UAS as an Inventory Tool: A Photogrammetric Approach to Volume Estimation

Richard Kramer Rhodes

University of Arkansas, Fayetteville

Follow this and additional works at: https://scholarworks.uark.edu/etd

Part of the Geographic Information Sciences Commons, Remote Sensing Commons, and the Spatial Science Commons

Citation

This Thesis is brought to you for free and open access by ScholarWorks@UARK. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of ScholarWorks@UARK. For more information, please contact scholar@uark.edu.
UAS as an Inventory Tool: A Photogrammetric Approach to Volume Estimation

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geography

by

Richard Kramer Rhodes
University of Arkansas at Monticello
Bachelor of Science in Spatial Information Systems, 2015

August 2017
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

________________________________________
Jason Tullis, Ph.D.
Thesis Director

________________________________________
W Fred Limp, Ph.D.
Committee Member

________________________________________
Jackson Cothren, Ph.D.
Committee Member
Abstract

Unmanned aircraft systems (UAS), also referred to as unmanned aerial vehicles (UAV) or remotely piloted vehicles (RPV), are associated with unmanned aircraft either controlled by a pilot on the ground or pre-programmed with specific flight paths. Small UASs have seen a massive increase in public interest in recent years as hobbyist platforms; they are, however, a potentially powerful tool in remote sensing and geospatial applications. Due to the increased availability of low-cost UAS, this technology could soon revolutionize many industries, including those that require volumetric estimation. Traditionally volumetric inventories have been performed with tape measurements, and in some instances where accuracy is of utmost importance, survey grade GPS and/or terrestrial light detection and ranging (LiDAR) equipment. UAS platforms can bridge a gap between traditional methods by providing accurate volume estimates quickly and efficiently along with valuable 3D digital data for a historical record. This project addressed this problem using photogrammetric techniques with an inexpensive UAS. Methods of data capture and post processing techniques were explored. Volumetric accuracies were assessed by comparing collected data against in situ reference measurements and engineering diagrams. The results show a promising future for UAS and photogrammetric volume estimation that is both cost and time efficient. Out of thirteen objects surveyed six had a relative error less than 5% and exhibited good quality 3D reconstruction. Of the remaining seven objects, four had a relative error greater than 15% and exhibited a very poor 3D reconstruction. The ability to accurately estimate volume is directly proportional to the quality of the 3D model with the highest quality scenes exhibiting the highest accuracy volume estimates. This project has demonstrated that when suitable circumstances are presented and 3D reconstruction is met with a high level of success, inexpensive UAS and photogrammetry present a powerful tool for performing volume estimation of many objects. Future efforts should include research into the
optimization of equipment parameters as well as the effects and limitations of site conditions in order to improve 3D modeling and thus volume estimation.
Acknowledgements

I would like to express my gratitude to my advisor and professor, Dr. Jason Tullis for your support, encouragement, and advice during the completion of my graduate research. I would also like to express my appreciation to my other committee members Dr. Fred Limp and Dr. Jackson Cothren. Additionally, I would like to extend thanks to colleagues that assisted with this project especially Joseph Jordan who on multiple occasions helped with data collection and provided excellent advice for post processing. I would like to extend a special thanks to Mr. Mayo Miller who assisted in securing the permissions to collect data at the facility managed by his company.
Dedication

I would like to dedicate this thesis to my wife, Rachel for all the support she has given me throughout my graduate studies and also to my parents, Roy and Vickie Rhodes for their dedication and support to furthering my education.
Contents

1. Introduction and Background ........................................................................................................... 1
   1.1 What is a UAS .......................................................................................................................... 1
   1.2 What is photogrammetry ......................................................................................................... 1
       1.2.1 History of Photogrammetry .......................................................................................... 2
   1.3 Importance of Volume Calculations ....................................................................................... 4
   1.4 Traditional volume calculation methods .................................................................................. 4
       1.4.1 Total Station .................................................................................................................... 5
       1.4.2 Global Navigation Satellite System (GNSS) .................................................................. 5
       1.4.3 Terrestrial Laser Scanning (TLS) ................................................................................... 6
       1.4.4 Airborne LiDAR ............................................................................................................. 7
       1.4.5 Volume by Differencing (DTM) approach ...................................................................... 8
   1.5 Ground Control Points (GCP) ................................................................................................ 8
   1.6 Project Accuracy ...................................................................................................................... 10
       1.6.1 Horizontal Accuracy ...................................................................................................... 11
       1.6.2 Vertical Accuracy ........................................................................................................... 11
   1.7 Automated Photogrammetric Software .................................................................................. 12
       1.7.1 Structure-from-motion (SfM) ........................................................................................ 13
       1.7.2 Scale-invariant feature transform (SIFT) ....................................................................... 14
   1.8 Statement of the Problem ......................................................................................................... 15
       1.8.1 Research Questions and Hypotheses .............................................................................. 15

2. Literature Review ............................................................................................................................ 17
   2.1 3D Modeling .......................................................................................................................... 17
       2.1.1 Photogrammetric image matching techniques ............................................................... 20
   2.2 Accuracy of 3D Models derived from UAS photogrammetry ............................................... 23
   2.3 UAS and Photogrammetry for volume calculations ............................................................... 25

3. Methods and Materials .................................................................................................................. 29
   3.1 Study Area .............................................................................................................................. 29
   3.2 Materials ................................................................................................................................. 31
       3.2.1 UAS system ..................................................................................................................... 32
       3.2.2 Camera .......................................................................................................................... 34
       3.2.3 GPS .............................................................................................................................. 36
3.2.4 Ground Control Points (GCPs) ............................................................... 37
3.3 Software ................................................................................................. 37
  3.3.1 Agisoft Photoscan ............................................................................. 38
  3.3.2 ESRI ArcMap .................................................................................... 39
  3.3.3 Microsoft Excel 2016 ........................................................................ 39
  3.3.4 3DR SOLO app .................................................................................. 39
  3.3.5 FAA B4UFly ...................................................................................... 40
3.4 Methods ................................................................................................. 40
  3.4.1 Flight planning and study site .......................................................... 40
  3.4.2 GCP placement and survey ............................................................. 41
  3.4.3 Data Collection ................................................................................ 43
  3.4.4 Image Processing ............................................................................ 47
4. Results ...................................................................................................... 55
  4.1 3D Model ............................................................................................. 55
  4.2 Time .................................................................................................... 55
  4.3 Measurements ..................................................................................... 58
    4.3.1 Volume .......................................................................................... 58
    4.3.2 Dimensions .................................................................................. 60
5. Discussion and Conclusion ..................................................................... 64
  5.1 Conclusions ......................................................................................... 64
    5.1.1 Volume Estimation Ability ......................................................... 64
    5.1.2 Measurement Comparison ....................................................... 65
    5.1.3 Effect of Size, Shape and Configuration of Objects .............. 66
    5.1.4 Time ............................................................................................ 67
  5.2 Limitations ............................................................................................ 68
    5.2.1 Accuracy of Volume Estimations .............................................. 68
    5.2.2 Data Holes .................................................................................. 68
    5.2.3 Poor Reconstruction of Objects ................................................. 70
  5.3 Processing Considerations ................................................................. 71
  5.4 Future Efforts ....................................................................................... 71
References ................................................................................................... 73
Appendix A – Site 1 Photoscan Processing Report .................................. 77
**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Map of First Study Site</td>
<td>30</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Map of Second Study Site</td>
<td>31</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Solo Overview (3DR Solo, Mar 10, 2017)</td>
<td>32</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Leica GS15 set up as base station</td>
<td>36</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Example of GCP being surveyed</td>
<td>37</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Methods overview</td>
<td>40</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Data collection workflow</td>
<td>45</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Data collection at Site 2</td>
<td>46</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Aligned photos and sparse points cloud</td>
<td>48</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Dense point cloud</td>
<td>49</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Non-textured mesh</td>
<td>50</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Textured mesh</td>
<td>51</td>
</tr>
<tr>
<td>Figure 13</td>
<td>GCP markers</td>
<td>52</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Agisoft Photoscan workflow</td>
<td>54</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Project time at Site 1</td>
<td>57</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Project time at Site 2</td>
<td>57</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Graph of Relative Error</td>
<td>60</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Site 2 showing large data hole</td>
<td>69</td>
</tr>
</tbody>
</table>
List of Tables

Table 1 - GoPro 35mm Equivalent Focal Lengths (GoPro, Mar 31, 2017) ........................................ 34
Table 2 - GoPro Hero 4 Silver Video mode resolutions (GoPro, Mar 10, 2017) .............................. 35
Table 3 - GoPro photo settings (GoPro, Mar 10, 2017) ................................................................. 35
Table 4 - GCPs Site 1 .................................................................................................................... 42
Table 5 - GCPs Site 2 .................................................................................................................... 43
Table 6 - Reference data ............................................................................................................. 46
Table 7 - Project time ................................................................................................................... 56
Table 8 - Results from volume calculations at Site 1 ................................................................. 58
Table 9 - Results from volume calculations at Site 2 ................................................................. 60
Table 10 - Results from height measurement analysis ............................................................. 62
Table 11 - Results from Width/Diameter Measurement Analysis .............................................. 63
1. Introduction and Background

1.1 What is a UAS

Given the sudden interest in Unmanned aircraft systems there can be some confusion as to what exactly a UAS is; “according to the UVS International definition, a UAS is a generic aircraft design to operate with no human pilot onboard” (Remondino et al. 2011, p. 25). Other commonly used terms used to describe UASs include remotely piloted vehicle (RPV), remote controlled (RC) airplane or helicopter, remotely operated aircraft (ROA), unmanned vehicle systems (UVS), unmanned aerial vehicle (UAV), drone, as well as others (Remondino et al. 2011). UASs provide an innovative solution to the age-old question of how to capture fine scale-specific or very high spatial resolution imagery under appropriate conditions suitable for a variety of remote sensing applications. UASs provide the flexibility for a remote pilot or field operations team to collect data at times and under conditions not typically convenient for traditional, aircraft-based, aerial photo acquisition, as well as the ability to fly low elevation missions that would otherwise require costly, piloted helicopter based acquisition.

1.2 What is photogrammetry

Photogrammetry is an important spatial analysis procedure that has a long history, “photogrammetric techniques, measuring objects from photographs, have been utilized since the late 1800s” (Yilmaz 2010, p. 48). Photogrammetry is the process of obtaining accurate mathematical measurements from multiple 2D images of a 3D scene for the production of concise spatial information (Matthews 2008; Yilmaz 2010, p.48). Photogrammetry utilizes overlapping photos recorded with a camera recording common features within overlapping photos enabling software to process the scene in 3D (Yilmaz 2010). Recently photogrammetry has become very popular among numerous fields, particularly engineering (Raeva et al. 2016).
The potential for the use of UAS for data collection is huge, according to Raeva et al. (2016) “UAS photogrammetry covers the gap between classical manned aerial photogrammetry and handmade surveying techniques as it works in the close-range domain” (Raeva et al. 2016, p.999). It is this close-range domain ability that makes the potential for UASs as a data collection system particularly exciting, opening up new windows for research that has not traditionally been possible.

1.2.1 History of Photogrammetry

Photogrammetry has a very long and storied history beginning with the acquisition of the first photograph by Joseph Nicéphore Niépce which required an eight-hour long exposure time (Burtch 2004). In 1837, Louis-Jacques-Mandé Daguerre developed a camera and obtained the first practical photograph using a process called the Daguerreotype (Burtch 2004). The first terrestrial photos used for topographic map creation were acquired in 1849 by Aimé Laussedat earning him the title “Father of Photogrammetry” (Burtch 2004). In 1855, Gaspard Felix Tournachon (AKA Nadar) was the first person to obtain an aerial photograph while suspended from a balloon 80-meters in the sky (Burtch 2004).

Photogrammetry has been continually evolving since these first successful flights being driven by forward first by military operations for reconnaissance purposes. In 1859 Emperor Napoleon ordered Nadar to obtain reconnaissance photographs in preparation for the Battle of Solferino and in the 1870s the Prussian army organized a photo field detachment to obtain stereo photos (Burtch 2004). The development of analog photogrammetry and the invention of the airplane by the Wright brothers in 1903 enhanced the ability to collect photogrammetric data. In 1908 Julius Neubronner patented a miniature pigeon based camera that was triggered by a timing device (The Public Domain Review May 2, 2017). Other important innovations include the
development of the photogrammetric plane table, stereo planigraph, Aerosimplex potter, Stereocomparator, various plotters, etc. All of these technological advancements led to the growth of photogrammetry and expansion of its usefulness (Burtch 2004). In 1904, the U.S. Geological Survey began to use photogrammetry for topographic mapping when C. W. Wright and F. E. Wright took photos from the ground using a panoramic camera for use in their survey of Alaska (Burtch 2004). In the years since photogrammetry has been used in many disciplines for many different purposes and innovations have presented themselves at the turn of every corner. A few disciplines that have benefited from the use of photogrammetric produces over the years include forestry, surveying, land management, urban planning, mining, oil and gas, and many others.

Photogrammetry has come a long way in approximately 160 years, from the first aerial photo being acquired in 1855 by Nadar to the development of high performance photogrammetric operations in 2017. The ability to utilize high-performance computing has made projects such as the research being conducted by the Oak Ridge National Laboratory possible. The Oak Ridge National Laboratory is working on a project that utilizes high performance computing to automatically register spatial imagery to the correct location on the earth, this process uses an image registration solution known as PRIMUS (Nemire 2016). It is also through computer based developments that three-dimensional modeling applications have become possible. These computer based algorithms include methods such as scale invariant feature transform (SIFT), and structure from motion (SfM) techniques which make photo matching possible through the identification of keypoints. It is through the matching of photos in a set that the 3-D scene reconstruction is made possible thus opening up many new possibilities for photogrammetric operations including the calculation of various measurements such as
volume. As more research is done on 3D modeling and measurement capability of computer based photogrammetric processes there appears to be massive potential in innovation for this age-old discipline.

1.3 Importance of Volume Calculations

Volume estimates are a vital portion of many industries and disciplines; therefore, the ability to do so quickly and accurately is essential in order to ensure cost efficiency. Cut and fill volume estimations are vitally important issues in many disciplines including the mining industry, open cast mining, surface mining as well as other engineering fields (Yilmaz 2010). Volume estimations are also very important in many surveying practices (Easa 1988). Achieving efficient and highly accurate volume estimation is both a theoretically and practically important question (Yilmaz 2010; Soole et al. 2000). Given the importance of volume estimation, it is essential to constantly adapt to the ever-changing world of technology and improve upon traditional methods. UAS technology is potentially highly complementary to the realm of volume computation given its flexibility, affordably, and ease of use (Raeva et al. 2016). The ability to calculate volumes of objects of many different shapes and sizes quickly and efficiently is a vital question across many different disciplines.

1.4 Traditional volume calculation methods

There are many traditional methods for determining volumes of objects. These methods include theodolite (TST), global positioning system (GPS), terrestrial laser scanning (TLS), and airborne light and direction ranging (LiDAR; Hugenholtz et al., 2015). These traditional methods, while highly accurate, are very time-consuming. Several studies have examined the manpower as well as timeliness for these methods vs. photogrammetric procedures concluding
that one trained individual is sufficient for photogrammetric methods whereas other methods traditionally require two (Raeva et al. 2016; Yilmaz 2010; Patikova 2004; Easa 1988). Yilmaz (2010) also considers the efficiency of photogrammetric volume estimation vs. traditional methods stating, “compared with classical surveying methods, close range photogrammetry is efficient and fast, significantly reducing the time required to collect data in the field” (Yilmaz 2010 p. 48). “Field measurements that can be done in less than 3 days would take 10 days in a classical survey method” (Yilmaz 2010, p. 48). There is also the issue of safety, traditional methods often times require surveyors to climb on top of unstable stockpiles/structures which can be viewed a potential safety hazard (Hamzah and Said 2011).

