning is active when aircraft is within 33 feet of the ground).

Vertical:
±4 inches (with Vision Positioning)
±18 inches (with GPS Positioning)
Horizontal:

±12 inches (with Vision Positioning)
±60 inches (with GPS Positioning)

Max Speed: 45mph
Max Flight Time: 28 minutes

Remote Controller:

Maximum Transmission and Video Downlink Range: 3.1 miles

Mobile Device: IPad mini 3

Apps:

Map Pilot. This app allows the user to easily create and autonomously fly a flight path to map an area. It also triggers the camera automatically.

DJI Go App 4.0. This app was created by the UAV manufacturer and allows for adjustment of all aircraft and camera settings and can be used to fly the aircraft.

FAA Regulations

In August 2016, the FAA released new requirements for commercial small UAV use in the U.S. Some key parts of the new rules, known as Part 107[1] are summarized as follows:

- Aircraft must be registered and must weigh less than 55 pounds.
- Operations must be directly performed or supervised by someone who has a remote pilot airman certificate with a small UAS rating. (Requires passing an aeronautical knowledge test at an FAA testing center. Testing cost is $150.)
- Flights must be made:
    - In daylight or civil twilight
    - At or below 400 feet above ground level (AGL) unless within 400 feet of a structure in which case the limit is 400 feet above the top of the structure.
    - In Class G airspace
    - Within the unaided line of site at all times.

1 https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20516

    - When visibility is at least 3 miles.
- The UAV cannot be flown over non-participants unless they are located under a covered structure or in a stationary vehicle. (Participants are those involved with operation of the UAS, including Visual Observers).

All regulations were followed during operation of the UAV.

Lincoln Rd. Section Yard

Flight Planning

The first step was to access the Montana Cadastral Mapping website[2] to identify the extents of the survey area and verify property boundaries/ownership to prevent accidental flyover of private property.

Next, the two apps were used to adjust settings and create the flight plan. A detailed workflow is provided in Appendix A of this report.

Figure 1 Screenshot of Map Pilot App

The app simplifies flight planning and execution. The user identifies the survey area on a map and specifies the Ground Sampling Distance (GSD) and photo overlap %. The app computes and sets all parameters such as altitude, flight speed, photo interval, and flight path. The same app will also autonomously take off the UAV, fly the route, take all the photos, return, and land the UAV with no intervention by the user. (The user can take over the controls at any time). Ground Sampling Distance was set to 1 inch per pixel. For the UAV camera at 12 MP resolution, this results in an altitude setting of 197 feet.

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2 http://svc.mt.gov/msl/mtcadastral

Imagery Collection

205 photos of the Lincoln Rd. site were collected in approximately 10 minutes. The EXIF tag in the photo file records GPS coordinates associated with each photo.

Image Processing

Image processing may be performed on a local computer using leased or purchased photogrammetry software or the images can be uploaded and processed via an on-line processing service (cloud processing).

<u>1. Pix4D Mapper Cloud Based Processing</u>: A 15-day trial was used to evaluate the cloud based service and desktop software offered by Pix4D. The 205 images were uploaded to Pix4D and were processed in about 2 hours. The on-line viewer allows viewing of a 2D orthomosaic map, a color coded elevation map (may not display well on MDT computers) and a 3D model:

Figure 2 Orthomosaic of Lincoln Rd. Site

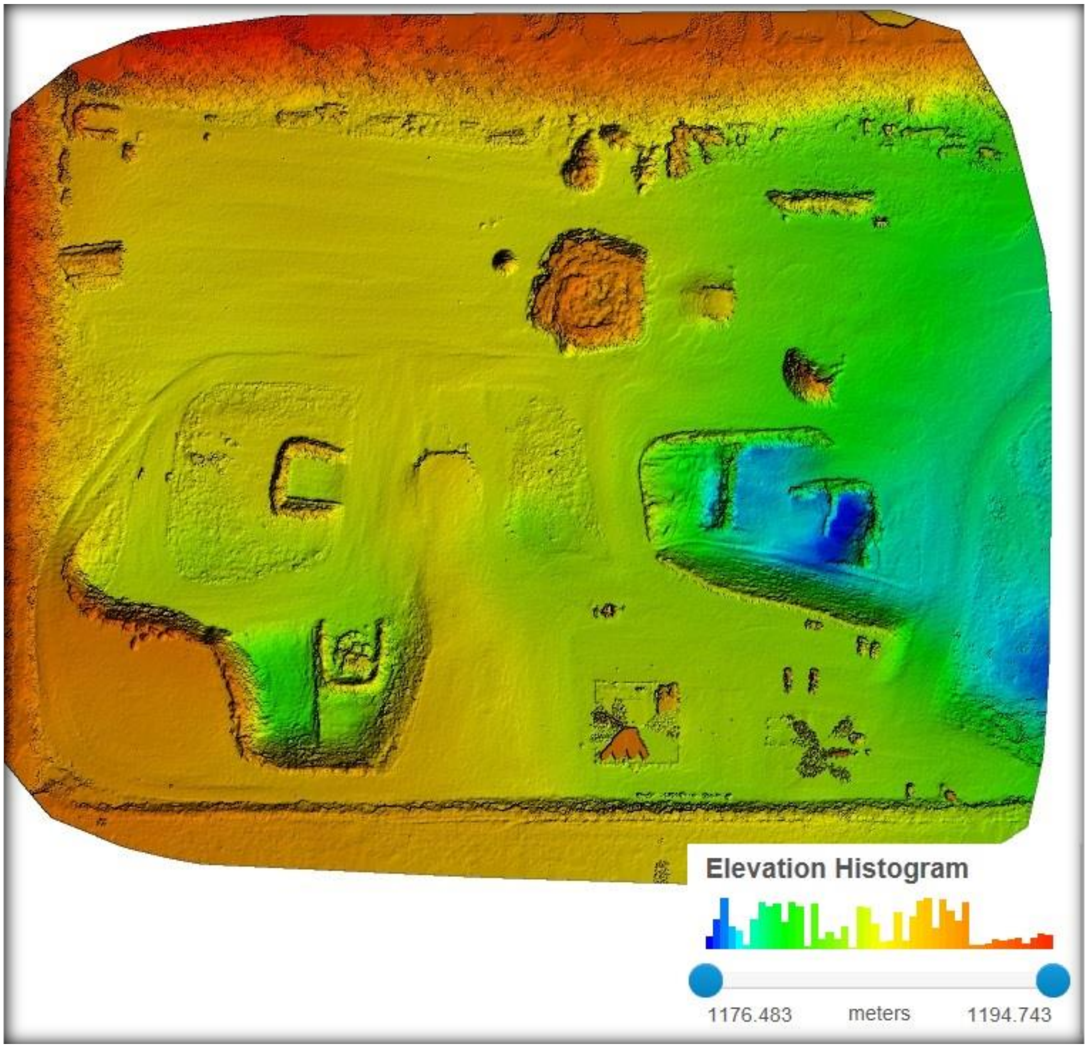


Figure 3 Digital Elevation Map

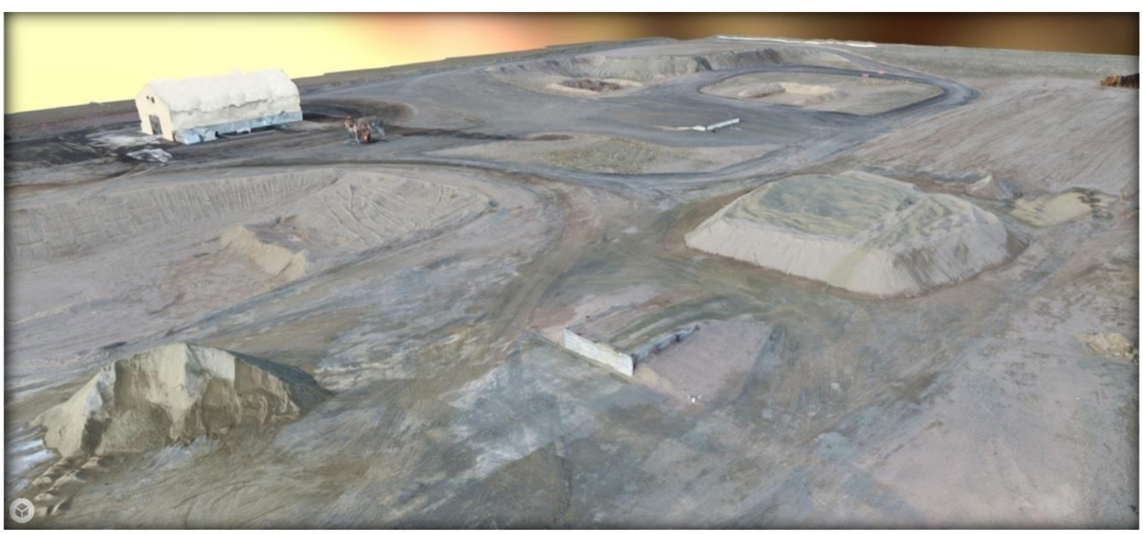


Figure 4 Screenshot of 3D model

Following is a link to the on-line map/model viewer. The link will only be active for the remainder of the software trial period.
https://cloud.pix4d.com/pro/public/83858-aa23bc67c77349dab7f03aa8fcb2bd7f

After cloud processing, various outputs are available that can be downloaded and imported into other programs such as Microstation or Pix4d desktop.

2. Pix4D Mapper Desktop: Once initial image processing is complete (using either the cloud or desktop processor) the desktop software has many tools for further processing and analysis of the data.

For the Lincoln Pit site, the desktop software was used to generate a rectified point cloud, a digital surface model, a 3D textured model, a fly-though video simulation and an orthomosaic. A stockpile volume was also measured.

Fly-through video:
\\mdthq\mdtshares\WebAppData\Internal\Const\Reports\construction_review_reports\GREAT-FALLS\flythrough2.mp4

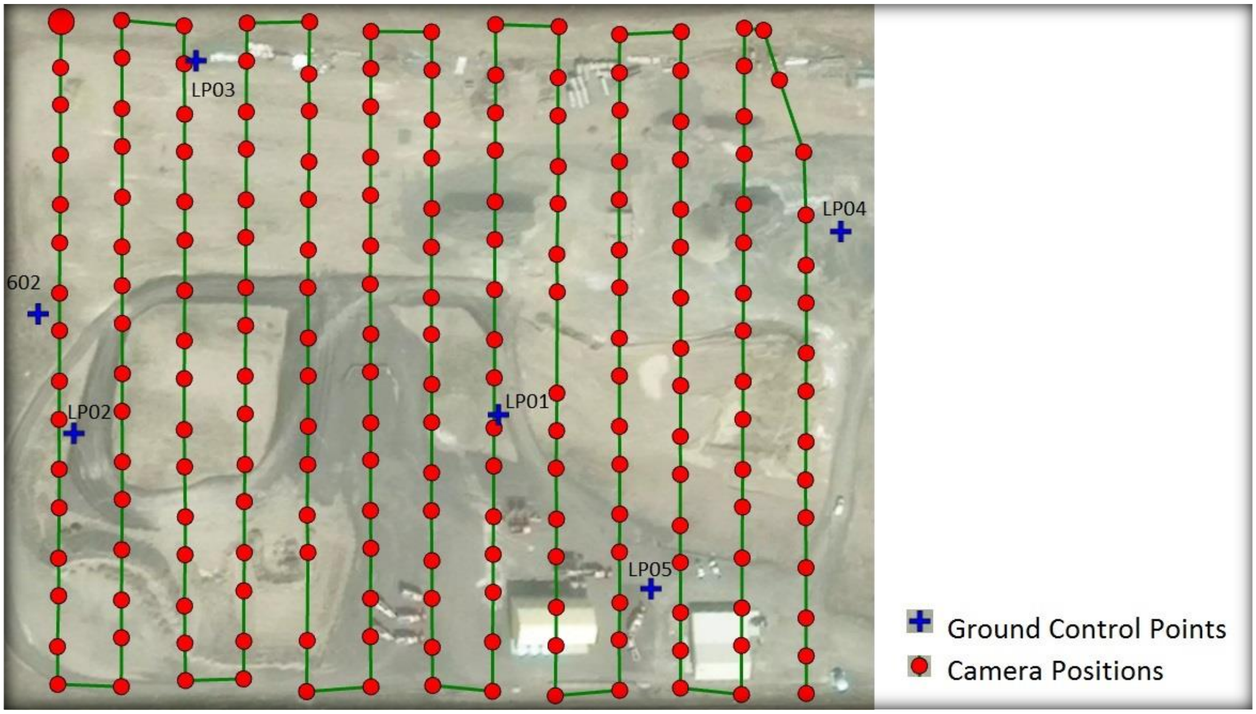


Figure 5 Ground Control Points - Lincoln Rd. Site.

