Assessing the Technology Used by UAVs in Data Acquisition on Construction Sites

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Abstract

Assessing the Technology Used by UAVs in Collecting Data and Their Limitations on Construction Sites

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The question this thesis intends to answer is whether General Contractors (GCs) can indeed benefit from the use of Unmanned Aerial Vehicles (UAVs) in the construction process. With the technology of UAVs, cameras, thermographic scanners, and laser scanners with Light Detection and Ranging (LiDAR), this research will investigate how 3D Building Information Models (BIMs) can be created for real time project management decision making. UAVs with camera and laser scanning abilities will be researched through a comprehensive study by determining where the current field of research is and where it is headed. Cameras being used for photogrammetric 3D models have the ability to deduce the current status of construction activities in a precise and accurate manner. The photogrammetric process gives the GC a snap shot of construction activities to facilitate project management decisions based on the potential for a 4D schedule relative to the BIM. LiDAR devices create a more complex and detailed point cloud for the higher quality 3D BIM. The use of

aerial thermography to look at the building envelope and create a 3D image will be investigated, as well. Lastly, the combination of photogrammetry and LiDAR will be investigated for their accuracy and usefulness within case studies presented by others. Interviews conducted with industry professionals are also presented in order to ascertain the current status and opinion of UAVs in the private GC sector for current as-built 3D BIMs.

CONTENTS

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ABBREVIATIONS

ALSM	Airborne Laser Swath Mapping
AR	Augmented Reality
AtiPE	Automatic Tie Point Extraction
BIM	Building Information Modeling
CMOS	Complementary Metal-Oxide Semiconductor
COA	Certificate of Authorization
COW	Certificate of Waiver
DGPS	Differential Global Positioning System
DSLR	Digital Single Lens Reflex Camera
DSM	Digital Surface Model
DTM	Digital Terrain Model
FAA	Federal Aviation Administration
GCP	Ground Control Points
GCS	Ground Control Station
GIS	Geographic Information System
GNSS/INS	Global Navigation Satellite System/Inertial Navigation System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IR	Infrared
LADAR	Laser Detection and Ranging
LiDAR	Light Detection and Ranging
LOD	Level of Detail
MAC	Mid Air Collision
MAV	Micro Aerial Vehicles
NAS	National Airspace System
NMAC	Near Mid-Air Collision
RC	Remote Controlled
ROA	Remotely Operated Aircraft
ROI	Region of Interest
RPV	Remotely Piloted Vehicle
SfM	Structure-from-Motion
S&A	Sense and Avoid
SLAM	Simultaneous Localization and Mapping
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line of Site

CHAPTER 1

INTRODUCTION

Even though Unmanned Aerial Vehicles (UAVs) are just another tool to use in the data collection process, UAVs bring an emerging field of technological research, unprecedented in the construction industry, to the table by utilizing photogrammetry, laser scanning, and thermography. The data collection technology that has started to come into its own is propelling the UAVs in a staggering upward spiral that the construction industry needs to address. The present research will include three methods of data collection. The software will be used for analysis of data and it will have a significant role in research. The accuracy of data will be reviewed because it is a key factor to determine whether the industry will accept the technology or not. The research will also process the data and discussion would be discussed regarding the application of data to the 3D BIM as-built condition.

There are many different areas in which the construction industry can utilize this technology. These include quality control, safety, project management, scheduling, inspection, and integrating 3D images into a 4D BIM. Different examples of this technology on a construction site would include the layout and processing of real time information of the site layout. This information will tell the Superintendent where equipment is located, it can measure areas where products need to be laid down, and it can give an aspect as to the future of where the site is going. Another example is that the UAV will provide detailed photographic images in order to conduct the safety analysis of a roof layout. The information provided can tell the Safety Officer where the fall protection needs to be installed, and again, make measurements and provide angles so as to not overextend the lifelines. Lastly, taking the photogrammetric process and applying that to a building under construction can provide an accurate depiction 3D BIM of the as-built conditions. This process can also provide a 4D solution by including the schedule. The data acquisition by laser scanning can also accomplish the creation of 3D BIM for the as-built conditions. But, it is through the combination of acquisition methods that the true power is realized. Given the capabilities of terrestrial scanning, and aerial, the level of detail (LOD) is much greater than that of only one method at a time.

It has only been since the past two to five years that the UAV manufacturing industry and computer software programs have come together and really grasped at the potentials for data collection. Lots of companies already exist with their own standards of industry like Kespry and Aerial Solutions. Such companies have already developed their UAVs and other software for processing of data for meeting the needs of clients. There is a need of software which can produce near survey standards to keep up with ongoing trends of industry. Construction Company is also searching for such surveys to produce more precise results. Analysis of different data collection methods will help to determine one best and most suitable method for collecting data in future.