1.4.1 Total Station

The total station method is a very commonly used approach across many disciplines. This method, while highly accurate, is potentially the most taxing on human resources requiring in most cases an entire crew of men. The number of individuals needed introduces more potential for human error; this is because a different individual operates each piece of equipment. This method is ideal for applications were accuracy within 3 millimeters (0.01 feet) is necessary (Smet 2012). When concerned with volume calculations small amounts of deviation in distance, or angle measurements could drastically influence the final calculation. Given the increased amount of manpower, there is also an increased cost associated with the total station approach versus the potential ability to determine the same information with a UAS.

1.4.2 Global Navigation Satellite System (GNSS)

By utilizing various software packages, it is possible to create 3D models from a collection of GPS coordinates. It should be noted that in order to created three-dimensional
surfaces from a collection of GPS points it is necessary to have elevation data for each point (Z) in addition to the planar information (X, Y). This method while potentially highly accurate is very time-consuming. GNSS survey provides a system that is suitable for large study sites that have accuracy requirements of 8 millimeters (0.03 feet) or less (Smet 2012). While only one individual is necessary for the collection of GPS points, multiple people make data collection easier, these surveyors must ensure the appropriate density of points to minimize error from interpolation methods, upon completion of acquiring points the data must then be processed in a lab. Various interpolation methods utilized in this method introduce some concern as to how accurate the method is. Various studies have utilized this method to reconstruct a 3D scene and then use that scene to acquire measurements of some kind. One such study performed by Raeva et al. utilized AutoCAD Civil 3D to create a surface from contours by utilizing points collected during a GNSS survey, once this surface was generated the authors proceeded to calculate volume using the generated surface (Raeva et al. 2016).

1.4.3 Terrestrial Laser Scanning (TLS)

TLS can be described as an active LiDAR (light detection and ranging) system that calculates the distance to surfaces by measuring the flight time of emitted pulses of light (O’Neal 2012). These laser pulses are used to generate 3D point clouds of the study area. Multiple survey locations are used with TLS to ensure no portions of a study area are excluded; this is because the instrument rotates on a base around a vertical axis and the distance between data observations increase with distance from the sensor (O’Neal 2012). TLS also requires manual filtering of a raw point-cloud to sort through object of interest points and other objects/noise (O’Neal 2012).

TLS has become an industry standard in many disciplines because of its relatively straightforward approach, and the level of small-scale detail that is missed by other techniques
TLS sounds great but “two related challenges associated with TLS volumetrics are cost and efficiency” (Hugenholtz et al., 2015, p. 1). While TLS is very precise, it is, too time-consuming for projects that have a need for frequently updated information (Patikova 2004). TLS has the ability to obtain measurements within 6mm of actual values at a range of 50 meters when optimal circumstances are present (Cuartero et al. 2010). These characteristics make TLS highly accurate but also costly and time consuming thus creating a demand for a system that is both highly accurate and affordable enough for individuals without the capital investment or knowledge required for TLS survey.

1.4.4 Airborne LiDAR

Airborne LiDAR systems can be described as, “3D laser scanning also known as LiDAR (Light Detection and Ranging), is a system that scans real objects to produce three-dimensional discretely sampled surfaces which represent those real objects” (Du and Teng 2007, p. 657). Traditional airborne LiDAR has revolutionized the concept of high accuracy elevation data, but it is not practical in all aspects of volume calculations. First, is the cost as “routine use of airborne LiDAR nevertheless requires a substantial financial investment” (Hugenholtz et al. 2015, p. 1). Another potential handicap of traditional airborne LiDAR systems is its inability to fly a piloted aircraft at low elevations and navigate around structures of interest. This is problematic when structures of interest for volume calculations are located in close proximity to other objects or even have overhead obstructions such as tree canopy or power lines. While this technique has revolutionized elevation data for large areas, it is not particularly suited for small-scale applications. Airborne LiDAR is not a perfect system for volume calculations given its
minimal flexibility, altitude constraints, cost, and the inability to maneuver around objects of interest to ensure adequate point distributions.

1.4.5 Volume by Differencing (DTM) approach

A DTM (digital terrain model) is essentially a model of the earth’s surface that is derived from elevation data. Several studies have focused on volume estimations by a process of differencing, for instance, “by differencing the two UAS DTMs, the gravel extracted from the stockpile was estimated” (Hugenholtz et al. 2015, p. 1); and “volumes can be calculated as a difference between old and new model” (Patikova 2004, p. 3). This process is completed by first utilizing photogrammetric measures to create a DTM (digital terrain model) of the area of interest before a change has occurred and after (pre-object and post-object), and then the two models can be differenced resulting in the volume of the change (object of interest). While this approach has produced promising results, it is not ideal in the fact that an area must be flown multiple times, once to get a baseline and again every time change has taken place resulting in twice the amount of data and processing time. Another concern in the problem of preexisting structures for example if the object of interest is a building, it is not always possible to acquire data pre-construction, making this method not applicable to this study.

1.5 Ground Control Points (GCP)

A ground control point (GCP) is simply an object placed within the study area, pre-data collection, which is surveyed using a highly precise GPS unit. These objects are most typically target type graphics painted or printed on a sheet of paper and secured to the ground to prevent movement between GPS survey and data collection, however, features such as the intersection of sidewalks and other visible locations that are stable can be used. GCPs are utilized to give the
study area of interest real world dimensions; Yilmaz (2010) states that “the GCPs in the photogrammetric method are used to calculate the position and orientation of each camera in a stereo pair of photographs” (Yilmaz 2010, 48). This factor makes GCPs of the utmost importance when the product of a photogrammetric mission will be used to acquire measurements such as volume.

One important factor to consider when utilizing GCPs is the number of GCPs needed in order to optimize photogrammetric results. According to several sources, the process can be carried out by utilizing a minimum of three GCPs, but higher accuracies are obtained the more GCPs are used (Rosnell and Honkavaara 2012; James and Robison 2012); Yilmaz (2010) on the other hand states that at least four GCPs are required in each module for photogrammetric operations to be completed (Yilmaz 2010). It is also important to consider the findings of Agüera-Vega (2016), who observed that accuracy increases with the number of GCPs utilized in a study concluding that 10 (the maximum number used in the study) with an altitude of 50 m yielded the best results (Agüera-Vega et al. 2016). While the optimal number of GCPs is disputed, the majority of studies agree that the more GCPs are used, the more accuracies are improved.

Typical GCPs consist of placed targets that are surveyed utilizing highly accurate GPS units before data collection. An important factor to consider when placing GCP points, other than the number utilized, is the distribution. Raeva et al. (2016) performed a study that utilized GCPs; the authors were careful to ensure the distribution of targets where relatively the same across the study area as to not accumulate errors in the model (Raeva et al. 2016). The consensus is that GCPs should be randomly distributed throughout the project study area avoiding clustering in any one location.
Ground control points do not necessarily need to be placed targets on the ground, according to one study, GCPs are not necessary if there are adequate numbers of distinctive points in the images that would suffice as reference points (Yilmaz 2010). This could potentially save time when collecting data. If there are enough easily identifiable points in a study area, (corners of sidewalks, building edges, fence posts, drain holes, etc.), it could be possible to use a GPS to acquire the coordinates of these objects for use as GCPs. While this method would reduce the amount of equipment needed to complete the study as well as time to complete the process it is important to understand that the accuracy of the product will be directly proportional to the accuracy of the method used to determine coordinates for the objects substituting for GCPs.

1.6 Project Accuracy

There are a lot of factors that go into the accuracy of any geospatial project, this is no different for photogrammetric operations, “the accuracy of photogrammetric method is based on the size of object, quality and resolution of images, precision of GCPs, and measurement ability of operator” (Yilmaz 2010, p. 48). The accuracy of volumes calculated from photogrammetric operations are directly proportional to the presentations of the land surface; and dependent on the number of X, Y, Z coordinate points, the distributions of these GCPs, and methods used for photogrammetric interpolation (Yilmaz 2010). When calculating volumes, it is of the utmost importance to ensure accuracy of all elements of the survey to ensure volume estimations are as close to real-world measurements as possible.
1.6.1 Horizontal Accuracy

Horizontal accuracy can be described as the accuracy of the dimensions horizontal to the ground or the X and Y plane. Agüera-Vega et al. (2016) concluded that the X and Y measurements are independent of flight altitudes, meaning the altitude had no influence on the accuracy of the horizontal measurements (Agüera-Vega et al. 2016). Agüera-Vega et al. (2016) also concluded that “horizontal accuracy improved as the number of GCPs increased” (Agüera-Vega et al. 2016). Horizontal measurements are very influential in the calculations of volumes as this is the plane that the lengths and widths on the ground of an object are calculated. While very important to any project, the horizontal accuracy is easily calculated and in that respect is less of a concern than the vertical accuracy.

1.6.2 Vertical Accuracy

Vertical accuracy is extremely influential when calculating volume from photogrammetric data since the height measurements are derived from the Z. According to Agüera-Vega et al. (2016), “Z accuracy decreases when flight altitude increases” (Agüera-Vega et al. 2016), because of this it will be of the utmost importance to maintain a flight altitude of the lowest possible safe and appropriate height. Agüera-Vega et al. (2016) also concluded that increased numbers of GCPs help reduce vertical accuracy loss (Agüera-Vega et al. 2016). It has been said that vertical accuracy in GPS measurements generally have two to three times more error than that of horizontal measurements (Meade 2000). There is a possibility that these vertical errors will be transferred into the photogrammetric project through GPS based GCPs. It is because of this that vertical accuracy of all projects will be of the utmost importance. There is also the possibility of error introduced by photogrammetric operations having minimal side profile information of objects of interest. An oblique image acquisition method, as opposed to
vertical photogrammetry, has the potential to reduce error in elevations since more coverage is available on the side profile of objects of interest.

1.7 Automated Photogrammetric Software

Traditional photogrammetry has been performed using hard copy aerial images with an object called a stereoscope. These photos when used with a stereoscope allow a photogrammetric specialist to visualize scenes in three dimensions making it possible to obtain all sorts of measurements in regard to the photographed terrain. These methods while useful are traditionally time-consuming and accuracy is dependent on the skill level of the photogrammetric specialist performing the calculations. Within the past decade, advances have been made in computer based photogrammetric operations, “the development of high-performance and user-friendly 3D modeling software has contributed significantly to the expansion of UAV photogrammetry” (Yanagi and Chikatsu 2016, p. 147). It is because of these advancements that many new photogrammetric abilities are possible. Using photogrammetry and computer algorithms the process of collecting images from various altitudes, directions, and orientations for high-quality photogrammetric products is now possible (Fernandes et al. 2015).

It is through the advancement of these automated photogrammetric software packages that the ability to reconstruct a scene in 3D on a computer screen is now possible. Remondino and El-Hakim (2006) described this process, “three-dimensional modeling of an object can be seen as the complete process that starts from data acquisition and ends with a 3D virtual model visually interactive on a computer” (Remondino and El-Hakim 2006, p. 269). Three-dimensional modeling is becoming more prevalent and is currently experiencing utilization in applications such as visualization and documentation, cultural heritage, documentation in case of loss or damage, virtual tourism, education resources, inspection, interaction without risk of harm,
navigation, object identification, and many others (Remondino and El-Hakim 2006). It is because of these issues and many other unmentioned applications that research into 3D modeling is a long-lasting research question (Remondino and El-Hakim 2006). The other major potential for three-dimensional reconstruction is the ability to use generated 3D models for measurement purposes.

1.7.1 Structure-from-motion (SfM)

SfM has substantially increased the application of computer-based photogrammetry and makes it possible to reconstruct scenes in 3D from overlapping photo images. According to Westoby, M.J. et al., “Structure-from-Motion (SfM) operates under the same basic tenets as stereoscopic photogrammetry, namely that 3-D structure can be resolved from a series of overlapping, offset images” (Westoby, M.J. et al. 2012). Agüera-Vega et al. (2016) said that progress in these areas contribute to the wide application of the structure-from-motion (SfM) technique in 3D modeling. This technology has opened many doors for research into photogrammetry’s ability for utilization in a broad series of fields.

SfM is a photogrammetric technique that automatically solves the geometry of the scene, the camera positions, and the orientation without requiring a prior specification of a network of targets that have known 3D positions (Agüera-Vega et al. 2016; Snavely et al. 2007; Westoby et al. 2012). SfM utilizes multiview stereopsis techniques to derive 3D scenes from overlapping photography acquired from multiple angles and locations (Agüera-Vega et al. 2016; James and Robson 2012; Furukawa and Ponce 2007). Yanagi and Chikatsu simplify this process by saying, “SfM (Structure from Motion) is composed of matching, scene reconstruction, and point cloud generation functions” (Yanagi and Chikatusu 2016, p. 147). SfM allows a user to input a series of photos into a computer software package, which automatically searches for common features
thus orienting and matching the photos producing a point cloud for geometric use. This significantly reduces time and error associated with human operated scene reconstruction.

In order to obtain good results from the SfM technique a number of considerations should be met. It is important that data sets are of the appropriate size and photo configuration. Photo sets with 10s to 100s of photos have been known to produce good results but it is especially important that any specific region to be reconstructed need be included in a minimum of three images (James and Robson 2012).

There is a need for research into the topic of how SfM can contribute to disciplines within the geosciences. Westoby et al. (2012) state that, “the possibilities of SfM appear boundless, however, to date, the technique has rarely been used within the geosciences and there exist few quantitative assessments of the quality of terrain products derived from this approach” (Westoby et al. 2012, p. 301). This project hopes to fill the some of the gaps in the literature where SfM contributes to 3D scene reconstruction and utilizing these scenes for the acquisition of measurements.

1.7.2 Scale-invariant feature transform (SIFT)

It is important to note that the SfM technique employs what is known as a scale-invariant feature transform (SIFT) algorithm which is used by many studies, some of whom conclude that SIFT is one of the best for large scale image processing (Lowe 2004; Remondino and ElHakim 2006; Juan and Gwun 2009, James and Robson 2012; Agüera-Vega et al. 2016). There is also research supporting the ability of the SIFT algorithm in extracting small objects among clutter, as well using keypoints for object recognition (Lowe 2004). The SIFT algorithm is used to detect key-points and photos and then generate 3D point clouds (Agüera-Vega et al. 2016). According
to Juan and Gwun,(2009), “SIFT consists of four major stages: scale-space extrema detection, key point localization, orientation assignment and key point descriptor” (Juan and Gwun, 2009, p. 144)

1.8 Statement of the Problem

Many studies have examined the potential use of UAS and photogrammetry for volume estimation in mining and dirt work operations and compared it to traditional methods. However, far less work has been done related to volume calculations of other structures. Photogrammetry, when combined with the flexibility of a UAS, potentially provide a method for calculating volume that is both relatively budget-friendly and less time-consuming than traditional methods. More research into the ability of UAV systems combined with photogrammetric operations for volume calculations in fields other than mining and dirt work operations is necessary to take full advantage of this technology, and to understand its limitations. As these questions are answered, there is a remarkable potential for utilization of this technology in fields such as agriculture, energy, wastewater, residential, etc.

1.8.1 Research Questions and Hypotheses

Question 1: How closely can UAS/photogrammetric volume estimates match those derived from in situ tape measure and/or engineering diagram-based calculations?

Null Hypothesis 1: There is no difference between volume estimations derived from traditional in situ measurements and/or engineering diagram-based calculations and those derived from UAS/photogrammetric methods.

Question 2: How well does UAS/photogrammetry represent real world dimensions in both the horizontal plane (X/Y) as well as the vertical (Z)?
Null Hypothesis 2: There is no difference between dimensions derived from photogrammetric processes and those determined by in situ measurements and/or engineering diagram-based figures.

Question 3: Does the shape, size or configuration of objects affect the ability of UAS photogrammetric operations to accurately estimate volume?