A rectified point cloud is a group of points that has been scaled, located and oriented to be accurate and relative to a particular coordinate system. Five GCPs with targets were placed at the Lincoln Rd. site and were surveyed using GPS RTK by Sam Ahlrich of MDT Construction to get accurate coordinates for them. One pre-existing GCP was also used. Coordinates of four of the GCPs were entered into the Pix4D software. The software rotated, scaled and oriented the project to the Montana State Plane Coordinates Zone 2500 system using those four points. The remaining GCP (LP01) and pre-existing control point (602) were used as check points to check the accuracy of the map.

Figure 6 Ground Control Point

The workflow for importing and processing the imagery with Ground Control Points is provided in Appendix A of this report.

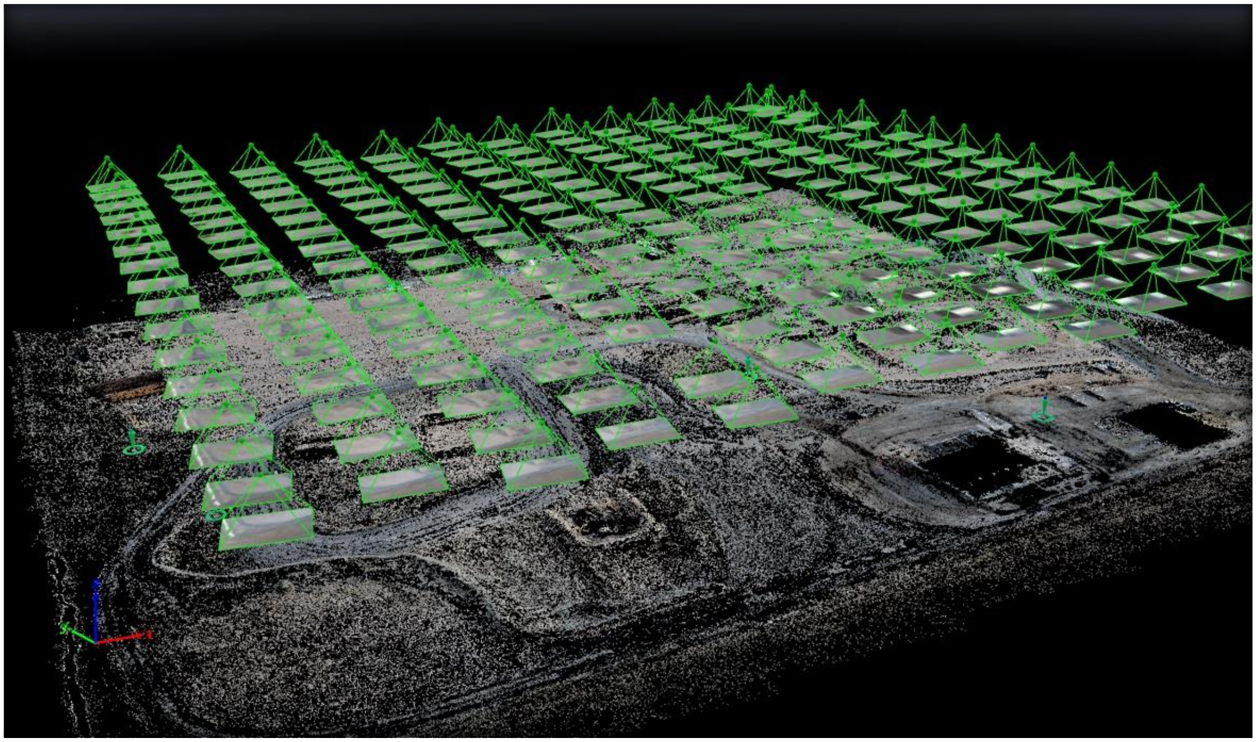


Figure 7 Pix4D Screenshot Showing Camera Positions and Point Cloud

The software generates a Quality Report that includes an accuracy assessment of the check points. Note the check point error was in the range of .03 to .05 feet for the Lincoln Rd. site. This is a measure of how accurate the computed point locations are as compared to the actual known coordinates. It should be noted that these values do not include the uncertainty of the check point coordinates (+/- .03 ft horizontal and +/- .04 vertical).

Geolocation Details

Ground Control Points

GCP Name	Accuracy XY/Z [ft]	Error X [ft]	Error Y [ft]	Error Z [ft]	Projection Error [pixel]	Verified/Marked
LP02 (3D)	0.030/ 0.040	-0.003	0.002	-0.004	0.547	6 / 6
LP03 (3D)	0.030/ 0.040	-0.005	-0.005	0.001	0.642	9 / 9
LP04 (3D)	0.030/ 0.040	0.014	-0.009	-0.010	0.726	7 / 7
LP05 (3D)	0.030/ 0.040	-0.002	0.013	-0.001	0.392	14 / 14
Mean [ft]		0.000987	0.000076	-0.003619		
Sigma [ft]		0.007694	0.008200	0.004181		
RMS Error [ft]		0.007757	0.008200	0.005530		

0 out of 2 check points have been labeled as inaccurate.

Check Point Name	Accuracy XY/Z [ft]	Error X [ft]	Error Y [ft]	Error Z [ft]	Projection Error [pixel]	Verified/Marked
LP01	0.0200/0.0200	-0.0315	-0.0005	-0.0526	0.6067	10 / 10
602	0.0200/0.0200	0.0356	-0.0268	0.0352	0.6678	8 / 8
Mean [ft]		0.002070	-0.013628	-0.008714		
Sigma [ft]		0.033543	0.013146	0.043913		
RMS Error [ft]		0.033607	0.018936	0.044769		

Figure 8 Quality Report Excerpt - Lincoln Rd. Site

Volume Measurement

The Pix4D software was also used to measure the volume of a stockpile at the Lincoln Rd. site. After creation of a Digital Surface Model (DSM), (step 3 in the software workflow), volume measurements are enabled. The user identifies the pile by drawing a shape around its base:

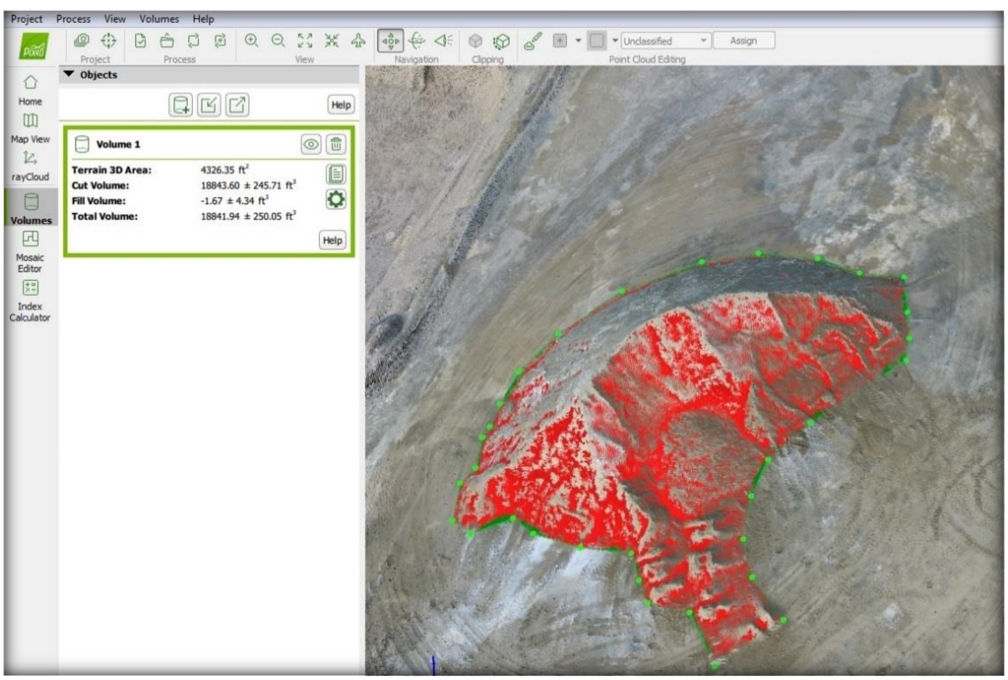


Figure 9 Pix4D Screenshot of Stockpile Measurment

The Pix4D computed volume of the pile was 698 cu yds. Two other computations were performed for comparison of results: Paul Rieger uploaded the UAV imagery to Stockpile Reports and Joey Renenger measured the pile using the Stockpile Reports' IPhone app. Results:

Image Collection Device Device / Computation Method	Stockpile Volume (cu yds)
MDT UAV / Pix4d Software	698
MDT UAV / Stockpile Reports Service	703
IPhone / Stockpile Reports	696

Figure 101 Comparison of Results of Stockpile Measurement

One advantage of Pix4D is the ability to measure volumes on cuts as well as fills/piles. Stockpile Reports is currently limited to stockpile volume measurements only. (However, the ability of Stockpile Reports to collect imagery with the IPhone *is* a huge advantage.)

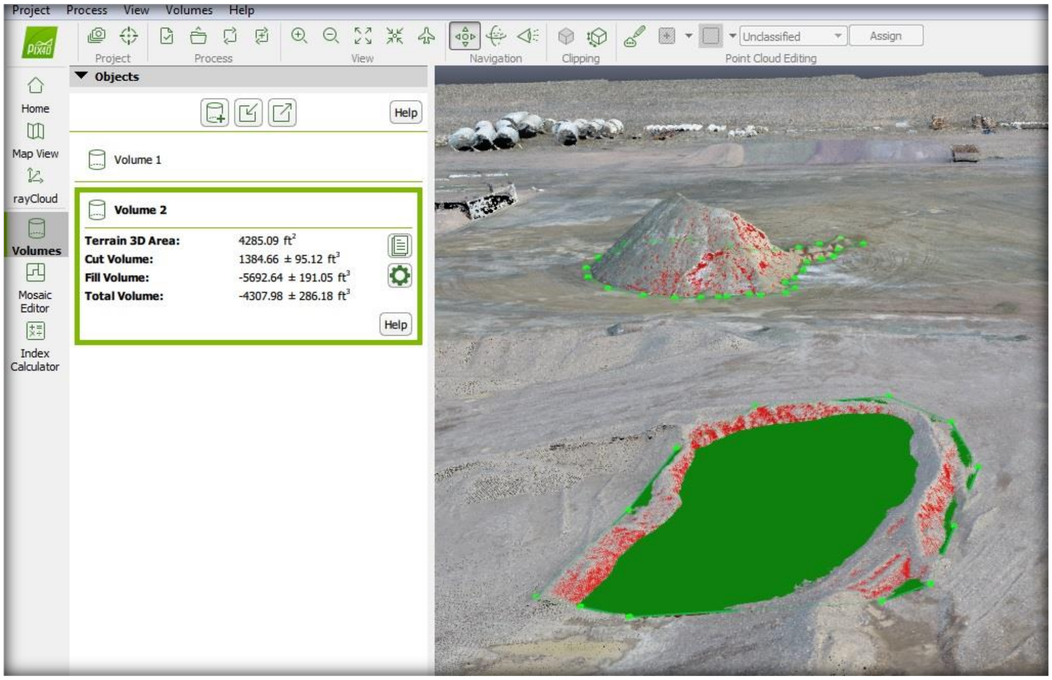


Figure 10 Pix4D screenshot of Volume Measurement

Discussion

UAVs have many potential applications and the technology is evolving quickly. Recent changes to FAA regulations have made it feasible for MDT to operate UAVs.

Cost for the UAV and autopilot app is low. The UAV that MDT owns (Phantom 4 Pro) costs around $1500. The Maps Made Easy App is $10-$38 dollars per device, depending on features.

The testing completed thus far has demonstrated that it is relatively easy to operate the UAV and collect the imagery when weather permits. In fact, the entire flight including takeoff and landing of the UAV can be performed automatically and without any intervention from the operator. The more challenging and expensive part of the workflow is the data processing;

however, outsourcing this work is likely to be a preferred option for some applications such as earthwork volume computations on MDT Construction Projects.

UAV operation will be limited by weather. Operation when wind speeds exceed 15mph is not recommended. Collecting imagery during lower light conditions requires longer camera exposure time. The autopilot app determines the proper exposure time and adjusts the aircraft speed to allow time for the photo to be taken and saved. The reduced speed increases the amount of flight time and can result in the need to interrupt flights for battery changes. If spare batteries are available, this does not create a problem since the app will resume a flight that has been interrupted for a battery swap.