Other industries, such as forestry and agriculture have accepted this technology and have started to utilize it as a means to improve productivity (Wallace et al. 2012; Laliberte et al., 2010). In general, the construction industry is slow to accept change with new technologies. For example, Building Information Modeling (BIM), has been working around for the past twenty years but has recently established as common practice in construction for the past five to ten years. This is a big problem. Private industry is typically uninterested with the untested, unproven, and undocumented findings related to technology. There are legal issues surrounding the use of UAVs in the United States, and when regulations are not in place, which has the ability to protect the users of UAVs, red flags are raised. Previously, there was a rule called the 333 Exemption for the flight of UAVs in a commercial sense and was part of the FAA Modernization and Reform Act of 2012 (FAA - Beyond the Basics, 2016). Recently, there have been updated regulations by the Federal Aviation Administration called, Part 107 (FAA 2016). This rule allows the commercial UAV flyer to become certified by taking an exam and register their UAV for flight. Part 107 has addressed many key concerns that the Exemption 333 did not, and streamlined the government's involvement in the UAV arena. The commercial aspects of flying UAVs have essentially been green-lighted for takeoff by the federal government.

1.0 TERMS

There are many terms which have been used when discussing the technology associated with Unmanned Aerial Vehicles. The point is to further understand the UAV as a tool by putting a value to the words which are used in the community of UAV users. Many publications that discuss UAVs use terminology which can be confusing, because these terms are interchangeable and can mean the same thing across the board. For beginners, the term Unmanned Aerial Vehicle (UAV) is the closest word that is the typical use meaning quadcopters, octocopter, helicopter, or fixed wing vehicle. Unmanned Aerial System (UAS) is another typical term used for the same vehicles described above but is more loosely describing any and all systems that make up the remote controlled portion of flying. Remotely Piloted Vehicle (RPV), Remotely Operated Vehicle (ROV), and Remote Controlled (RC) are used to discuss the same systems as the UAS. These terms are what the laymen are talking about when they say the word "drone." The term UAV is the most popular term being used in recent publications. When utilizing a UAV there are known terms such as Global Positioning System (GPS) that are commonplace within the community. Federal Aviation Administration (FAA) is the government entity responsible for rules and regulations regarding the use of UAVs in public. They use terminology such as National Airspace System

(NAS) to describe the flying space in the USA. Near Mid-Air Collision (NMAC) and Mid-Air Collision (MAC) are terms the UAV community like to avoid. Sense and Avoid (S&A) are technologies that are on the market for UAVs when eluding crashes in the air.

When discussing the technology of data collection, there are specialized terms that are used for laser scanning. For instance, Light Detection and Ranging (LiDAR), Laser Detection and Ranging (LADAR), and Airborne Laser Swath Mapping (ALSM) are all describing the same method of utilizing a laser in order to collect data from a specific region. One aspect of data collection is the use of the Global Navigation Satellite System/Inertial Navigation System (GNSS/GNS) and are typically found within the computer programs that allow for autonomous flight modes in a UAV. The GNSS/GNS act in conjunction with the GPS to keep the data lined up along with the Ground Control Points (GCPs) and Ground Control Stations (GCSs). These are all vital details to keep the data under control for post processing.

1.2 CURRENT

Currently, UAVs are being used to show the owner the overall structure of a completed build through photographs as well as for the GCs marketing purposes. The typical user of a UAV on a construction site is not interested in collecting data via LiDAR or photogrammetry, but by using the UAV as a surveillance tool. Watching how workers are going about their day and ensuring the safety policies are being implemented are just examples of how the current situation of UAVs being utilized on construction sites are being done (Irizarry et al., 2012; Gheisari et al., 2014). UAVs are also being used for quality control on projects, in that they are surveying and inspecting the work being put in place and making sure it is correct (Morgenthal and Hallerman, 2014). Surveillance on a construction project via UAV should not be discounted as it can provide real-time data to project managers, engineers, and interested parties without having them conduct a site visit.