Null Hypothesis 3: The shape, size, or configuration of objects does not influence the ability for accurate volume estimation using the UAS/photogrammetric method.

Question 4: Does UAS and photogrammetry provide a timely alternative to traditional volume estimation methods?

Hypothesis 4: There is no difference between the time it takes to estimate volume of an object from UAV photogrammetric methods and traditional volume estimation techniques.
2. Literature Review

Since there are many techniques used to calculate volume, UASs are useful in such a wide range of fields for many different applications, and photogrammetry has many different uses many sources that contribute to particular segments have been utilized. Few studies have combined UASs and photogrammetry to examine the volume of objects; therefore, it is essential to reach into research completed in various studies using one or more of the ideas emphasized in this project. The methods and concepts discussed below come from literature having to do, in some capacity, with UASs, photogrammetry, or volume estimations.

2.1 3D Modeling

Many studies have examined the ability for 3D reconstruction of various objects utilizing many different techniques and methods. Some of the literature on these topics will be reviewed below but is in no way meant to be exhaustive as there is a plethora of research on the topic of 3D modeling and instead will focus on photogrammetric methods used in conjunction with unmanned aerial vehicles.

Rosnell and Honkavara (2012) tested the ability of different micro drone systems, digital cameras and photogrammetric software to generate 3D models. The study utilized two UAS systems. The first system uses the Microdrone md4-200 capable of carrying a payload of 300g equipped with a Ricoh GR Digital III camera. The second system uses the Microdrone md4-1000 system capable of operating with payloads up to 1.2kg equipped with a Panasonic Lumix GF1 Camera. The study consisted of two test areas, one in which the md4-200 was utilized and another with the md4-1000 and their corresponding digital cameras. The study also examined the ability of two photogrammetric software packages Bae Systems’ SOCET SET and Microsoft’s
Photosynth. The study concluded that the method used is suitable for applications, which do not require real-time response given the amount of time it takes to collect and possess the data. Of the two photogrammetric software packages test, SOCET SET produced higher density and accurate point clouds but Photosynth was able to orient all images without the implementation of GCPs. The study identified several areas of consideration when performing photogrammetric processes utilizing UAS systems. The first of which being poor image quality because of windy conditions. Objects with a thin profile such as light poles and trees as well as object with homogeneous surfaces such as roofs and large parking lots were also problematic. The authors also discussed differences in the matching methods of Photosynth and SOCET SET, which lead to differing results between the two software packages.

James and Robson (2012) preformed a number of case studies in order to assess the ability to create reconstructed 3D surfaces from images acquired with a digital camera for geoscience applications. The first of these case studies examine the ability of SfM at a decimeter level. The authors utilized a EOS 450D camera with a 50mm fixed focal length lens to capture two hundred and ten images of a bread-crust bomb sample from a volcano. The complex exterior of the volcanic rock and the small size yielded a perfect subject for the project. The object was placed on a turntable and rotated while photos were acquired from the camera on a tripod in order to insure consistent photo angles and minimal movement. Results were compared to laser scanning results performed by a Arius3D system. The authors conclude that the SfM data provided a good fit to the scanner data with the only differenced occurring in areas with steep faces. Another case study was performed in which the authors took a series of photos of the summit region of Piton de la Fournaise volcano. The study utilized 45 GCPs and one hundred and thirty-three images were acquired using a Canon Eos D60 digital camera. The authors
concluded that the resulting point cloud was denser but not as evenly distributed as traditional methods. A third and final case study was conducted on an outcrop with dimension of approximately 3 m high by 50 m long in order to examine the results of erosion. A TLS survey was also performed to validate photogrammetric results. A total of 133 images were obtained with a Cannon EOS 450D camera. The authors concluded that all SfM surveys of the cliff provide similar quality data. A final conclusion based on the three individual case studies was made, “the case studies demonstrate that SfM-MVS approach can produce surface or topographic data over scales and scenarios relevant to a broad range of geoscience applications” (James and Robson 2012, p. 12).

Mancini et al. (2013) used a Hexacopter UAS system equipped with a Canon EOS model 550D digital camera to collect images for photogrammetric point cloud generation over a 200-meter-wide dune patch along the coastal resort area of Marina di Ravenna Italy. The generated 3D point was used to create a high spatial resolution DSM of the dunes. The produced DSM was then compared to a GNSS survey of the same region completed using a Topcon GRS1 networked real-time kinematic (NRTK) GPS system, and terrestrial laser scanner survey (TLS) produced by a CAM2 Focus3D system. Photogrammetric post-processing was performed by Agisoft Photoscan. The authors concluded, “the UAV-based approach was demonstrated to be a straightforward one and accuracy of the vertical dataset was comparable with results obtained by TLS technology” (Mancini et al. 2013, p. 6881). They also found comparable results with the GNSS survey data indicating that UAS scene reconstruction via photogrammetry is a perfectly viable solution for the creation of 3D products.

Fernández-Hernandez et al. (2015) utilized a Microdrone md4-1000 UAV system equipped with an Olympus EPL-2 digital camera for generation of a 2D orthophoto and 3D
digital surface map of the Celtic settlement of Las Cogotas. A Leica 1200 set up to operate in RTK mode was used to acquire GCPs. Las Cogotas is located in the northern Meseta in Avila Spain and has a peak elevation of approximate 1,156 m and covers an area of approximately 14.5 ha making it a perfect site for 3D reconstruction. The flight consisted of a target altitude of 65 meters covering an area of approximately 5 ha. A total of 30 images in three strips with 10 images per strip were obtained. Post processing yielded a final 3D model that had a total of 12 million points, and had a density of 240 points per m². A ortho image with a GSD of 3 cm was also produced. The authors concluded that the results from this study are useful for both archeological interpretation and inspection.

2.1.1 Photogrammetric image matching techniques

Numerous studies have utilized SIFT, Structure from Motion (SfM) and other photogrammetric image matching techniques for various scene reconstruction purposes. A number of these studies are reviewed below.

Lowe (2004) examined the ability of the SIFT algorithm to correctly match keypoints from a large database of other keypoints. The author found that SIFT allows for large numbers of keypoints to be efficiently extracted from standard images which provides a robust ability for extracting small objects among clutter. The author also presented a method that uses keypoints for object recognition within photographs which utilizes approximate nearest-neighbor lookup, Hough transform for cluster identification, least-squares pose determination, and final verification. Other potential applications identified by Lowe include view matching for 3D reconstruction, robot localization, image panorama assembly, as well as others that require the matching of locations between images. Lowe concludes by stating that there are many future research opportunities and potential applications for the SIFT algorithm.
Snavely, Seitz and Szeliski (2007) examined the ability to model the world using a SIFT algorithm and SfM in conjunction with internet photo collections. The study first created a data set of photos for each object to be modeled from photos available on the internet. Feature points in the photos were then found using a SIFT algorithm, then images were matched using the approximation of nearest neighbors. A matrix of image pairs was created and system of tracks where a set of matching keypoints across multiple images was created. Then by using camera parameters such as focal length, and rotation for each individual photo in the collection a SfM technique was applied. This process allowed the authors to create 3D point clouds of tourist attractions such as Notre Dame, Mt. Rushmore, Yosemite, and the Roman Colosseum. The authors experienced various levels of success ultimately concluding that there is a need for more research into the utilization of internet photo collections for modeling purposes and the future looks bright for this application.

In 2009 Juan and Gwun (2009) performed a study comparing various feature detection methods including SIFT, PCA-SIFT, and SURF. The project utilized 8 sets of images each with different transformations in order to test the strengths and weaknesses of each method. The methods were tested against changes in image scale, rotation, blur, and illumination. The authors were able to identify the methods that had the best and worst results for each transformation however no one method proved to be superior in all the tests. Ultimately the authors concluded that each method has its strengths and weakness and no one method is necessary overall superior to another (Juan and Gwun 2009).

Turner et al. (2012) used a structure from motion (SfM) technique to map moss beds in Antarctica. The study utilized a multi-rotor OktoKopter and a Canon 550d digital camera for data acquisition. The study focused on two separate study sites with one data collection mission
apiece. The first site consisted of two hundred photos acquired from an altitude of approximately 50 meters and the second had a total of 69 photos also acquired at an elevation of 50 meters. Small orange disks approximately 10 cm in diameter and large orange trays approximately 30 cm in diameter were used as GCPs for geometric correction. The authors concluded that when GCPs are utilized a mosaic DTM with accuracy of approximately 10-15 cm can be produced.

Mancini et al. (2013) conducted a study to test the ability of SfM to create accurate 3D surface of a fore-dune formation located in Ravenna Italy. The UAS system utilized was a VTOL (Vertical Takeoff and Landing) hexacopter manufactured by SAL (Sea Air Land) Engineering and was equipped with a Canon EOS 550D digital camera. The flight was pre-programmed with flight lines and altitude was set at 40 meters with an automatic photo capture rate of one image per second. A total of 550 images were post processed using Agisoft Photoscan which uses a SfM algorithm to generate dense point clouds of the study area. The products generated from Photoscan were compared to a GNSS survey and a TLS mission that was performed at the same time as photo acquisition. The authors concluded that “The SfM technique applied to images acquired by a low-altitude UAS system produced a point cloud and derived DSM representing a beach dune system with high topographic quality and vertical accuracy, comparable with GNSS survey data” (Mancini et al. 2013, p. 6895).

Lucieer et al. (2014) used a MikroKopter OktoKopter equipped with a Canon 550D digital camera to test a SfM technique for micro-topography mapping of moss beds in Antarctica. Photos were acquired at a rate of every 1-2 seconds at an altitude of 50 meters in approximately 200 photos. 12 circular discs with a 22 cm diameter were used for GCPs and surveyed using a Leica 1200 operating in RTK mode. Agisoft Photoscan was used for 3D photo
processing. The study was successful in producing a 2 cm resolution DSM for a one ha study area as well as a one cm orthophoto.

Tonkin et al. (2014) examined the accuracy, precision, and potential applications of the SfM technique. The study consisted of 543 aerial images acquired at Cwm Idwal in northern Wales utilizing a Canon EOS-M digital camera attached to a DJI S800 Hexacopter. The software package Agisoft Photoscan was used for model reconstruction. A total station survey session of the same area undertaken in 1997 and 1998 using a Leica TC600 was used for comparison. The study concluded that the DSM produced though the photogrammetric method compared well with a DSM generated though the total station survey. The authors alluded to advantages provided from the UAS method by saying, “the technique is shown to be superior to conventional total station survey in terms of resolution and time required for data acquisition, and has the additional benefit of providing ultra-high-resolution orthorectified aerial imagery” (Tonkin et al. 2014, p. 42).

2.2 Accuracy of 3D Models derived from UAS photogrammetry

While many studies have examined the ability for 3D scene reconstruction using photogrammetry fewer still have been designed to strictly examine the accuracy of products derived from these methods. This is a very important consideration when these derived models are used for various types of calculations. Many of these relevant studies will be reviewed below.

Harwin and Lucieer (2012) examined the accuracy of georeferenced point clouds created using UAS Imagery and multi-view stereopsis (MVS). A TerraLuma UAS based on the OktoKopter platform equipped with a Canon 550D digital SLR camera was utilized for image acquisition. The study also used a Leica Viva RTK system for surveying of all GCPs used in the
generated point cloud. Two different sized GCPs were utilized, 10 cm and 22 cm in diameter, to test whether or not the size of GCPs affect the accuracy of generated point clouds. The study area consisted of a 100-meter section of shelter coast in southern Tasmania, Australia. The point cloud generated from photogrammetric UAS flights was compared to a total station survey in order to assess accuracy. The study was able to generate point clouds with 1 – 3 cm point spacing and an accuracy of 2.5 – 4 cm under optimal conditions. The authors conclude that the method is capable of monitoring sub-decimeter terrain changes for applications such erosion in coastal environments (Harwin and Lucieer 2012). The authors did note the limitation of the technique to obtain adequate results when there is dense vegetation present noting that more research into the technology is required (Harwin and Lucieer 2012).

Anders et al. (2013) utilized a fixed wing MAVinci Sirius 1 UAS with a Panasonic Lumix GX1 camera to test quality of DSM derived from photogrammetric measurements. The authors conclude, “UAVs provide a level of detail that could not have been obtained this easily in the past” (Anders et al. 2013, p. 4). While the authors praised the ability for subtle geomorphologic feature detection, they also allude to the fact that more research is needed by stating, “Yet, more effort is required to better align the surface model to dGPS measurements for more accurate elevation values” (Anders et al. 2016, p. 4).

Yanagi and Chikatsu (2016) used a hexarotor UAS with a Canon EOS Kiss X7 camera to capture images over a test site with 58 CPs. The data collect was processed utilizing three different software packages (Smart3DCapture, Pix4Dmapper, and Photoscan). The study utilized various numbers of CPs entered as GCPs and then calculated RMSE to determine the best configuration and number of positions to minimize error. The study concluded that both Smart3DCapture and Pix4Dmapper are suitable for obtaining practical accuracy at the sub-pixel
level (Yanagi and Chikatsu, 2016). Unfortunately, the authors did not explore Photoscan to the extent of the other software packages and they had little to say about its performance.

Agüera-Vega, Carvajal-Ramirez, and Martinez-Carricondo (2016) used a rotatory-wing UAS with eight MicroKoptor brand motors and a payload of 2.5kg equipped with a motion-compensated gimbal and Sony Nex 7 digital camera to assess the influence of flight altitude, terrain morphology, and the number of GCPs on photogrammetric derived products. The study consisted of 60 separate photogrammetric projects considering five different terrain morphologies, four flight altitudes (50, 80, 100, and 120m) and three different numbers of GCPs (3, 5, and 10). GCPs and CPs were surveyed utilizing a GNSS in RTK mode. Agisoft Photoscan Professional version 1.0.4 was utilized for all image processing. Based on results of the study the authors were able to make numerous conclusions. The authors were also able to conclude that neither the terrain morphology nor elevation had a significant effect on accuracy of the X of Y. Numbers of GCPs was seen to have a significant influence on the accuracy of X and Y; with the highest accuracies coming from the projects utilizing 10 GCPs. Terrain morphology was seen to have a significant effect on the accuracy of Z; with the highest Z accuracies coming from nearly flat terrains. The accuracy of Z was seen to decrease as flight altitude increases. The authors determined that the most accurate results for this study were obtained when flying at an altitude of 50m with 10 GCPs (Agüera-Vega et al., 2016).

2.3 UAS and Photogrammetry for volume calculations

There is not a large body of work detailing the use of UASs and photogrammetry for the purpose of volume estimations; therefore, the literature reviewed below examines the most appropriate case studies on the topic available to date.
Yilmaz (2010) designed a number of studies to test the performance of close range photogrammetry when applied to volume calculations. A preliminary study was performed in a lab setting in which an artificial object of a conical shape with a volume of 364.2 cm$^3$ was photographed using a Sony F828 digital camera (Yilmaz 2010). The photos were then processes using PhotoModeler 5.0 to generate a 3D point cloud of the object. Software packages Surfer 8.0 and Netcad generated volume calculations of 359.5 cm$^3$ and 359.7 cm$^3$ respectively. The author concludes, “An error of 1.28% is acceptable for most practical purposes” (Yilmaz 2010, p. 5).

The author performed another lab study using the same methodology only on a cube with dimensions of 10-cm resulting in a photogrammetric accuracy of 99.99% (Yilmaz 2010, p. 51).

Upon completion of the lab studies, the methodology was taken to the field in order to assess the ability on a natural hill. The author used both classical and photogrammetric techniques for volume calculation and then compared the two results. The hill has dimensions of 6m wide 9m long and 3m tall. Thirty-four test targets were placed in a well-distributed pattern on the hill and coordinates were measured using a Topcon total station instrument. The volume of the hill was calculated as 29.9 m$^3$ using the GNSS approach. Photogrammetric processing resulted in a volume calculation of 28.8 m$^3$ a difference of 3.7%. The author concluded that “the photogrammetric method, when compared to the classical method, has more than 21.43% advantage in terms of time-saving, more than 10.62% in accuracy, and more than 33.33% in cost saving” (Yilmaz 2010, p. 53).