Although not evaluated in this report, it should be noted that more advanced mapping UAS are equipped with RTK or PPK corrected GPS capability and produce a much higher level of precision while reducing the need for many ground control points.

Acknowledgements
Thanks to Jack Carlson, Sam Ahlrich, Fred Ziesman, Joey Renenger, Bill Weber, Bryce Larson, John Ascheman and Paul Rieger for their help with this demonstration.

Attachments

copies:

Kevin Christensen	CES Bureau	Dwane Kailey	Dustin Rouse	Mike Dyrdahl	MDT
Maintenance	Kent Barnes	DCEs	Lisa Durbin	Bryce Larsen	
Bill Weber	Fred Ziesman	Joey Renenger	Jack Carlson	Sam Ahlrich	

Appendix A

Workflows

1. Using DJI Go App and Map Pilot App to create flight plan and collect imagery:

Set general flight control settings using the DJI Go App:

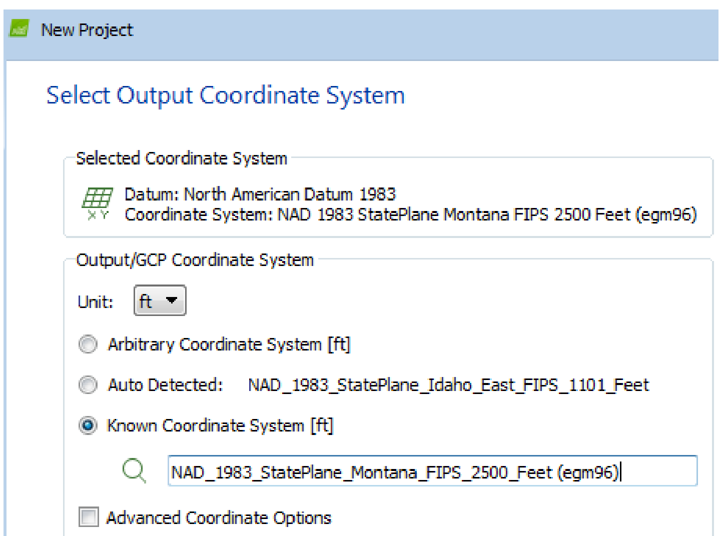
- Intelligent flight modes were enabled. (Necessary for the Map Pilot App to work).
- Set Return to Home Altitude (RTH) to 300 feet. In the event of a low battery, signal loss, or user command, the aircraft will ascend to the RTH altitude and return to the home point. (The home point is automatically set as the aircraft location at the time it is powered on and connected to enough satellites).

Next, close the DJI Go App and use the Map Pilot App to create the autonomous flight plan, summarized as follows:

1. Open app, create new mission.
2. Scroll/zoom map view to the survey site.
3. Double click the approximate location where the UAV take off location will be (blue dot).
4. Tap and hold to create boundary points (orange dots). Adjust the boundary points to enclose the intended survey area. The flight path is shown as a white line with the start and end points shown as green and red dots, respectively.
5. Set the maximum altitude.
6. Rotate the flight path by using the two finger rotate gesture on the touchscreen to align the flight legs with a boundary.
7. Check flight duration / number of aircraft batteries required. For this flight it was desirable to limit the number of batteries to one even though the app is supposed to be capable of mapping large sites requiring multiple battery exchanges.

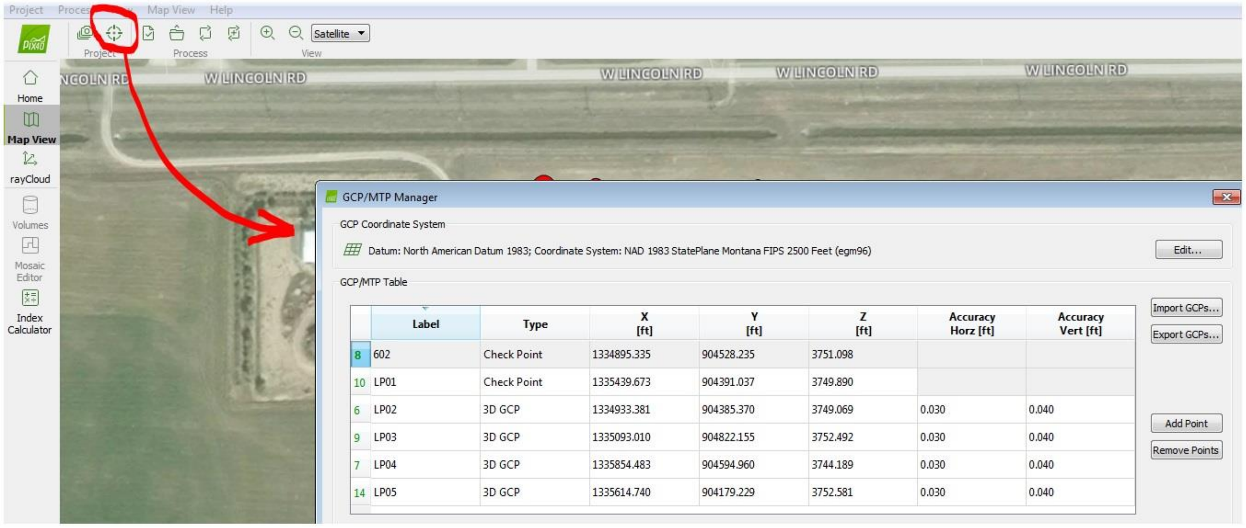
<u>2. Rectification of point cloud with ground control points using Pix4D software:</u>

Open Pix4D, create a new project, import imagery [set units to feet, do not change imagery coordinate system]. For the output coordinate system, select the Montana State Plane Zone 2500 system:



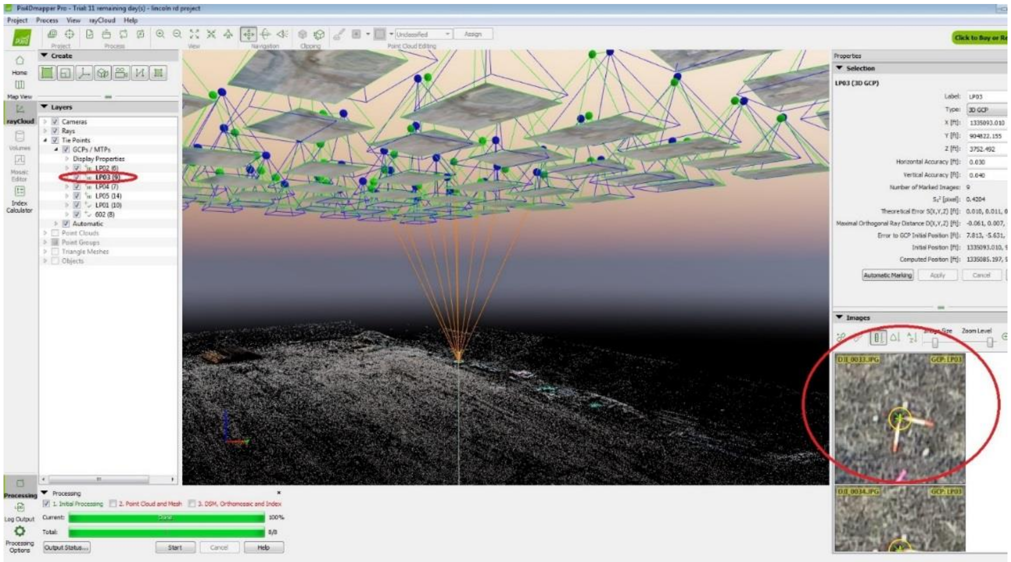
Enter the Ground Control Point Data using the GCP/Manual Tie Point Manager[3]:

3 See https://support.pix4d.com/hc/en-us/articles/202560769-How-to-mark-GCPs-in-the-rayCloud#gsc.tab=0 for more detail.



Process step 1 only:

After initial processing is complete, select ray cloud and expand the GCP pulldown list. Select a control point from that list. Images associated with that location appear. Zoom in and manually mark the precise control point location in at least two images using a left click of the mouse. Select Automatic Marking to have the software mark other images. Verify the accuracy of those marks and correct as needed by left clicking. Marking the GCP location in multiple images increases accuracy. Once satisfied, click apply. Repeat for the other GCPs and any check points.



Select Process/ Reoptimize.

Appendix B

Pix4D Quality Report

(See https://support.pix4d.com/hc/en-us/articles/202557339#gsc.tab=0
for information about Quality Report Interpretation)

Quality Report

Generated with Pix4Dmapper Pro version 3.1.23

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	lincoln rd project
Processed	2017-03-29 06:37:08
Camera Model Name(s)	FC6310_8.8_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	1.51 cm / 0.59 in
Area Covered	0.0983 km^2 / 9.8271 ha / 0.038 sq. mi. / 24.296 acres

Quality Check

Images	median of 44969 keypoints per image	✓
Dataset	205 out of 205 images calibrated (100%), all images enabled	✓
Camera Optimization	0.56% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 24637.8 matches per calibrated image	✓
Georeferencing	yes, 4 GCPs (4 3D), mean RMS error = 0.006 ft	✓

Preview

Figure 1: Orthomosaic and the corresponding sparse Digital Surface Model (DSM) before densification.

Calibration Details

Number of Calibrated Images	205 out of 205
Number of Geolocated Images	205 out of 205

Initial Image Positions

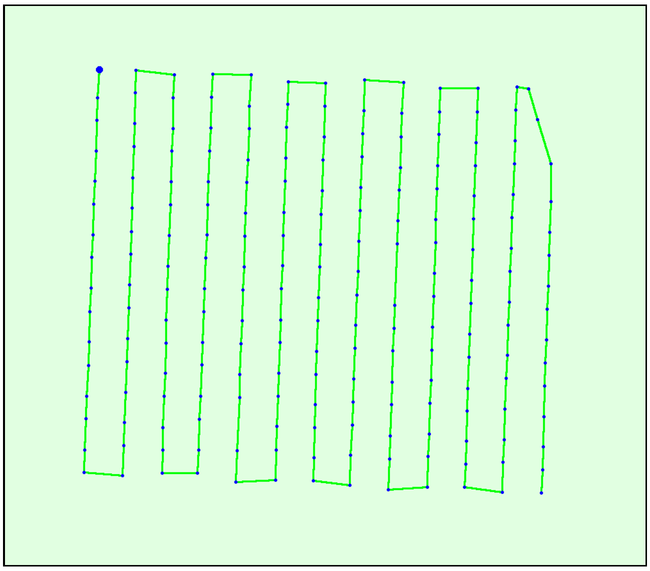
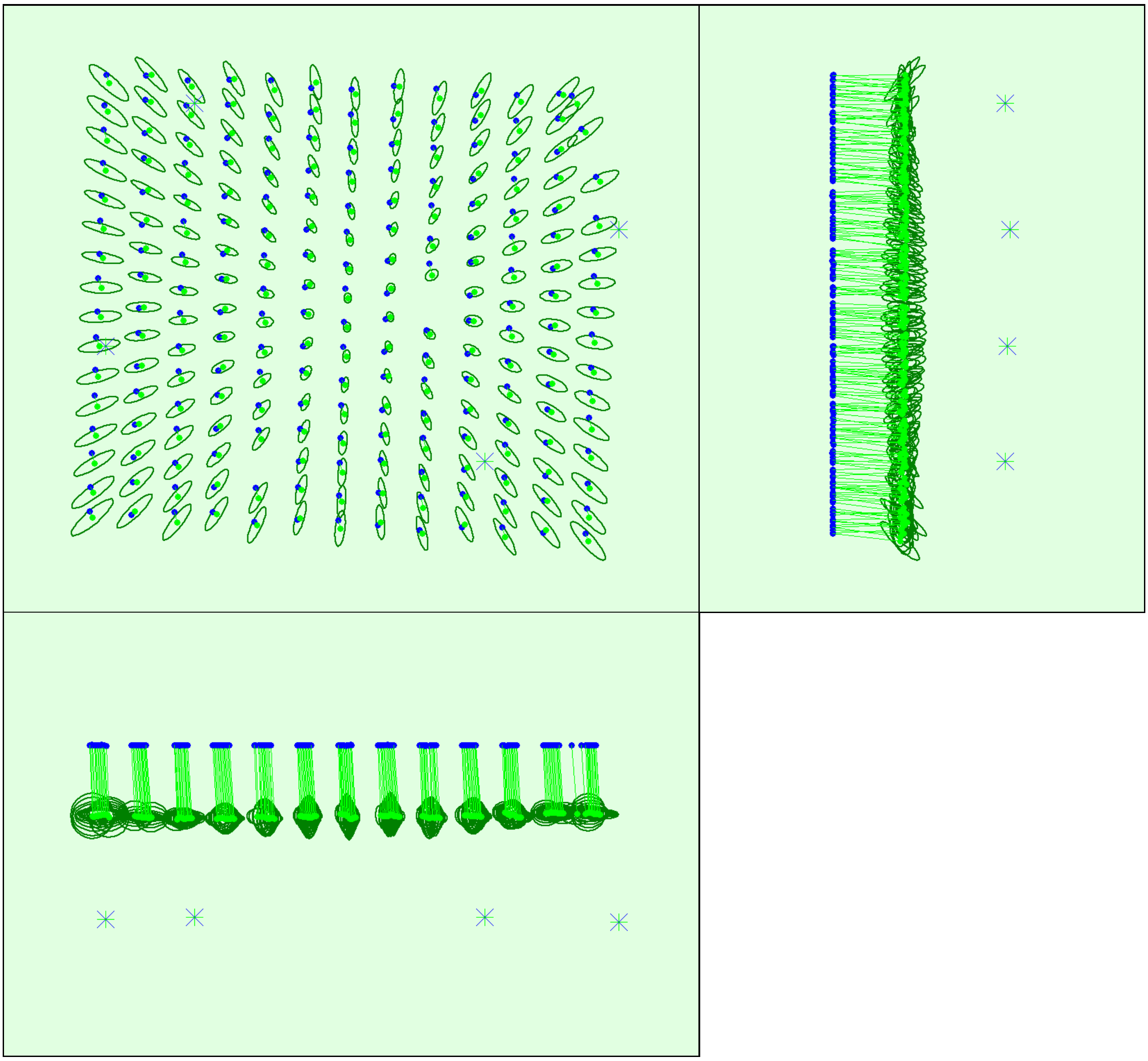