There have been projects that do include the UAV as a primary source of data collection. Using photogrammetry to collect the data, one project in specific was the Sacramento Kings arena built by Turner construction. The company utilized drones with cameras to capture work in progress for 3D BIM and produce 4D models, which incorporates time and future risks (Koon, 2016). To be able to visually see and have the ability to plan in a weekly meeting and discuss where potential problems may occur are part of the 4D program. It is a powerful tool to utilize on a mega arena project. Other projects utilizing photogrammetry for data acquisition are finding the applications via DSLR camera to be as accurate as a LiDAR scanner (Golparvar-Fard et al., 2011). The photographs that the camera produces also lead to issues that can limit the accuracy of the 3D models. Data processing of point clouds can also be an issue, for example, if there are too many points for the computer to sort, it can take a toll on the computational processing period (). Or, if there are not enough points due to surface reflectivity, a range of the photographs, edges, angles, occlusions, and even environmental considerations are all limitations that can cause poor data acquisition from objects within the construction project (Boehler and Marbs, 2003).

In another research project the use of LiDAR was applied with an UAV to collect data for the precision required of quality control (Wang et al., 2014). The UAV was utilized to collect data of work that had been installed previously and overlay the results with the 3D BIM as-planned images.

1.3 RESEARCH OBJECTIVES

Research problem/questions: The problem is that UAVs are becoming technologically advanced enough to be collecting massive amounts of data on construction sites, but are not being utilized to the extent that should be employed.

Are the data collection methods solid enough to supply accurate information to create 3D models?

1. Can photogrammetry provide enough information to formulate a 3D BIM?
2. Can Laser scanning provide enough info to formulate a 3D BIM?
3. Can thermography provide enough info to formulate a 3D BIM?
4. What are the limitations of each method?
5. Will the construction industry integrate this tool into it's daily workflow?

Research Objectives: The objective of this research is to determine if the technologies available for use by a UAV will provide a benefit to the construction industry. The research will look into the uses of photogrammetry, laser scanning, and thermography and how these are applied to the 3D BIM as an as-built. Why does this research matter? There are many research papers looking at the terrestrial aspect of collecting photogrammetry and laser scanning data, but only a handful of data exist for looking towards the UAV as a means to collect as-built data.

Hypothesis: Regardless that the UAV is just another tool in the shed, the UAV can provide a benefit to the construction industry by utilizing the technology associated with data collection.

Outline Order of Information: The thesis will contain information regarding the research conducted on photogrammetry, laser scanning, and thermographic scanning. The research will take an in-depth look into what the current status is regarding what industry is doing with this technology, and how the technology developed into what it is today. The research will include a basic knowledge of how the technologies work on a terrestrial level, and how they have been modified to include flying with UAVs. Interviews will be incorporated in the research in order to confirm or deny, the realities present in the current literature. An analysis of the findings conducted in the interviews will take place and then further discussion with future research will be recommended in the conclusion.

1.4 METHODOLOGY

This study is to determine the technologies that are utilized to further enhance the 3D BIM in an as-built manner. The technologies existing are the uses of photogrammetry, laser scanning, and thermography. In the previous few years, the exponential increase in studying and improvements that have taken place are part of this research. The subjects that have accommodated the interview process have been taken from industry professionals with construction experience and collegiate professors who have extensive research within these categories. The study was done in this manner in order to better grasp at where the current status is, not only in the private industry but in the academic sense as well. The interviews were an important part of discovery and further insight as some of the technologies have surpassed the dates of the latest published research papers.

Each interviewee was selected due to their standings within the community of either researchers (having written many academia driven papers in regards to this topic), or people in the private industry that have many years experience with backgrounds in engineering and piloting UAVs.

Lastly, the interviews were typically not formal, in that they were a discussion, with focused questions. Some of the questions led to further discussion in one area and the remaining areas were not touched upon. Time was a factor for most interviews due to busy schedules, and typically lasted about 40 minutes.

CHAPTER 2

LITERATURE REVIEW

1.0 UAV DATA COLLECTION METHODS

In order to understand the data collection process that has lead to utilizing UAVs on construction projects, it is important to acknowledge what this technology is and where it came from. The methods described in this section will be relating to the laser scanner, photogrammetry, and thermographic scan. This discussion will not only include what the technologies are doing in and of themselves but how they are being combined to provide an even further accurate portrayal of data that is collected on a construction jobsite. Lastly, this research will look at the UAVs themselves and discuss the technology that drives them.