Pierzchala et al. (2014) used a Mikrokopter Okto UAS equipped with a Sony NEX 5N camera to estimate the volume of soil displaced in a post-forest harvest skid trail located in western Norway. The study utilized six ground control points arranged in V shape at a 90° angle surveyed using a GPS operating in RTK. All photogrammetric processing was completed using
Agisoft Photoscan Professional software. Results indicate that 554 m$^3$ of earth had been displaced by the construction skid trails over a distance of 210 m. The authors conclude that this method shows potential for improved environmental management and is highly suited for estimating soil displacement from skid trails given the conditions (Pierzchala et al. 2014).

Hugenholtz et al. (2015) assess the accuracy of volume estimation of a stockpile by surveying a stockpile using a UAS before and after a portion was excavated. Photogrammetric operations were applied to the UAS images before and after the excavation in order to produce two DTMs. The study utilized 10 GCPs and a GNSS survey-using RTK was performed. The total stockpile volume for the first flight was determined to be 10,202.66 m$^3$ and 8,681.05 m$^3$ for the second resulting in a percent difference of 2.6 and 3.9 respectively from the GPS based estimations. The removed gravel estimated at 1,521.44 m$^3$ from the UAS survey differed by 2.5% from the volume estimated from the haul ticket of 1,483.44 m$^3$. The authors concluded that UASs could be a valuable tool for geomatics but more research into the accuracy, limitations, cost efficiency and operationalization is need (Hugenholtz et al. 2015).

Raeva et al. (2016) used an eBee fixed wing UAS system coupled with a Canon S110 camera to fly a quarry including a stockpile to be used for volume calculations. The study also performed a GNSS survey in order to calculate the volume of the stockpile of interest and provide a comparison to the photogrammetric results. RTK was collected using a Leica Viva GS08 plus. The study utilized seven GCPs, which were surveyed using RTK mode of the previously mentioned GPS receiver. The UAS flight resulted in 417 images, which were processed using Pix4DMapper. The results of the study are very positive as the UAS method had a volume calculation of 12,749m$^3$ and the traditional GNSS survey method 12,606m$^3$ or a difference of 1.1%. The authors concluded that the potential for UAS volume calculation should
not be over looked and it is reasonable to assume that with the ever-increasing improvements in technology future studies could receive better results (Raeva et al. 2016).
3. Methods and Materials

3.1 Study Area

This project utilized two primary study sites each containing various numbers of structures suitable for 3D reconstructions and volume estimation. The structures of interest at each site range in size from approximately 2m³ to 30,000 m³.

The first of the two sites was located in an agricultural field at Ecclesia College in Springdale, Arkansas. This location had a number of individual round hay bales and one single configuration of bales arranged in a line as to represent a single object. These bales of hay where the primary object of interest at this location having a diameter of 1.52 meters and a height of 1.19 meters. The large configuration of bales in the center of the flight consisted of 9 bales arranged end to end as to represent one cylindrical object approximately 10.82 meters long.
The second site was located at a wastewater treatment facility west of Fayetteville, Arkansas. Permission to collect data at this site was secured thanks to Mr. Mayo Miller who provided excellent assistance communicating with the facilities management officials as well as providing valuable insight for project planning purposes. The site consisted of a number of tanks of various shapes and sizes. The largest structure was a domed shaped holding tank with a diameter of 72 meters and the smallest tanks having a diameter of 3.5 meters. There was a total of nine structures all within a relatively small area with close proximity to one another allowing for all necessary data collection to be performed in one day.

*Figure 1 - Map of First Study Site*
3.2 Materials

All materials utilized in this study were chosen because of their ability to aid in the accomplishment of the project goals. These materials include an appropriate UAS system, Camera for photo collection, GPS for GCP acquisition, ground control points, and a 100’ tape measure for in situ measurements.
3.2.1  UAS system

The UAS system used in this study was a Solo manufactured by 3D Robotics (3DR). Solo can be classified as a small UAS which is powered by four electric motors each attached to a propeller (3DR Solo, Mar 10, 2017). Solo is a user-friendly UAS that allows for absolute user control by utilizing a controller that provides all navigation mechanisms and displays in-flight data as well as an App that is compatible with Android and iOS devices which utilizes telemetry and the SoloLink network to control and receive video outputs from the device while in flight (3DR Solo, Mar 10, 2017). The live video output allows for a real-time view of what the drone is visualizing and allows the user to adjust accordingly.

Figure 3 - Solo Overview (3DR Solo, Mar 10, 2017)

Solo also utilizes what is known as a gimbal to improve data acquisition control and quality. The 3-axis Solo gimbal provides increased control of the onboard camera allowing the user to control the tilt angle of the camera at all times during flight (3DR Solo, Mar 10, 2017).
The gimbal also handles camera balancing and camera stabilization automatically during flight reducing error introduced by movement of the UAS caused by aerial maneuvers and conditions such as the wind (3DR Solo, Mar 10, 2017).

The Solo App provides several useful functions for the purpose of this study. Smart shots are Solo’s automated flight options and include Cable Cam, Orbit, Selfie, and Follow. Of the four smart shot modes, the orbit function will be the most beneficial for the purpose of this study. Orbit provides parameters to fly Solo around a preset circle while maintaining a fixed camera on a central object. The ability to maintain a consistent distance from an object and altitude while collecting data will be very beneficial and remove the error introduced from human controlled flights.

Solo has the ability to fly for up to 25 minutes at a time while carrying a one-pound payload within a range of 0.5 miles (3DR Solo, Mar 10, 2017). It is important however to note that flight time will decrease as the payload increases. Other factors such as the wind, speed, and onboard equipment may reduce the flight time as well. It is possible multiple flights will be necessary to cover the entire study area and all objects of interest. Given a large study area, it is imperative to have access to multiple charged Solo smart batteries for decreased time between flights. There are a number of preflight considerations outlined in the 3DR Solo user manual. These items are included in a Preflight Checklist and include items such as location concerns, components check, power, and video. It is essential to follow the items in this checklist to ensure a safe and successful flight. Solo is a very powerful tool that has seen success for utilization by various U.S. government agencies such as the USGS.
3.2.2 Camera

The camera used in this study was the GoPro Hero 4 silver edition. The decision to use this camera was based on its ability to be used in many different environments and its compatibility with the 3DR Solo. Hero 4 is a small action style camera weighing approximately 2.93oz capable of operating in extreme environments. Onboard camera memory consists of a removable microSD card that can accept up to 64GB of storage. Focal length varies depending on which of the 3 FOV options is utilized (See table 1). The GoPro Hero 4 silver edition has the ability to collect data in three distinct modes: video mode, photo mode, and multi-shot mode (GoPro, Mar 10, 2017)

<table>
<thead>
<tr>
<th>FOV</th>
<th>Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>17.2 mm</td>
</tr>
<tr>
<td>Medium</td>
<td>21.9 mm</td>
</tr>
<tr>
<td>Narrow</td>
<td>34.4 mm</td>
</tr>
</tbody>
</table>

*Table 1 - GoPro 35mm Equivalent Focal Lengths (GoPro, Mar 31, 2017)*

Video mode has a number of different parameters that are useful under various conditions. There are four sub modes within video mode: video, time lapse video, video + photo, and video looping. Each sub-mode has a different set of video settings. Interval setting determines the amount of time that passes between each captured frame and applies to time lapse video, video + photo, and looping modes. When using the video + photo mode it is possible to adjust photo intervals from 5 – 60 seconds. It is possible to adjust video resolution from WVGA all the way up to 4K. Field of view (FOV) options include narrow, medium, and ultra-wide and options vary depending on video resolution utilized. See the table 2 for more information on video mode parameters.
### Table 2 - GoPro Hero 4 Silver Video mode resolutions (GoPro, Mar 10, 2017)

<table>
<thead>
<tr>
<th>Video Resolution</th>
<th>FOV</th>
<th>Screen Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>4K</td>
<td>Ultra Wide</td>
<td>3840x2160, 16:9</td>
</tr>
<tr>
<td>2.7K</td>
<td>Ultra Wide, Medium</td>
<td>2704x1520, 16:9</td>
</tr>
<tr>
<td>1440p</td>
<td>Ultra Wide</td>
<td>1920x1440, 4:3</td>
</tr>
<tr>
<td>1080p</td>
<td>Ultra Wide, Medium, Narrow</td>
<td>1920 x1080, 16:9</td>
</tr>
<tr>
<td>1080p SuperView</td>
<td>Ultra Wide</td>
<td>1920 x1080, 16:9</td>
</tr>
<tr>
<td>960p</td>
<td>Ultra Wide</td>
<td>1280x960, 4:3</td>
</tr>
<tr>
<td>720p</td>
<td>Ultra Wide, Medium, Narrow</td>
<td>1280x720, 16:9</td>
</tr>
<tr>
<td>720p SuperView</td>
<td>Ultra Wide</td>
<td>1280x720, 16:9</td>
</tr>
<tr>
<td>WVGA</td>
<td>Ultra Wide</td>
<td>848x480, 16:9</td>
</tr>
</tbody>
</table>

Photo mode includes three sub capture modes including: single, continuous and night. The setting selected determines the optional settings available for adjustment. There are options to adjust shutter speeds, photo intervals, and photo megapixels. The camera has the ability to collect photos at resolutions of 5MP, 7MP, and 12MP each with differing FOV settings. Please see table 3 or information regarding photo resolution and available FOV parameters.

### Table 3 - GoPro photo settings (GoPro, Mar 10, 2017)

<table>
<thead>
<tr>
<th>Photo Resolution</th>
<th>Field of View (FOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12MP</td>
<td>Wide</td>
</tr>
<tr>
<td>7MP</td>
<td>Wide, Medium</td>
</tr>
<tr>
<td>5MP</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Multi-Shot contains three sub capture modes including: burst, time lapse, and night lapse. Burst has the ability to capture up to 30 photos per second while both time lapse modes capture a series of photos at specific intervals ranging from every 0.5 seconds to 60 seconds. Photo resolutions for multi-shot options are the same for photo mode (see table 3).
3.2.3 GPS

Ground control points (GCPs) were collected using two Leica GS15s and one Leica CS15. First the CS15 controller was powered on and configured to collect RTK data as instructed by the Center for Advanced Spatial Technologies (CAST) specifications. Next, the first of the two GS15s was configured as a base station by using the CS15. Last, the remaining GS15 was configured as a rover to be used for RTK point collection. Once all set up procedures are followed and double checked each GCP was surveyed. It is important to ensure that adequate numbers of points were stored for each GCP and satellite signal was acceptable. Once collection was complete the system was powered off and transported to the lab for post processing.

Figure 4 - Leica GS15 set up as base station
3.2.4 Ground Control Points (GCPs)

Ground control points utilized for this study consisted of coded targets provided by Agisoft Photoscan Pro 1.3. These targets were printed on standard 8.5 by 11-inch sheets of paper and secured to the backs of metal cookie sheets using double sided tape. The cookie sheets provide an easily transportable and stackable device to adhere the targets to while also being heavy enough to be placed without concern of wind or needing tie-down stakes.

![Figure 5 - Example of GCP being surveyed](image)

3.3 Software

Various software packages were utilized in this study. Without the ability provided by these packages analysis would not have been possible. The primary software used included
Agisoft Photoscan, ESRI ArcMap, Microsoft Excel, 3DR SOLO iPhone application, and FAA B4UFly

3.3.1 Agisoft Photoscan

Agisoft Photoscan version 1.3 was used for all image processing. “Photoscan is an advanced image-based solution for creating three-dimensional content from still images” (Verhoeven 2011, p. 68). Photoscan is produced by the Russian company Agisoft and is built to operate on windows operating systems post XP, but it also runs on Mac and Linux systems (Verhoeven 2011). The major assumption when recreating a scene in 3D is that the object of interest is visible in at least two photographs (Verhoeven 2011).

There are some considerations when determining a system capable of running Photoscan. A 64-bit operating system with a multicore processor and a decent amount of RAM is strongly recommended. As soon as the computer runs out of main memory, it automatically switches to virtual memory slowing down processing time dramatically. When processing large amounts of data, it is advisable to break the data into “chunks” ensuring that each chunk contains at least two images from other chunks for chunk alignment once processing is complete (Verhoeven 2011).

The Photoscan software takes a three-step processing approach (Agüera-Vega et al. 2016). The first step in this process is image alignment where photos are aligned resulting in a sparse point cloud, the camera locations, and calibration parameters (Verhoeven 2011). Next, the majority of scene details are built by applying Multiview stereo reconstruction on the previously aligned photos resulting in a dense point cloud. Finally, the mesh is generated and textured using the photographs (Verhoeven 2011).
3.3.2 ESRI ArcMap

ArcMap version 10.4 was used for various geospatial operations including site identification, map production, and mapping of GCPs post survey. ArcMap provides is an excellent research tool capable of preforming extremely robust geospatial workflows. This study however simply took advantage of ArcMap’s ability to scout out potential study sites, identify any problems that may be encountered at these sites, visualize GCPs after then have been surveyed, and produce various maps.

3.3.3 Microsoft Excel 2016

Microsoft Excel 2016 was utilized for all data recording, management, and calculations. Variables such as object diminutions, calculated volumes, percent error, and RMSE where recorded or calculated within Excel. Excel was also utilized for generation of various graphs, tables, and charts.

3.3.4 3DR SOLO app

The 3DR SOLO application was installed on an iPhone 6s + and used to control various functions of the UAS system during the mission as well as monitor various conditions. The application provided the orbit function used to ensure consistent distance and flight path while surveying individual objects. Various conditions such as altitude, distance from takeoff location, battery power, GPS signal, connection strength, as well as various other functions. Additionally, the app provides a live video stream from the attached GoPro Hero 4.
3.3.5 FAA B4UFly

The FAA B4UFly smart phone application was used on an iPhone 6s plus. This application consists of a map of airspace around the country and all special considerations need for consideration before flying in any particular area. It also has information about airports in the vicinity of potential flight locations with information about said airports and other legal precautions that need to be considered.

3.4 Methods

There are a set of predefined steps associated with preparing, capturing, and post processing photogrammetric data obtained from a UAS, “a typical image-based field survey with UAS systems require a flight or mission planning, GCPs measurements, image acquisition, camera calibration and image orientation, image processing for 3D extraction” (Remondino et al. 2011, p. 26). This frame work was used to define the structure for setting up this project and was followed as closely as possible.

![Figure 6 - Methods overview](image)

3.4.1 Flight planning and study site

All mission flight and data acquisition is first planned in a lab setting utilizing appropriate software and includes considerations such as the area of interest (AOI), required ground sample distance (GSD), and understanding the parameters of all equipment utilized (Remondino et al. 2011).
Prior to performing data collection procedures all necessary steps were taken to ensure familiarity of each site chosen for testing. Both study sites were examined utilizing ArcGIS in order to become familiar with the potential obstacles and challenges associated with the sites. Steps were also taken to ensure all FAA guidelines were followed. The website knowbeforeyoufly.org and the smartphone application B4UFLY were utilized to ensure all regulations were adhered too. Mission pilot and UAS platform were both registered as hobbyist with the FAA per guidelines.

Once all legal matters were considered it was time to determine flight parameters. The goal of the project was to obtain stereoscopic information of the highest possible resolution therefore ensuring the most accurate volume estimations possible. This was considered when determining appropriate flight altitudes. The lowest possible consistent safe altitude was chosen to optimize spatial resolution; in this case the altitudes of 30 to 40 meters was determined. This elevation was high enough to clear and potential hazards while maintaining a high spatial resolution. Targets to be used for GCPs were printed and organized in order to ensure a smooth placement process once in the field. All other equipment specifications and considerations were explored and parameters were decided upon during this phase of the project.