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions



Uncertainty ellipses 100x magnified

Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X [ft]	Y [ft]	Z [ft]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.201	0.192	0.207	0.058	0.059	0.007
Sigma	0.095	0.077	0.099	0.027	0.029	0.002

Overlap

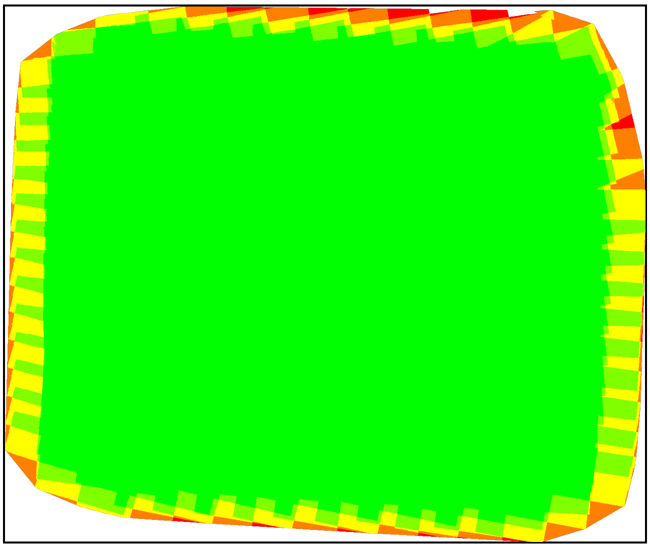


Figure 4: Number of overlapping images computed for each pixel of the orthomosaic.
Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Bundle Block Adjustment Details

Number of 2D Keypoint Observations for Bundle Block Adjustment	5109194
Number of 3D Points for Bundle Block Adjustment	1461748
Mean Reprojection Error [pixels]	0.138

Internal Camera Parameters

FC6310_8.8_5472x3648 (RGB). Sensor Dimensions: 12.833 [mm] x 8.556 [mm]

EXIF ID: FC6310_8.8_5472x3648

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	3668.759 [pixel] 8.604 [mm]	2736.001 [pixel] 6.417 [mm]	1823.999 [pixel] 4.278 [mm]	0.003	-0.008	0.008	-0.000	0.000
Optimized Values	3689.313 [pixel] 8.652 [mm]	2744.764 [pixel] 6.437 [mm]	1842.595 [pixel] 4.321 [mm]	0.002	-0.006	0.006	0.001	0.001
Uncertainties (Sigma)	1.321 [pixel] 0.003 [mm]	0.696 [pixel] 0.002 [mm]	0.616 [pixel] 0.001 [mm]	0.001	0.001	0.001	0.000	0.000

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	44969	24638
Min	21802	13843
Max	74189	40563
Mean	46124	24923

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	811790
In 3 Images	235771
In 4 Images	113169
In 5 Images	71212
In 6 Images	53423
In 7 Images	42241
In 8 Images	32816
In 9 Images	27893
In 10 Images	24305
In 11 Images	19199
In 12 Images	13164
In 13 Images	9328
In 14 Images	5312
In 15 Images	2064
In 16 Images	61

2D Keypoint Matches

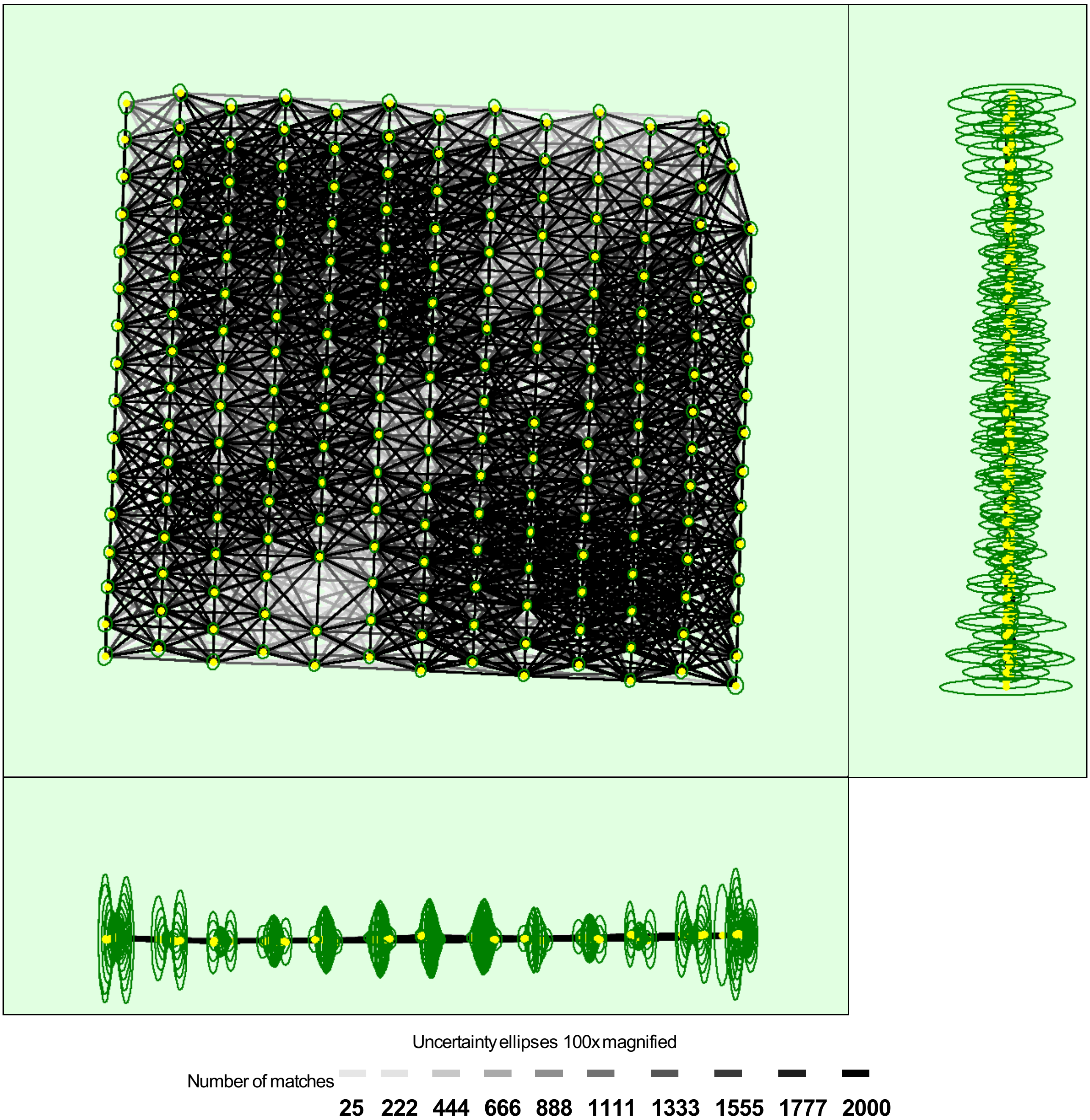


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X [ft]	Y [ft]	Z [ft]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.072	0.087	0.300	0.102	0.115	0.009
Sigma	0.012	0.014	0.193	0.060	0.065	0.003

Geolocation Details

Ground Control Points

GCP Name	Accuracy XY/Z [ft]	Error X [ft]	Error Y [ft]	Error Z [ft]	Projection Error [pixel]	Verified/Marked
LP02 (3D)	0.030/ 0.040	-0.003	0.002	-0.004	0.547	6 / 6

LP03 (3D)	0.030/ 0.040	-0.005	-0.005	0.001	0.642	9 / 9
LP04 (3D)	0.030/ 0.040	0.014	-0.009	-0.010	0.726	7 / 7
LP05 (3D)	0.030/ 0.040	-0.002	0.013	-0.001	0.392	14 / 14
Mean [ft]		0.000987	0.000076	-0.003619		
Sigma [ft]		0.007694	0.008200	0.004181		
RMS Error [ft]		0.007757	0.008200	0.005530		

0 out of 2 check points have been labeled as inaccurate.

Check Point Name	Accuracy XY/Z [ft]	Error X [ft]	Error Y [ft]	Error Z [ft]	Projection Error [pixel]	Verified/Marked
LP01	0.0200/0.0200	-0.0315	-0.0005	-0.0526	0.6067	10 / 10
602	0.0200/0.0200	0.0356	-0.0268	0.0352	0.6678	8 / 8
Mean [ft]		0.002070	-0.013628	-0.008714		
Sigma [ft]		0.033543	0.013146	0.043913		
RMS Error [ft]		0.033607	0.018936	0.044769		

Localisation accuracy per GCP and mean errors in the three coordinate directions. The last column counts the number of calibrated images where the GCP has been automatically verified vs. manually marked.

Absolute Geolocation Variance

Min Error [ft]	Max Error [ft]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	3.41	0.00
-15.00	-12.00	0.00	6.34	0.00
-12.00	-9.00	0.00	9.76	0.00
-9.00	-6.00	0.00	12.20	7.80
-6.00	-3.00	0.98	6.34	11.71
-3.00	0.00	45.37	9.27	23.90
0.00	3.00	53.66	11.22	36.10
3.00	6.00	0.00	9.27	20.49
6.00	9.00	0.00	10.73	0.00
9.00	12.00	0.00	14.15	0.00
12.00	15.00	0.00	6.83	0.00
15.00	-	0.00	0.49	0.00
Mean [ft]		-6.876131	6.200471	127.613958
Sigma [ft]		1.646054	8.775361	3.261726
RMS Error [ft]		7.070409	10.744897	127.655635

Min Error and Max Error represent geolocation error intervalsbetween -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the intial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Geolocation Bias	X	Y	Z
Translation [ft]	-6.876131	6.200471	127.613958

Bias between image initial and computed geolocation given in output coordinate system.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	100.00	33.17	100.00
[-2.00, 2.00]	100.00	66.34	100.00
[-3.00, 3.00]	100.00	96.10	100.00
Mean of Geolocation Accuracy [ft]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [ft]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	1.448
Phi	0.467
Kappa	7.672

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-4770 CPU @ 3.40GHz RAM: 16GB GPU: Intel(R) HD Graphics 4600 (Driver: 10.18.10.3907), RDPDD Chained DD (Driver: unknown), RDP Encoder Mirror Driver (Driver: unknown), RDP Reflector Display Driver (Driver: unknown)
Operating System	Windows 7 Enterprise, 64-bit

Coordinate Systems

Image Coordinate System	WGS84 (egm96)
Ground Control Point (GCP) Coordinate System	NAD_1983_StatePlane_Montana_FIPS_2500_Feet (egm96)
Output Coordinate System	NAD_1983_StatePlane_Montana_FIPS_2500_Feet (egm96)

Processing Options

Detected Template	3D Maps
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Aerial Grid or Corridor
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes Bundle Adjustment: Classic