3.4.2 GCP placement and survey

Ground control points were placed in a random but dense arrangement in a way to prevent clustering in any one area at each project site. Given the simplistic arrangement of objects at Site 1 and the small overall study area only 8 targets were utilized for GCPs. At Site 2, however, given its much more complex nature and consisting of a larger area 24 targets were utilized for GCPs. GCPs at each location were placed in a random fashion around objects of interest with particular attention being taken to avoid clustering and linear arrangements of
targets. Given the height of several objects at Site 2 and the concern for the vertical accuracy of the project targets were not only placed on the ground but also on the tops of structures in order to capture the heights of objects in the GNSS survey.

Once all targets were placed the survey was performed. All data was collected using the World Geodetic System 1984 (WGS84) datum. Special attention was taken to ensure that the GS15 being used as the rover was placed directly above the center of the targets prior to data collection. This was done by ensuring the tripod used for holding the rover was positioned precisely on the center of the target and that the pole was also perfectly vertically level. Once the survey was completed the system was powered off and transported to the lab for data extraction. Resulting coordinates can be seen below in table 4 and table 5.

<table>
<thead>
<tr>
<th>Point</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCP01</td>
<td>36.21701086° N</td>
<td>94.24097735° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP02</td>
<td>36.21713301° N</td>
<td>94.24099792° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP03</td>
<td>36.2171937° N</td>
<td>94.24110647° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP04</td>
<td>36.21714926° N</td>
<td>94.24116634° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP05</td>
<td>36.21720667° N</td>
<td>94.24129142° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP06</td>
<td>36.2170176° N</td>
<td>94.24134296° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP07</td>
<td>36.21695041° N</td>
<td>94.24123382° W</td>
<td>381</td>
</tr>
<tr>
<td>GCP08</td>
<td>36.21703855° N</td>
<td>94.24113541° W</td>
<td>381</td>
</tr>
</tbody>
</table>

*Table 4 - GCPs Site 1*
<table>
<thead>
<tr>
<th>Point</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCP01</td>
<td>36.06449121° N</td>
<td>94.2347395° W</td>
<td>346.7188</td>
</tr>
<tr>
<td>GCP02</td>
<td>36.06444399° N</td>
<td>94.2348624° W</td>
<td>346.5958</td>
</tr>
<tr>
<td>GCP03</td>
<td>36.06431878° N</td>
<td>94.234832° W</td>
<td>346.8572</td>
</tr>
<tr>
<td>GCP04</td>
<td>36.06438002° N</td>
<td>94.2351452° W</td>
<td>346.4485</td>
</tr>
<tr>
<td>GCP05</td>
<td>36.06444738° N</td>
<td>94.2351851° W</td>
<td>350.0528</td>
</tr>
<tr>
<td>GCP06</td>
<td>36.06458301° N</td>
<td>94.2351741° W</td>
<td>348.0993</td>
</tr>
<tr>
<td>GCP07</td>
<td>36.0647647° N</td>
<td>94.2354097° W</td>
<td>348.083</td>
</tr>
<tr>
<td>GCP08</td>
<td>36.0647625° N</td>
<td>94.2357802° W</td>
<td>348.1845</td>
</tr>
<tr>
<td>GCP09</td>
<td>36.06442626° N</td>
<td>94.2360395° W</td>
<td>348.1362</td>
</tr>
<tr>
<td>GCP10</td>
<td>36.06415241° N</td>
<td>94.2359124° W</td>
<td>345.617</td>
</tr>
<tr>
<td>GCP11</td>
<td>36.06407104° N</td>
<td>94.2355541° W</td>
<td>345.7204</td>
</tr>
<tr>
<td>GCP12</td>
<td>36.0641655° N</td>
<td>94.2353172° W</td>
<td>345.9786</td>
</tr>
<tr>
<td>GCP13</td>
<td>36.06422305° N</td>
<td>94.2351615° W</td>
<td>346.188</td>
</tr>
<tr>
<td>GCP14</td>
<td>36.06421083° N</td>
<td>94.2349295° W</td>
<td>346.556</td>
</tr>
<tr>
<td>GCP15</td>
<td>36.06397226° N</td>
<td>94.2347391° W</td>
<td>346.5141</td>
</tr>
<tr>
<td>GCP16</td>
<td>36.0638895° N</td>
<td>94.2349214° W</td>
<td>345.7725</td>
</tr>
<tr>
<td>GCP17</td>
<td>36.06399809° N</td>
<td>94.2350889° W</td>
<td>351.3937</td>
</tr>
<tr>
<td>GCP18</td>
<td>36.06398404° N</td>
<td>94.235142° W</td>
<td>351.4055</td>
</tr>
<tr>
<td>GCP19</td>
<td>36.06388° N</td>
<td>94.2350846° W</td>
<td>345.8582</td>
</tr>
<tr>
<td>GCP20</td>
<td>36.06379013° N</td>
<td>94.2353551° W</td>
<td>345.3739</td>
</tr>
<tr>
<td>GCP21</td>
<td>36.06399084° N</td>
<td>94.2354279° W</td>
<td>345.712</td>
</tr>
<tr>
<td>GCP22</td>
<td>36.06406809° N</td>
<td>94.2351963° W</td>
<td>346.0727</td>
</tr>
<tr>
<td>GCP23</td>
<td>36.06410907° N</td>
<td>94.2351227° W</td>
<td>346.2374</td>
</tr>
</tbody>
</table>

Table 5 - GCPs Site 2

3.4.3 Data Collection

Once GCPs have been placed and surveyed with the Leica GNSS equipment data collection equipment was prepped for use. Data was collected using the 3DR Solo UAS system and attached 3DR gimbal mount connected to a GoPro Hero 4 Silver edition detailed above. A live camera stream was broadcast to an IPhone 6s plus via the 3DR solo app. The 3DR solo smart shot orbit feature was utilized to maintain a consistent distance from objects of interest. This feature allowed for a heightened ability to control the UAS and acquire data of the best possible accuracy. GoPro video + photo mode was used for data collection. Photo interval was
set at one photo every 5 seconds in order to maximize overlap however video mode was also 
utilized for data redundancy. If a circumstance where not enough coverage is encountered photos 
can be extracted from the video in order to supplement photos. Photo Resolution was set at 7MP 
with a medium FOV having a focal length of 2.9mm or a 35mm equivalent 21.9mm in order to 
maximize quality while reducing fish eye. Video resolution was set at 1080p, a medium FOV, 
with a screen resolution of 1920x1080. These settings were constant at both study sites for all 
objects of interest.

Target flight elevation for both sites was 35 meters and varied by 10 meters due to 
obstacles such as power lines, trees, buildings, and wind. Oblique images where captured for 
each site with the hope of obtaining as much information as to the side profile of each object. 
Vertical imagery was also obtained for supplemental purposes. Weather conditions for data 
collection at each site was less than ideal however very similar to one another, both being 
overcast with wind speeds of 5 – 10 mph. Data collection was also performed between the hours 
of 10:00 a.m. and 2:00 p.m. for both locations. Site 1 resulted in a total of 80 photos while Site 2 
had a total of 290 photos plus numerous videos.
Aside from UAS data collection *in situ* measurements of all objects of interest were performed. Measurements were performed with a 100-foot tape measure and later converted to meters. Objects surveyed at Site 2 (waste water treatment facility) were compared against engineering specifications provided by the company responsible for maintaining the facility. These measurements were used for calculating volumes of the various structures for comparison with UAS generated estimates. See table 6 for *in situ* measurements or engineering specifications.
<table>
<thead>
<tr>
<th>Site</th>
<th>Object</th>
<th>Height (m)</th>
<th>Radius (m)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bale 1</td>
<td>1.19</td>
<td>0.76</td>
<td>2.18</td>
</tr>
<tr>
<td>1</td>
<td>Bale 2</td>
<td>10.82</td>
<td>0.76</td>
<td>19.74</td>
</tr>
<tr>
<td>1</td>
<td>Bale 3</td>
<td>1.19</td>
<td>0.76</td>
<td>2.18</td>
</tr>
<tr>
<td>1</td>
<td>Bale 4</td>
<td>1.19</td>
<td>0.76</td>
<td>2.18</td>
</tr>
<tr>
<td>2</td>
<td>Structure 1</td>
<td>9</td>
<td>35.96</td>
<td>18703.47</td>
</tr>
<tr>
<td>2</td>
<td>Structure 2</td>
<td>5.33</td>
<td>13.21</td>
<td>2919.78</td>
</tr>
<tr>
<td>2</td>
<td>Structure 3</td>
<td>5.33</td>
<td>13.21</td>
<td>2919.78</td>
</tr>
<tr>
<td>2</td>
<td>Structure 4</td>
<td>3.96</td>
<td>1.75</td>
<td>38.12</td>
</tr>
<tr>
<td>2</td>
<td>Structure 5</td>
<td>7.3</td>
<td>2.05</td>
<td>96.38</td>
</tr>
<tr>
<td>2</td>
<td>Structure 6</td>
<td>3.96</td>
<td>1.75</td>
<td>38.12</td>
</tr>
<tr>
<td>2</td>
<td>Structure 7</td>
<td>7.3</td>
<td>2.05</td>
<td>96.38</td>
</tr>
<tr>
<td>2</td>
<td>Structure 8</td>
<td>3.96</td>
<td>1.75</td>
<td>38.12</td>
</tr>
<tr>
<td>2</td>
<td>Structure 9</td>
<td>7.3</td>
<td>2.05</td>
<td>96.38</td>
</tr>
</tbody>
</table>

*Table 6 - Reference data*

*Figure 8 - Data collection at Site 2*
3.4.4 Image Processing

Image processing began with importing photos into Agisoft Photoscan version 1.3. This was accomplished by using the ‘Add Photos’ tool. All photos were imported into one chunk for Site 1 given the relatively small set of photos (80 images), but Site 2 was divided into three separate chunks in order to speed up processing time. Chunks used for Site 2 consist of 100 photos for structure one, 62 photos for structures 2 and 3, and 86 photos for the remaining structures. All remaining processes were performed on each chunk one at a time until all products were produced, then a merge was used to create one chunk for all of Site 2.

Once photos are added the first step involves photo alignment. This is the process in which Photoscan searches each individual photo for tie points and matches up the photos with common features in other images. The ‘align photos’ tool was used to complete this process, accuracy was set on high for all chunks with exception to Site 1 where better results were achieved by using medium accuracy. Processing time for each chunk ranged from in-between 4 to 15 minutes with Site 1 being the shortest and the Site 2 chunk with 62 photos being the longest. Please refer to appendix items 1- 4 for detailed processing parameters.
Upon completion of the photo alignment process the dense point cloud was generated. This was accomplished by using the ‘build dense cloud’ tool with quality set to high for all chunks with the exception of the chunk containing structure one at Site 2. The chunk containing structure one was set to an accuracy of medium because of improved results over the point cloud generated with quality set to high, the improved result from the lower quality setting is theorized to be a result of the large data hole in the top of the structure. Default settings were maintained for all other settings in this step. Processing time ranged from one minute to one hour and eight minutes while points generated ranged from 1,300,000 to 13,850,00. Please refer to appendix items 1 – 4 for more details.
In order to calculate estimates such as volume it was necessary to generate a mesh. This was accomplished by using Photoscan’s ‘build mesh’ tool. The surface type was set to arbitrary, source data set to dense cloud, and interpolation was enabled. Quality was set to high for all chunks with exception to the chunk containing structure one at Site 2 which was set to medium because of better results, again this is theorized to be a result of the large data hole in the structure. Processing times ranged from approximately one minute to one hour fifty-five minutes. Please refer to appendix items 1-4 for more detail.
The mesh produced in the step above by default was an unappealing flat grey color. In order to appropriately color the generated model, it was necessary to perform a texturing process. This process uses information from the photos in order to assign color to the previously generated mesh. This was completed by using the ‘build texture’ tool within Photoscan. Mapping mode was set to generic, blending mode set to mosaic, and defaults were maintained for all other parameters. Processing time ranged from approximately one minute to eight minutes.
Upon the completed processing of each chunk it was necessary to insert GCP information. Each GCP was identified within the chunks and assigned a marker with the correct ID. Once all GCPs had been given a marker it was possible to use the referencing pane to assign coordinates. Setting the coordinate system provided a correct scaling of the model allowing for the calculation of surface area and volume calculations. In order to correctly reference the model, real world coordinates of at least 3 points were necessary. The reference pane was opened within Photoscan by clicking view, panes and then reference. Models can be referenced in either local Euclidean or georeferenced coordinate systems as Photoscan supports a wide range of systems including WGS84. Using the referencing pane, it was possible to enter each GCPs latitude, longitude, and elevation. The WGS84 coordinate system was utilized for the referencing process since all GCPs were obtained using this system. Once this was completed the model was adjusted to represent real world dimensions and location making it possible to preform various measurements and calculations. At this point the three chunks that represent Site 2 were merged.
together using the GCP locations in order to have one chunk with all objects for use in preforming various calculations (Agisoft 2017).

*Figure 13 - GCP markers*

Once the models were generated and referenced it was possible to preform various measurements and calculations. It was essential that the model coordinate system was initialized before performing calculations, alternately, the model could have been scaled using known distances within the model. The measure tool was utilized to capture the heights, and widths of all objects for comparison to *in situ* measurements or engineering specifications. The calculation of volume was a little more complicated than the measurement tool. First, each object must be isolated, this was accomplished by using the ‘clip’ tool to remove the entire scene except the object to me measured. It is important to note that volume calculations can only be performed on models with closed geometry, because of this once an object was isolated it was necessary to close all holes including the large area where the ground would have been. This was completed
by utilizing the ‘close holes’ tool located in the mesh toolbox. Holes must be set to 100% closed in order to cap any voids on the object. Once all holes have been closed it is possible to use the ‘measure area and volume’ tool located within the mesh toolbox. This tool produced an output of the volume for any solid closed object within the scene, which is why it is important to first isolate the object of interest. The same procedure can be replicated in order to get volume estimates of each object in the scene (Agisoft 2017).

Once all measurements and volume calculations were performed within Photoscan it was time to compare computer based photogrammetric results to those based on in situ measurements or engineering specifications. To do this both reference results and experimental results were recorded and compared to one other within Microsoft Excel 2016. Statistical tests such as RMSE and percent difference were performed on the results to evaluate the accuracy of photogrammetric operations.
Figure 14 - Agisoft Photoscan workflow
4. Results

4.1 3D Model

Two separate 3D models were produced, one for Site 1 and one for Site 2. The resulting 3D models have a resolution of approximately 2.5 cm for Site 1 and approximately 4.5 cm for Site 2. These resolutions are more than adequate for the acquisition of accurate volume estimations as well as preforming of various linear measurements.

Due to unforeseen circumstances a number of the objects surveyed at Site 2 exhibited data holes of various sizes. This is believed to be a result of the proximity of one object to another and the inability to acquire data between the structures. The holes while visually unappealing should not affect the accuracy of data measurements. The close holes tool in the mesh tool box was used to close these holes in a way that, as closely as possible, mimics the real-world structure.

4.2 Time

The entire project from start to finish took approximately 5 hours for Site 1 and 4.5 hours for Site 2. Data collection for Site 1 consumed approximately 2 hours from the time of arrival to time of departure while Site 2 took approximately 3 hours. The bulk of the time was spent setting up and surveying GCPs which reflects the larger amount of time spent at Site 2 given approximately triple the number of targets. Processing time for Site 1 took approximately 3 hours while Site 2 took around 1 hour 30 min. Project times can be seen in detail in table 7 below.
<table>
<thead>
<tr>
<th>Process</th>
<th>Site 1 time</th>
<th>Site 2 time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Collection</td>
<td>2 hours</td>
<td>3 hours</td>
</tr>
<tr>
<td>Matching and Alignment Time</td>
<td>3 min</td>
<td>30 min</td>
</tr>
<tr>
<td>Dense Point Cloud</td>
<td>1 hour 8 min</td>
<td>23 min</td>
</tr>
<tr>
<td>Mesh</td>
<td>1 hour 55 min</td>
<td>26 min</td>
</tr>
<tr>
<td>Texturing</td>
<td>1 min</td>
<td>8 min</td>
</tr>
<tr>
<td>Total</td>
<td>5 hours 7 min</td>
<td>4 hours 27 min</td>
</tr>
</tbody>
</table>

*Table 7 - Project time*
Figure 15 - Project time at Site 1

Figure 16 - Project time at Site 2
4.3 Measurements

All measurements performed within the generated models were compared to either *in situ* reference data or engineering specifications. These measurements were recorded within Excel and compared to one another via percent difference as well as RMSE. Measurements consist of volume estimations for all structures of interest as well as various dimensions such as height and diameters.

4.3.1 Volume

Results from volume estimation provided various levels of success. Site 1 exhibited very promising results with 3 of the 4 objects surveyed having a relative error of less than 5% and two bales with a percent error of only 1%. The other bale however had a percent error of 35% but the volume calculation was only off by approximately 0.76 m$^3$. Absolute Error did not exceed 1 m$^3$ for any of the four objects and the overall RMSE for Site 1 was 0.39 m$^3$. Of the four objects surveyed at Site 1 three were overestimated by Photoscan while only one was underestimated. It should be noted that the object with the least accurate result also had poor photo coverage resulting in a bad reconstruction by Photoscan. This was case by the location of the bale being on the edge of the study area and less than ideal photos being acquired at its location. Table 8 shows the results from Site 1.

<table>
<thead>
<tr>
<th>Object</th>
<th>Reference Volume</th>
<th>Experimental Volume</th>
<th>Absolute Error</th>
<th>Relative Error</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bale 1</td>
<td>2.18 m$^3$</td>
<td>2.16 m$^3$</td>
<td>0.02 m$^3$</td>
<td>-1%</td>
<td>0.39</td>
</tr>
<tr>
<td>Bale 2</td>
<td>19.74 m$^3$</td>
<td>19.85 m$^3$</td>
<td>0.11 m$^3$</td>
<td>+1%</td>
<td></td>
</tr>
<tr>
<td>Bale 3</td>
<td>2.18 m$^3$</td>
<td>2.94 m$^3$</td>
<td>0.76 m$^3$</td>
<td>+35%</td>
<td></td>
</tr>
<tr>
<td>Bale 4</td>
<td>2.18 m$^3$</td>
<td>2.26 m$^3$</td>
<td>0.08 m$^3$</td>
<td>+4%</td>
<td></td>
</tr>
</tbody>
</table>

*Table 8 - Results from volume calculations at Site 1*
Site 2 was also met with various levels of success with possible variations a direct relation to the complexity of the site. The sheer size and close proximity of the objects as well as various obstacles such as power lines and other buildings could account for some of the deviations. Out of the nine objects surveyed at Site 2 only three objects achieved a relative error less than 5% and interestingly these objects were all underestimated. The two objects that are arguably the most uniform in shape and in the most optimal position for photo acquisition both achieved a percent error of -2%. The largest object at the site exhibited a percent error of +8% with most error likely coming from the failure of the software to properly model the top of the dome structure, this object was also the only at Site 2 whose volume was over estimated. All other objects were of a similar shape and size in a very close proximity to one another and achieved percent errors between -11% and -28% with exception to one object that had a percent error of -4%. The error in these objects is likely caused by the poor reconstruction due to a clustering of the objects and the inability to acquire object specific imagery, this could have possibly been remedied by including vertical aerial imagery in addition to the oblique imagery. RMSE was calculated for four specific groups of tanks: all objects, all objects with exception to the largest structure, structures 2 and 3 which have a similar shape and size, and structures 4 through 9 which are also similar in shape and size. RMSE values were calculated as 393.62 m³, 31.59 m³, 56.38 m³, and 16.48 m³ respectively. Results from volume calculations can be seen in table 9 below.
### Table 9 - Results from volume calculations at Site 2

<table>
<thead>
<tr>
<th>Object</th>
<th>Reference Volume</th>
<th>Experimental Volume</th>
<th>Absolute Error</th>
<th>Relative Error</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure 1</td>
<td>18703.47 m³</td>
<td>20119.9 m³</td>
<td>1416.43 m³</td>
<td>+8%</td>
<td></td>
</tr>
<tr>
<td>Structure 2</td>
<td>2919.78 m³</td>
<td>2865.35 m³</td>
<td>54.43 m³</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Structure 3</td>
<td>2919.78 m³</td>
<td>2861.51 m³</td>
<td>58.27 m³</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Structure 4</td>
<td>38.12 m³</td>
<td>33.9 m³</td>
<td>4.22 m³</td>
<td>-11%</td>
<td></td>
</tr>
<tr>
<td>Structure 5</td>
<td>96.38 m³</td>
<td>83.6 m³</td>
<td>12.78 m³</td>
<td>-13%</td>
<td></td>
</tr>
<tr>
<td>Structure 6</td>
<td>38.12 m³</td>
<td>28.76 m³</td>
<td>9.36 m³</td>
<td>-25%</td>
<td></td>
</tr>
<tr>
<td>Structure 7</td>
<td>96.38 m³</td>
<td>69 m³</td>
<td>27.38 m³</td>
<td>-28%</td>
<td></td>
</tr>
<tr>
<td>Structure 8</td>
<td>38.12 m³</td>
<td>36.55 m³</td>
<td>1.57 m³</td>
<td>-4%</td>
<td></td>
</tr>
<tr>
<td>Structure 9</td>
<td>96.38 m³</td>
<td>71.7 m³</td>
<td>24.68 m³</td>
<td>-26%</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 17 - Graph of Relative Error**

#### 4.3.2 Dimensions

Various dimensions of objects were examined to attempt to find any weakness in the Photoscan generated 3D models. The heights as well as the diameter or length of all objects were recorded in situ and then compared against the same measurements performed on 3D models created in Photoscan. The purpose of this experiment was to determine if any one dimension...
(vertical or horizontal) has a larger effect on the calculations of figures such as volume and to test the strengths and weaknesses of Photoscan’s three-dimensional reconstruction ability.

Height calculations recorded in the field and measurements generated by Photoscan’s measurement tool were recorded within Microsoft Excel. Statistics such as absolute error, relative error and RMSE were calculated based on the data set. Absolute and relative error was calculated for all objects with exception to structure one at Site 2 as its height could not be calculated in Photoscan due to the dome shaped top, Photoscan is designed to measure distances on the surface of objects while the height needed is the distance from the top of the dome to the ground directly below it and not the distance along its surface. Absolute error did not exceed 0.5 meters for any single object and was less than 0.25 for all but two structures. Relative error ranged from approximately 0% to 11% with the majority of structures having a relative error of 5% or less and only one exceeding 10%. Out of the 12 objects surveyed, and having height information, the height was over estimated for 7 and underestimated for 4. RMSE of all objects excluding structure 1 was calculated as 0.15 m. See table 10 for all height results.
<table>
<thead>
<tr>
<th>Object</th>
<th>Reference Height (m)</th>
<th>Experimental Height (m)</th>
<th>Absolute Error (m)</th>
<th>Relative Error</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure 1</td>
<td>9</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.15</td>
</tr>
<tr>
<td>Structure 2</td>
<td>5.334</td>
<td>5.62</td>
<td>0.286</td>
<td>+5%</td>
<td></td>
</tr>
<tr>
<td>Structure 3</td>
<td>5.334</td>
<td>5</td>
<td>0.334</td>
<td>-6%</td>
<td></td>
</tr>
<tr>
<td>Structure 4</td>
<td>3.9624</td>
<td>3.99</td>
<td>0.0276</td>
<td>+1%</td>
<td></td>
</tr>
<tr>
<td>Structure 5</td>
<td>7.3</td>
<td>7.2</td>
<td>0.1</td>
<td>-1%</td>
<td></td>
</tr>
<tr>
<td>Structure 6</td>
<td>3.9624</td>
<td>3.99</td>
<td>0.0276</td>
<td>+1%</td>
<td></td>
</tr>
<tr>
<td>Structure 7</td>
<td>7.3</td>
<td>7.31</td>
<td>0.01</td>
<td>+0%</td>
<td></td>
</tr>
<tr>
<td>Structure 8</td>
<td>3.9624</td>
<td>4</td>
<td>0.0376</td>
<td>+1%</td>
<td></td>
</tr>
<tr>
<td>Structure 9</td>
<td>7.3</td>
<td>7.33</td>
<td>0.03</td>
<td>+0%</td>
<td></td>
</tr>
<tr>
<td>Bale 1</td>
<td>1.19</td>
<td>1.17</td>
<td>0.0238</td>
<td>-2%</td>
<td></td>
</tr>
<tr>
<td>Bale 2</td>
<td>10.82</td>
<td>11</td>
<td>0.1796</td>
<td>+2%</td>
<td></td>
</tr>
<tr>
<td>Bale 3</td>
<td>1.19</td>
<td>1.1</td>
<td>0.0938</td>
<td>-8%</td>
<td></td>
</tr>
<tr>
<td>Bale 4</td>
<td>1.19</td>
<td>1.06</td>
<td>0.1338</td>
<td>-11%</td>
<td></td>
</tr>
</tbody>
</table>

Table 10 - Results from height measurement analysis

Similar to height measurements the diameter or width of all objects was recorded in the field as well as calculated via Photoscan measure tool and recorded in Microsoft Excel. The same statistical tests were performed to assess the accuracy of the measurements. Absolute error ranged from 0.016 meters to 1.1672 meters with only three objects having an error greater than 0.5 meters. Relative error ranged from approximately 1% to 11% with the majority of objects being 5% or less and only three being 10% or greater. Out of the 13 objects surveyed widths for 4 were overestimated while 9 were underestimated. RMSE of all objects was calculated as 0.39 m. See table 11 for all diameter/width measurements.
### Table 11 - Results from Width/Diameter Measurement Analysis

<table>
<thead>
<tr>
<th>Object</th>
<th>Reference Width/Diameter (m)</th>
<th>Experimental Width/Diameter (m)</th>
<th>Absolute Error (m)</th>
<th>Relative Error</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure 1</td>
<td>71.93</td>
<td>73.1</td>
<td>1.1672</td>
<td>+2%</td>
<td></td>
</tr>
<tr>
<td>Structure 2</td>
<td>26.42</td>
<td>25.6</td>
<td>0.8159</td>
<td>-3%</td>
<td></td>
</tr>
<tr>
<td>Structure 3</td>
<td>26.42</td>
<td>25.6</td>
<td>0.8159</td>
<td>-3%</td>
<td></td>
</tr>
<tr>
<td>Structure 4</td>
<td>3.5</td>
<td>3.15</td>
<td>0.35</td>
<td>-10%</td>
<td></td>
</tr>
<tr>
<td>Structure 5</td>
<td>4.1</td>
<td>3.66</td>
<td>0.44</td>
<td>-11%</td>
<td></td>
</tr>
<tr>
<td>Structure 6</td>
<td>3.5</td>
<td>3.47</td>
<td>0.03</td>
<td>-1%</td>
<td></td>
</tr>
<tr>
<td>Structure 7</td>
<td>4.1</td>
<td>3.9</td>
<td>0.2</td>
<td>-5%</td>
<td></td>
</tr>
<tr>
<td>Structure 8</td>
<td>3.5</td>
<td>3.12</td>
<td>0.38</td>
<td>-11%</td>
<td></td>
</tr>
<tr>
<td>Structure 9</td>
<td>4.1</td>
<td>3.84</td>
<td>0.26</td>
<td>-6%</td>
<td></td>
</tr>
<tr>
<td>Bale 1</td>
<td>1.52</td>
<td>1.55</td>
<td>0.026</td>
<td>+2%</td>
<td></td>
</tr>
<tr>
<td>Bale 2</td>
<td>1.52</td>
<td>1.55</td>
<td>0.026</td>
<td>+2%</td>
<td></td>
</tr>
<tr>
<td>Bale 3</td>
<td>1.52</td>
<td>1.47</td>
<td>0.054</td>
<td>-4%</td>
<td></td>
</tr>
<tr>
<td>Bale 4</td>
<td>1.52</td>
<td>1.54</td>
<td>0.016</td>
<td>+1%</td>
<td>0.39</td>
</tr>
</tbody>
</table>
5. Discussion and Conclusion

5.1 Conclusions

Based upon the results, a number of conclusions can be made as well as the decision to accept or reject the null hypotheses examined. Conclusions made pertain to the ability of a UAS system and photogrammetric computer software to calculate volume, assess the strengths and or weakness of generated model dimensions, determine if there is a weakness in either the X, Y or Z within generated models, and asses the feasibility based on the time it takes to perform a UAS survey and process data.

5.1.1 Volume Estimation Ability

Volume estimations show varying results. At Site 1 where minimal obstacles were present results were overall very good with exception to Bale 3 which had a lack of photo coverage. Site 2 was met with less optimistic results. Only two structures experienced a relative error of less than 5%. It is important to understand that the two structures with the best result were potentially positioned in the best location for photogrammetric survey and were possibly the two least complex structures at the site while the other objects illustrated less than ideal conditions. The objects located in the North East of the study site were in close proximity to one another and very complex. It is also possible that texture played a large part in the correct calculation of volume by influencing the results of photogrammetric reconstruction. Structure 1 at Site 2 for instance illustrated a large data hole in the top of the structure that was most likely caused by a lack of varying texture. This data hole needed to be filled using the ‘close holes’ tool prior to calculating volume and it is likely that this process influenced the volume calculation of the object.
Various disciplines that utilize volumetric estimations have set accuracy standards. Acceptable volume accuracy within the forestry industry includes all measurements that are within 10% of the true value (Forsman, 2017). The mining industry in some countries have set accuracy standards of 3% of the whole material (Raeva et al. 2016). Many earth movement construction projects rely upon truck count estimates which yields questionable accuracy’s due to assumed soil swelling estimates and inconsistent load sizes (Toledo and Isamitt 2017). Given the acceptable accuracy assessment in various fields it is possible to conclude that the UAS and photogrammetric method is adequate for estimating volumes of objects in the forestry industry, some earth moving projects, as well as disciplines that do not require high accuracy such as agriculture, while it may not be suitable for disciplines that require a high level of accuracy such as some mining practices and engineering applications.

Given the successful volume estimation of several of the most straightforward objects and the minimal difference from reference measurements for these objects it is possible to accept the null hypothesis 1 that there is no marked difference between UAS photogrammetric derived volume estimations and those determined by traditional methods when optimal conditions are present. Under less than ideal conditions where all variables cannot be controlled however it appears that the success of photogrammetric derived products decrease significantly and should not be relied upon, it is potentially possible however when the opportunity presents itself to acquire more photos of less than ideal objects in order to improve results.

### 5.1.2 Measurement Comparison

Based on analysis of measurements performed in situ or provided via engineering specifications and those determined by photogrammetric methods no marked difference was found. The majority of relative error calculations were less than 5% for both vertical and
horizontal measurements. Vertical measurements were observed to be more accurate than horizontal measurements having a RMSE of 0.15 while horizontal measurements had a RMSE of 0.39. Based on these statistics the null hypothesis 2 was accepted there is no discernible difference between dimensions derived from photogrammetric processes and those determined by in situ measurements and/or engineering diagram-based figures.

5.1.3 Effect of Size, Shape and Configuration of Objects

The influence of object size, shape and/or configuration on the accurate estimation of volumes determined by UAS photogrammetric operations were examined in this study. The accuracy of each object was assessed by comparing reference data to estimations determined through photogrammetric methods. These results were then ranked by relative error from smallest to largest. Once the objects were ordered by accuracy each individual object was examined in order to determine if deviations related to size, shape or configuration could be responsible for the difference between objects with less accurate results and those with more accurate results.

Out of the 13 structures surveyed six had a relative error of less than 5%, and three of these were part of the four objects surveyed at Site 1. The fourth object surveyed at Site 1 however had poor photo coverage and was not considered in this assessment. This is important because Site 1 as a whole was much more simplistic than Site 2. Site 1 had minimal elevation change across the study area, all objects where of a similar regular cylindrical shape, and were arranged in a way that there was no clustering or potential affect from one object on another. Of the remaining 3 objects with a relative error of less than 5% two were very similar cylindrical shaped objects in close proximity to one another at Site 2 and the other was a structure grouped among five similar shaped objects that as a whole did not experience the same amount of success
possibly due to the proximity of the objects to one another and the inability to collect data between structures. The two objects with the best results at Site 2 interestingly were also of the most uniform shape with all other objects being either dome shaped or more complex tanks with tubular attachments and dome shaped ends. The only other structure with a percent error less than 10% was the largest structure surveyed at either site. The large dome shaped structure in the north-west corner of Site 2 had a percent error of 8% which is likely contributed to the large data hole in the top of the dome and not associated with its size, shape, or configuration. The remaining five structures were met with the least amount of success with relative error ranging from 11% to 26%. These objects were all upright tanks with dome shaped tops which had large pipes protruding from various locations and where in extreme close proximity to one another. These objects can easily be considered the most structurally complex objects surveyed and also have a very tight clustering pattern. It is likely due to these conditions that volume estimations were met with poor results.

It would seem that the size, shape, and/or configuration of objects does indeed affect the ability to accurately estimate volume using the UAS photogrammetric approach demonstrated in this study. Structures with the most simplistic structure that were not in close proximity to other objects repeatedly obtained better volumetric results. It is because of this that null hypothesis number 3 is rejected in favor of the alternate hypothesis. The size, shape, and/or configuration does indeed have some effect on the ability to obtain accurate volume estimations from photogrammetric data.

5.1.4 Time

Time for data collection and processing, without consideration for the commute to and from study site and time, spent becoming familiar with materials and processes involved, took
approximately 4 hours 30 min for Site 1 and 5 hours 7 min for Site 2. These times lead to the conclusion that UAS and photogrammetry is a time efficient means for estimating the volume of objects when compared to traditional methods; when a long commute is not necessary it is not unthinkable to collect and process all data in one day. It is because of this that null hypothesis 4 is rejected in favor of the alternative. UAS and photogrammetry does indeed potentially provide a more time efficient method for estimating volume than traditional methods.

5.2 Limitations

A number of limitations that warrant further investigation were discovered during the course of this project. Some of these limitations are mentioned below and should be considered by any future study utilizing similar methods.

5.2.1 Accuracy of Volume Estimations

It is important to understand that the accuracy of the measurements (XYZ) were observed to be much better than the volume estimates. It is because of this that the volume estimations performed by Photoscan are brought into question. If volumetric estimates would have been obtained through the measurement tool and formulas for the various shapes surveyed results could have been much more accurate. It is because of this that it is essential to reiterate that poor volume estimations were likely not a result of photogrammetric operations but the algorithms utilized by Photoscan to estimate volume.

5.2.2 Data Holes

When examining the finished model of Site 2 it became apparent that there were numerous data holes present in a number of the objects. The most pronounced of these holes existed on the top of the large dome shaped holding tank. According to measurements performed
using Photoscan’s ‘measure’ tool the void is approximately 20 meters across at the widest
section and 10 meters at the narrowest. There are other less significant data holes in a couple of
the other structures as well. Holes were filled using Photoscan’s ‘fill holes’ tool prior to
preforming measurements such as volume and it should be noted that the interpolation methods
that are utilized for this procedure are not fully understood. These filled holes could potentially
affect the volume measurements of structures in question but it is not known to what extent and
likely marginal on all structures except the large dome shaped holding take mentioned above.

Figure 18 - Site 2 showing large data hole

There are three primary theories as to what could have caused these data holes. The first
is texture and is most likely the cause of issues with the large dome structure. The top of the
structure where the gap is located is largely uniform in texture possibly inhibiting the software’s
matching algorithms to identify key points in this area. The lack of key points could have
prevented the software program from generating a surface in an area that it could not match any
unique features among photos. Another potential issue and likely a contributing factor to the other data holes is lack of photo coverage. The other small data holes are located on the sides of objects in areas that had obstacles preventing adequate UAS position and thus resulting in a lack of photos in the given region. Last, is the presence of shadows. In the areas where the small data holes are present it should be noted that in most cases there is a presence of a shadow cast from either the structure being surveyed or surrounding structures. These shadows result in a darkening of the affected portion of the scene and likely inhibited the software ability to detect key points and regenerate the scene. Most instance of data holes in this project can likely be traced back to an issue related to either one or multiple of these theorized factors.

5.2.3 Poor Reconstruction of Objects

A number of objects at both Site 1 and Site 2 experienced poor reconstruction results. At Site 1 these objects include a couple of the hay bales that were located on the perimeter of the study area and not focal points of the survey. Site 2 had a number of structures in the north-east section of the study area that also experienced poor photogrammetric reconstruction. These objects were very close one another and it is hypothesized that the objects concealed details of other objects at various perspectives. In each of these instances the suspect influential factor is the inadequate photo coverage. Other objects that experienced good results had excellent 360-degree photo coverage with no obstructions in photos. Given these results future studies should be sure to maximize photo coverage of each individual object and preferably isolate each object instead of attempting to fly groups of objects at once.
5.3 Processing Considerations

It should be noted that all processing for Site 1 data was done on a standard 64 bit windows 10 desktop machine while processing for Site 2 was completed on CAST server SIRIS. This is the reason for the dramatic difference in processing time for Site 1 and Site 2. Individuals working to duplicate this research who are working on a standard desktop should expect to see processing times similar to those exhibited by Site 1 procedures.

5.4 Future Efforts

Future efforts should focus on a number of factors that could potentially improve photogrammetric results as well as further understanding of this technique. Research should be conducted into the optimization of parameters, and the effect of site conditions. These areas are viewed as potentially the most influential on the accuracy of results and steps should be taken to identify a method that generates results the highest possible accuracy.

Research into the optimization of equipment parameters could include variations in UAS system parameters, camera calibration specifics, adjusted GCP acquisition techniques, or research into improving products from Photoscan. Some potentially influential UAS system parameters that could be improved upon or further understood include optimal altitude for data collection, distance from object being survey, as well as angle of the camera during data collection. There is the potential to improve photogrammetric results by optimizing camera calibration specifics. These specifics include what is the optimal camera lens, focal length, lens angle, as well as photo resolutions. Research into the most optimal arrangement of GCPs and the system used for GCP surveying could also improve results. Research into the optimization of Photoscan software should also be undertaken in order to further understand how the software
creates scenes and how dimensions can preserved in best possible way. There are potentially many other influential parameters that could influence the results of this study and each should be examined in detail in further studies to identify optimal setting in order to increase the accuracy of future projects.

Further research into the physical conditions of a specific site should also be conducted. These conditions include weather, site layout, and position of objects being surveyed. Weather is potentially a very influential factor in the success of a UAS project. Both sites used in this study were flown on overcast days and could have potentially received improved results with better lighting conditions. It is because of this that research into the effect of light and sun angle on the results of a project should be completed. Site layout should also be considered in future studies. This project identified some potential limitations when a target object is located in close proximity to other objects that could hinder consistent photo collection. Last, further research into the position of objects should be performed. For instance, this project identified a weakness in the accuracy of objects clustered closely together while objects located in an isolated fashion received the best results.

Identification of optimal conditions for inexpensive UAS photogrammetric methods to estimate volume could potentially eliminate inconsistencies. Given the elimination of inconstant results UAS and photogrammetry have the potential to replace traditional methods of volume estimation presenting a more cost and time efficient method.
References


Matthews, Neffra A. Aerial and close-range photogrammetric technology: providing resource documentation, interpretation, and preservation. 2008.


Survey Data

Fig. 1. Camera locations and image overlap.

Number of images: 80
Flying altitude: 19.7 m
Ground resolution: 8.98 mm/pix
Coverage area: 5.58e+03 m²

Camera stations: 80
Tie points: 49,387
Projections: 132,329
Reprojection error: 1.03 pix

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
<th>Precalibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERO4 Silver (3 mm)</td>
<td>3000 x 2250</td>
<td>3 mm</td>
<td>1.73 x 1.73 μm</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1. Cameras.
**Camera Calibration**

![Image residuals for HERO4 Silver (3 mm).](image)

**HERO4 Silver (3 mm)**
80 images

<table>
<thead>
<tr>
<th>Type</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>3000 x 2250</td>
<td>3 mm</td>
<td>1.73 x 1.73 μm</td>
</tr>
</tbody>
</table>

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F:</td>
<td>1768.06</td>
<td>3 mm</td>
<td>1.73 x 1.73 μm</td>
</tr>
<tr>
<td>Cx:</td>
<td>-4.69593</td>
<td>B1:</td>
<td>0</td>
</tr>
<tr>
<td>Cy:</td>
<td>36.0507</td>
<td>B2:</td>
<td>0</td>
</tr>
<tr>
<td>K1:</td>
<td>-0.258877</td>
<td>P1:</td>
<td>-3.63689e-05</td>
</tr>
<tr>
<td>K2:</td>
<td>0.0895844</td>
<td>P2:</td>
<td>-0.000472033</td>
</tr>
<tr>
<td>K3:</td>
<td>-0.0164601</td>
<td>P3:</td>
<td>0</td>
</tr>
<tr>
<td>K4:</td>
<td>0</td>
<td>P4:</td>
<td>0</td>
</tr>
</tbody>
</table>
Ground Control Points

Fig. 3. GCP locations.

<table>
<thead>
<tr>
<th>Count</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>XY error (cm)</th>
<th>Total (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>3.09312</td>
<td>6.34364</td>
<td>5.65079</td>
<td>7.05756</td>
<td>9.04105</td>
</tr>
</tbody>
</table>

Table 2. Control points RMSE.

X - Longitude, Y - Latitude, Z - Altitude.
<table>
<thead>
<tr>
<th>Label</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>Total (cm)</th>
<th>Image (pix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>point 1</td>
<td>-2.3764</td>
<td>2.42441</td>
<td>-1.51782</td>
<td>3.71871</td>
<td>0.000 (51)</td>
</tr>
<tr>
<td>point 2</td>
<td>-3.28396</td>
<td>-5.43999</td>
<td>-6.04217</td>
<td>8.76845</td>
<td>0.000 (58)</td>
</tr>
<tr>
<td>point 3</td>
<td>-2.23015</td>
<td>-1.18573</td>
<td>-0.865445</td>
<td>2.66993</td>
<td>0.000 (76)</td>
</tr>
<tr>
<td>point 4</td>
<td>0.730924</td>
<td>1.12958</td>
<td>3.64162</td>
<td>3.88221</td>
<td>0.000 (80)</td>
</tr>
<tr>
<td>point 5</td>
<td>-0.747827</td>
<td>4.96376</td>
<td>3.06869</td>
<td>5.88345</td>
<td>0.000 (76)</td>
</tr>
<tr>
<td>point 6</td>
<td>5.25944</td>
<td>3.9557</td>
<td>-10.7171</td>
<td>12.5764</td>
<td>0.000 (66)</td>
</tr>
<tr>
<td>point 7</td>
<td>-2.05592</td>
<td>-13.5578</td>
<td>5.45774</td>
<td>14.7589</td>
<td>0.000 (78)</td>
</tr>
<tr>
<td>point 8</td>
<td>4.70656</td>
<td>7.7254</td>
<td>6.96917</td>
<td>11.4194</td>
<td>0.000 (60)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.09312</strong></td>
<td><strong>6.34364</strong></td>
<td><strong>5.65079</strong></td>
<td><strong>9.04105</strong></td>
<td><strong>0.000</strong></td>
</tr>
</tbody>
</table>

Table 3. Control points.

X - Longitude, Y - Latitude, Z - Altitude.
Digital Elevation Model

Fig. 4. Reconstructed digital elevation model.

Resolution: 1.8 cm/pix
Point density: 0.31 points/cm²
Processing Parameters

General
- Cameras: 80
- Aligned cameras: 80
- Markers: 8
- Coordinate system: WGS 84 (EPSG::4326)
- Rotation angles: Yaw, Pitch, Roll

Point Cloud
- Points: 49,387 of 53,572
- RMS reprojection error: 0.116532 (1.0259 pix)
- Max reprojection error: 0.351939 (19.5881 pix)
- Mean key point size: 7.69103 px
- Effective overlap: 2.91481

Alignment parameters
- Accuracy: Medium
- Generic preselection: No
- Reference preselection: No
- Key point limit: 40,000
- Tie point limit: 4,000
- Constrain features by mask: No
- Matching time: 2 minutes 57 seconds
- Alignment time: 28 seconds

Dense Point Cloud
- Points: 13,580,113

Reconstruction parameters
- Quality: High
- Depth filtering: Aggressive

Model
- Faces: 905,332
- Vertices: 453,945
- Texture: 4,096 x 4,096, uint8

Reconstruction parameters
- Surface type: Arbitrary
- Source data: Dense
- Interpolation: Enabled
- Quality: High
- Depth filtering: Aggressive
- Face count: 905,332
- Processing time: 1 hours 55 minutes

Texturing parameters
- Mapping mode: Generic
- Blending mode: Mosaic
- Texture size: 4,096 x 4,096
- UV mapping time: 8 minutes 3 seconds

Software
- Version: 1.3.0 build 3772
- Platform: Windows 64
Appendix B – Site 2 Chunk One Photoscan Processing Report

Agisoft PhotoScan
Processing Report
03 April 2017
Survey Data

Fig. 1. Camera locations and image overlap.

Number of images: 100  Camera stations: 100
Flying altitude: 20 m  Tie points: 44,432
Ground resolution: 2.04 cm/pix  Projections: 127,356
Coverage area: 5.8e+03 m²  Reprojection error: 0.817 pix

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
<th>Precalibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>unknown</td>
<td>1920 x 1080</td>
<td>unknown</td>
<td>unknown</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1. Cameras.
Camera Calibration

Fig. 2. Image residuals for unknown.

unknown
100 images

<table>
<thead>
<tr>
<th>Type</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>1920 x 1080</td>
<td>unknown</td>
<td>unknown</td>
</tr>
</tbody>
</table>

F: 866.904
Cx: 2.14257
Cy: 4.87231
K1: -0.224749
K2: 0.0546887
K3: -0.00619249
K4: 0
B1: 0
B2: 0
P1: -0.000169219
P2: 0.00161677
P3: 0
P4: 0
Ground Control Points

Fig. 3. GCP locations.

<table>
<thead>
<tr>
<th>Count</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>XY error (cm)</th>
<th>Total (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>27.654</td>
<td>25.3198</td>
<td>8.66771</td>
<td>37.4945</td>
<td>38.4833</td>
</tr>
</tbody>
</table>

Table 2. Control points RMSE.
X - Longitude, Y - Latitude, Z - Altitude.
<table>
<thead>
<tr>
<th>Label</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>Total (cm)</th>
<th>Image (pix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>point 4</td>
<td>3.48725</td>
<td>-8.03859</td>
<td>-6.79272</td>
<td>11.087</td>
<td>0.000 (49)</td>
</tr>
<tr>
<td>point 5</td>
<td>19.5639</td>
<td>-5.68044</td>
<td>19.5248</td>
<td>28.2175</td>
<td>0.000 (51)</td>
</tr>
<tr>
<td>point 6</td>
<td>0.364602</td>
<td>-1.85134</td>
<td>4.66392</td>
<td>5.03116</td>
<td>0.000 (46)</td>
</tr>
<tr>
<td>point 7</td>
<td>-36.8664</td>
<td>6.62511</td>
<td>0.646276</td>
<td>37.4626</td>
<td>0.000 (38)</td>
</tr>
<tr>
<td>point 8</td>
<td>-56.3755</td>
<td>-21.2818</td>
<td>-7.46996</td>
<td>60.72</td>
<td>0.000 (29)</td>
</tr>
<tr>
<td>point 9</td>
<td>50.0072</td>
<td>72.378</td>
<td>-0.523274</td>
<td>87.9749</td>
<td>0.000 (34)</td>
</tr>
<tr>
<td>point 10</td>
<td>12.7845</td>
<td>-1.55804</td>
<td>5.85081</td>
<td>14.1458</td>
<td>0.000 (28)</td>
</tr>
<tr>
<td>point 11</td>
<td>-0.529617</td>
<td>-12.4642</td>
<td>1.37635</td>
<td>12.5511</td>
<td>0.000 (44)</td>
</tr>
<tr>
<td>point 12</td>
<td>-0.439769</td>
<td>-10.5373</td>
<td>-3.32403</td>
<td>11.0579</td>
<td>0.000 (43)</td>
</tr>
<tr>
<td>point 13</td>
<td>7.09935</td>
<td>-17.5046</td>
<td>-14.0895</td>
<td>23.5654</td>
<td>0.000 (39)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27.654</strong></td>
<td><strong>25.3198</strong></td>
<td><strong>8.66771</strong></td>
<td><strong>38.4833</strong></td>
<td><strong>0.000</strong></td>
</tr>
</tbody>
</table>

Table 3. Control points.

X - Longitude, Y - Latitude, Z - Altitude.
Fig. 4. Reconstructed digital elevation model.

Resolution: 8.15 cm/pix
Point density: 150 points/m²
# Processing Parameters

## General
- Cameras: 100
- Aligned cameras: 100
- Markers: 10
- Coordinate system: WGS 84 (EPSG::4326)
- Rotation angles: Yaw, Pitch, Roll

## Point Cloud
- Points: 44,432 of 64,073
- RMS reprojection error: 0.188436 (0.816674 pix)
- Max reprojection error: 0.574106 (16.251 pix)
- Mean key point size: 4.08792 pix
- Effective overlap: 3.15432

### Alignment parameters
- Accuracy: High
- Generic preselection: No
- Reference preselection: No
- Key point limit: 40,000
- Tie point limit: 4,000
- Constrain features by mask: No
- Matching time: 7 minutes 41 seconds
- Alignment time: 1 minutes 2 seconds

## Dense Point Cloud
- Points: 1,229,904

## Reconstruction parameters
- Quality: Medium
- Depth filtering: Aggressive
- Dense cloud generation time: 1 minutes 33 seconds

## Model
- Faces: 37,363
- Vertices: 19,018
- Texture: 4,096 x 4,096, uint8

## Reconstruction parameters
- Surface type: Arbitrary
- Source data: Dense
- Interpolation: Enabled
- Quality: Medium
- Depth filtering: Aggressive
- Face count: 81,993
- Processing time: 1 minutes 35 seconds

## Texturing parameters
- Mapping mode: Generic
- Blending mode: Mosaic
- Texture size: 4,096 x 4,096
- UV mapping time: 57 seconds
- Blending time: 31 seconds

## Software
- Version: 1.3.0 build 3772
- Platform: Windows 64
Appendix C – Site 2 Chunk Two Photoscan Processing Report

Agisoft PhotoScan
Processing Report
03 April 2017
Survey Data

Fig. 1. Camera locations and image overlap.

Number of images: 62
Flying altitude: 29.8 m
Ground resolution: 1.26 cm/pix
Coverage area: 5.33e+03 m²

Camera stations: 62
Tie points: 47,094
Projections: 144,200
Reprojection error: 1.47 pix

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
<th>Precalibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERO4 Silver (3 mm)</td>
<td>3840 x 2160</td>
<td>3 mm</td>
<td>1.73 x 1.73 µm</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1. Cameras.
Camera Calibration

Fig. 2. Image residuals for HERO4 Silver (3 mm).

HERO4 Silver (3 mm)
62 images

<table>
<thead>
<tr>
<th>Type</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>3840 x 2160</td>
<td>3 mm</td>
<td>1.73 x 1.73 μm</td>
</tr>
</tbody>
</table>

F:
1734.53

Cx:
2.93375

Cy:
25.0828

K1:
-0.231183

K2:
0.0597163

K3:
-0.00722444

K4:
0

B1: 0

B2: 0

P1: -0.00019481

P2: 8.21859e-05

P3: 0

P4: 0
Ground Control Points

Fig. 3. GCP locations.

<table>
<thead>
<tr>
<th>Count</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>XY error (cm)</th>
<th>Total (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>60.1278</td>
<td>44.692</td>
<td>29.8447</td>
<td>74.9182</td>
<td>80.6439</td>
</tr>
</tbody>
</table>

Table 2. Control points RMSE.
X - Longitude, Y - Latitude, Z - Altitude.
<table>
<thead>
<tr>
<th>Label</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>Total (cm)</th>
<th>Image (pix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>point 14</td>
<td>-38.4708</td>
<td>-82.8804</td>
<td>-41.0857</td>
<td>100.186</td>
<td>0.000 (17)</td>
</tr>
<tr>
<td>point 15</td>
<td>-125.232</td>
<td>-34.197</td>
<td>-61.535</td>
<td>143.663</td>
<td>0.000 (19)</td>
</tr>
<tr>
<td>point 16</td>
<td>-112.98</td>
<td>-9.46572</td>
<td>-42.2737</td>
<td>121</td>
<td>0.000 (23)</td>
</tr>
<tr>
<td>point 17</td>
<td>-44.9561</td>
<td>-8.52397</td>
<td>-32.6452</td>
<td>56.2087</td>
<td>0.000 (60)</td>
</tr>
<tr>
<td>point 18</td>
<td>-33.7625</td>
<td>17.1463</td>
<td>-28.2862</td>
<td>47.2653</td>
<td>0.000 (58)</td>
</tr>
<tr>
<td>point 19</td>
<td>-76.7472</td>
<td>33.2179</td>
<td>-25.1749</td>
<td>87.3346</td>
<td>0.000 (20)</td>
</tr>
<tr>
<td>point 20</td>
<td>-56.8051</td>
<td>94.3</td>
<td>1.67968</td>
<td>110.101</td>
<td>0.000 (26)</td>
</tr>
<tr>
<td>point 21</td>
<td>4.49172</td>
<td>65.5927</td>
<td>7.71997</td>
<td>66.198</td>
<td>0.000 (26)</td>
</tr>
<tr>
<td>point 22</td>
<td>-11.8007</td>
<td>13.5421</td>
<td>-14.0069</td>
<td>22.0195</td>
<td>0.000 (23)</td>
</tr>
<tr>
<td>point 23</td>
<td>-26.375</td>
<td>-16.662</td>
<td>-19.4096</td>
<td>36.7423</td>
<td>0.000 (26)</td>
</tr>
<tr>
<td>point 13</td>
<td>3.18311</td>
<td>-26.7201</td>
<td>-17.0662</td>
<td>31.8646</td>
<td>0.000 (27)</td>
</tr>
<tr>
<td>point 12</td>
<td>17.6586</td>
<td>-0.596253</td>
<td>0.766211</td>
<td>17.6853</td>
<td>0.000 (32)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>60.1278</strong></td>
<td><strong>44.692</strong></td>
<td><strong>29.8447</strong></td>
<td><strong>80.6439</strong></td>
<td><strong>0.000</strong></td>
</tr>
</tbody>
</table>

Table 3. Control points.

X - Longitude, Y - Latitude, Z - Altitude.
Digital Elevation Model

Fig. 4. Reconstructed digital elevation model.

Resolution: 2.53 cm/pix
Point density: 0.157 points/cm²
## Processing Parameters

### General
- Cameras: 62
- Aligned cameras: 62
- Markers: 12
- Coordinate system: WGS 84 (EPSG:4326)
- Rotation angles: Yaw, Pitch, Roll

### Point Cloud
- Points: 47,094 of 69,217
- RMS reprojection error: 0.279766 (1.47492 px)
- Max reprojection error: 0.867389 (61.1004 px)
- Mean key point size: 5.0267 px
- Effective overlap: 3.29743

### Alignment parameters
- Accuracy: Hckh
- Generic preselection: No
- Reference preselection: No
- Key point limit: 40,000
- Tie point limit: 4,000
- Constrain features by mask: No
- Matching time: 13 minutes 47 seconds
- Alignment time: 48 seconds

### Dense Point Cloud
- Points: 13,851,266

### Reconstruction parameters
- Quality: High
- Depth filtering: Aggressive
- Dense cloud generation time: 10 minutes 3 seconds

### Model
- Faces: 455,721
- Vertices: 229,412
- Texture: 4,096 x 4,096, uint8

### Reconstruction parameters
- Surface type: Arbitrary
- Source data: Dense
- Interpolation: Enabled
- Quality: High
- Depth filtering: Aggressive
- Face count: 923,416
- Processing time: 18 minutes 34 seconds

### Texturing parameters
- Mapping mode: Generic
- Blending mode: Mosaic
- Texture size: 4,096 x 4,096
- UV mapping time: 4 minutes 34 seconds
- Blending time: 49 seconds

### Software
- Version: 1.3.0 build 3772
- Platform: Windows 64
Agisoft PhotoScan
Processing Report
03 April 2017
Survey Data

Fig. 1. Camera locations and image overlap.

<table>
<thead>
<tr>
<th>Number of images:</th>
<th>86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flying altitude:</td>
<td>30.1 m</td>
</tr>
<tr>
<td>Ground resolution:</td>
<td>2.55 cm/pix</td>
</tr>
<tr>
<td>Coverage area:</td>
<td>3.96e+03 m²</td>
</tr>
<tr>
<td>Camera stations:</td>
<td>86</td>
</tr>
<tr>
<td>Tie points:</td>
<td>45,854</td>
</tr>
<tr>
<td>Projections:</td>
<td>169,062</td>
</tr>
<tr>
<td>Reprojection error:</td>
<td>1.04 pix</td>
</tr>
</tbody>
</table>

Table 1. Cameras.

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
<th>Precalibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>unknown</td>
<td>1920 x 1080</td>
<td>unknown</td>
<td>unknown</td>
<td>No</td>
</tr>
</tbody>
</table>
Camera Calibration

Fig. 2. Image residuals for unknown.

unknown
86 images

<table>
<thead>
<tr>
<th>Type</th>
<th>Resolution</th>
<th>Focal Length</th>
<th>Pixel Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>1920 x 1080</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>F:</td>
<td>864.703</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cx:</td>
<td>5.7349</td>
<td>B1:</td>
<td>0</td>
</tr>
<tr>
<td>Cy:</td>
<td>16.1417</td>
<td>B2:</td>
<td>0</td>
</tr>
<tr>
<td>K1:</td>
<td>-0.224363</td>
<td>P1:</td>
<td>-7.36111e-05</td>
</tr>
<tr>
<td>K2:</td>
<td>0.0554754</td>
<td>P2:</td>
<td>0.000465383</td>
</tr>
<tr>
<td>K3:</td>
<td>-0.00645958</td>
<td>P3:</td>
<td>0</td>
</tr>
<tr>
<td>K4:</td>
<td>0</td>
<td>P4:</td>
<td>0</td>
</tr>
</tbody>
</table>
Ground Control Points

Fig. 3. GCP locations.

<table>
<thead>
<tr>
<th>Count</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>XY error (cm)</th>
<th>Total (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>21.38</td>
<td>41.2488</td>
<td>23.4041</td>
<td>46.4604</td>
<td>52.0223</td>
</tr>
</tbody>
</table>

Table 2. Control points RMSE.
X - Longitude, Y - Latitude, Z - Altitude.
<table>
<thead>
<tr>
<th>Label</th>
<th>X error (cm)</th>
<th>Y error (cm)</th>
<th>Z error (cm)</th>
<th>Total (cm)</th>
<th>Image (pix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>point 1</td>
<td>45.22</td>
<td>-25.064</td>
<td>-29.3837</td>
<td>59.4681</td>
<td>0.000 (46)</td>
</tr>
<tr>
<td>point 2</td>
<td>13.1595</td>
<td>-25.7948</td>
<td>-25.0298</td>
<td>38.2758</td>
<td>0.000 (57)</td>
</tr>
<tr>
<td>point 3</td>
<td>5.37569</td>
<td>-64.1893</td>
<td>-36.5911</td>
<td>74.0815</td>
<td>0.000 (51)</td>
</tr>
<tr>
<td>point 4</td>
<td>-9.32461</td>
<td>-17.12</td>
<td>-6.21301</td>
<td>20.4608</td>
<td>0.000 (31)</td>
</tr>
<tr>
<td>point 5</td>
<td>10.1899</td>
<td>-0.122711</td>
<td>8.40533</td>
<td>13.2098</td>
<td>0.000 (32)</td>
</tr>
<tr>
<td>point 6</td>
<td>11.8254</td>
<td>3.68985</td>
<td>12.6501</td>
<td>17.7054</td>
<td>0.000 (31)</td>
</tr>
<tr>
<td>point 13</td>
<td>2.44354</td>
<td>-17.8564</td>
<td>-13.1439</td>
<td>22.3066</td>
<td>0.000 (32)</td>
</tr>
<tr>
<td>point 12</td>
<td>7.61949</td>
<td>-13.4655</td>
<td>-1.45602</td>
<td>15.5401</td>
<td>0.000 (27)</td>
</tr>
<tr>
<td>point 23</td>
<td>-5.47299</td>
<td>6.17086</td>
<td>-17.3701</td>
<td>19.229</td>
<td>0.000 (16)</td>
</tr>
<tr>
<td>point 14</td>
<td>-43.5837</td>
<td>-103.71</td>
<td>-43.6217</td>
<td>120.657</td>
<td>0.000 (33)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21.38</strong></td>
<td><strong>41.2488</strong></td>
<td><strong>23.4041</strong></td>
<td><strong>52.0223</strong></td>
<td><strong>0.000</strong></td>
</tr>
</tbody>
</table>

Table 3. Control points.
X - Longitude, Y - Latitude, Z - Altitude.
Digital Elevation Model

Fig. 4. Reconstructed digital elevation model.

Resolution: 5.1 cm/pix
Point density: 385 points/m²
### Processing Parameters

#### General
- Cameras: 86
- Aligned cameras: 86
- Markers: 10
- Coordinate system: WGS 84 (EPSG:4326)
- Rotation angles: Yaw, Pitch, Roll

#### Point Cloud
- Points: 45,854 of 61,453
- RMS reprojection error: 0.234795 (1.03894 pix)
- Max reprojection error: 0.715747 (26.7541 pix)
- Mean key point size: 3.99352 pix
- Effective overlap: 4.27205

#### Alignment parameters
- Accuracy: High
- Generic preselection: No
- Reference preselection: No
- Key point limit: 40,000
- Tie point limit: 4,000
- Constraining features by mask: No
- Matching time: 4 minutes 55 seconds
- Alignment time: 1 minute 16 seconds

#### Dense Point Cloud
- Points: 3,728,436

#### Reconstruction parameters
- Quality: High
- Depth filtering: Aggressive
- Dense cloud generation time: 10 minutes 50 seconds

#### Model
- Faces: 67,670
- Vertices: 34,220
- Texture: 4,096 x 4,096, uint8

#### Reconstruction parameters
- Surface type: Arbitrary
- Source data: Dense
- Interpolation: Enabled
- Quality: High
- Depth filtering: Aggressive
- Face count: 248,380
- Processing time: 5 minutes 3 seconds

#### Texturing parameters
- Mapping mode: Generic
- Blending mode: Mosaic
- Texture size: 4,096 x 4,096
- UV mapping time: 1 minute 34 seconds
- Blending time: 34 seconds

#### Software
- Version: 1.3.0 build 3772
- Platform: Windows 64