1.1 PHOTOGRAMMETRY

UAVs are not just another tool in the chest in the acquisition and processing of photogrammetric data on construction sites. A picture speaks a thousand words. Nothing is truer than a picture, or pictures, from an as-built work in progress on a construction jobsite. There are many ways in which to document and keep track of ongoing work on a jobsite through the use of photographs. One example is the use of jobsite photographs, taken by subcontractors, field engineers, or any party that is interested in jobsite progress. Without the use of UAVs, the photographs can be taken, organized, and processed through the computer to create the 3D BIM. This was demonstrated by Bae et al. (2013) as a means for real time photo documentation by taking single images from a smartphone, or tablet, and directly loading them into the server which processed the image into a 3D point cloud. This research in taking unordered photographs and processing them through a computer program stemmed from the study of Golparvar-Fard et al.(2011). The intent is to be able to take digital photos, taken throughout the job site in no specific order, and be able to process them into a working 3D model. The true value of comparing the as-planned to the as-built models is the creation of a 4D (3D model plus time) model. The benefits being increased communication and planning (Golparvar-Fard et al., 2011).

Taken from the air, a photograph can present a totally different point of view than would have been seen otherwise whether it be from an MUAV, fixed wing, quadcopter, octocopter, or helicopter. In the construction industry, taking photographs and processing them to create a 3D BIM is being studied for its usefulness in as-built documentation (Nielsen and Holley, 2015; Lin et al., 2015). Research conducted by Vacanas et al.(2015) explores how photographs taken by a UAV can produce more "accurate, efficient, and possibly automated results" when used jointly with BIM. The research conducted by Braun et al. (2014) demonstrated that the use of photogrammetry on a five story building has the capabilities of accurately representing as-built conditions up to a 2cm distance on the 3D model plane.

There are more uses being studied that can be directly crossed over to the construction industry as well. Utilizing UAVs to monitor and collect data for huge earth moving operations are being researched for volumetric calculations (Kima et al., 2015; Seibert and Teizer, 2014). The documentation of cultural heritage sites is another method in which archaeologists, and architects, are utilizing UAVs to capture data and create 3D computer images (Achille et al., 2015; Puschel et al., 2008). UAVs with four cameras have also been researched as a means to eliminate discrepancies, such as geometric information being lost in the data (Feifei et al., 2012). There has also been researching conducted by Jizhou et al. (2004) demonstrating the results of a fixed wing, single image capture to create a 3D image of city buildings. Inspections of buildings and structures are another aspect in which photographic data has been collected and analyzed.

This process allows for real-time information to be viewed by professionals and keeps workers out of harm's way that may otherwise put them in a spot they are unable to reach or the cost of putting them in that location is costly (Yamazaki et al., 2015; Achille et al., 2015). The basic principles associated with this type of data collection, taking photos for the advancement of a construction project, has been with us for many years (Moffitt, 1959). From manual style film cameras, to the advancement of digital cameras, the increase in photogrammetric capabilities has grown exponentially. Starting with the application of new computer programs, the ability to digitize photos with the help of Geographic Information Systems (GIS), and Global Positioning System (GPS) has brought the technology to the forefront of the 21st Century (McGlone et al., 1980). With the advent of 3D BIM, the capabilities to visualize and input the photos into a computer program and create a 3D structure has, more or less, revolutionized the construction industry.

Are there limitations to utilizing UAVs for photogrammetry on a job site? Some difficulties that can limit the collection of data are the high altitude, windy conditions that can cause excess use of gasoline on the turbine engines (Remondino et al., 2011; Nex and Remondino, 2014). Huge blocks of images that require extensive time in the data processing method is another limiting factor (Fassi et al., 2013). It was also demonstrated in the fixed wing experiment of Laliberte et al. (2010), that not only were the costs associated with starting up the program (training, maintenance, personnel, etc.) a limiting factor to collecting data, but also the FAA legalities in obtaining the Certificate of Authorization (COA).

What are the uses for photogrammetry with a UAV in the construction industry?

How can photogrammetry benefit the construction industry?

What are the limitations to utilizing photogrammetry on a construction project?

These are the questions proposed to be answered in the following section.

1.2 LASER SCANNING

How does a UAV providing laser scanning help the construction industry? What are the limitations to using laser scanning on a project? This discussion shall look at what industries, other than construction are doing to maximize the potential usefulness of the UAV and LiDAR scanning. This section will also talk about the technology behind the laser scan and LiDAR, and the effectiveness related to UAV scans in the construction industry during the ongoing project process.

There is a crossover of technologies from industries that have not implemented their applications towards the construction industry.

Terrestrial laser scanning is the choice option for GCs building ground-up projects in the current state of the industry. However, the technology provided by a UAV on a construction project utilizing the latest in LiDAR laser technology can produce results that are a great alternative to any terrestrial version. This begs the question about how the UAV, scanning with laser, can improve upon an already solid method of terrestrial data collection?

1.3 THERMOGRAPHIC

The last bit of technology that will be looked at is the use of thermographic scanning with the purpose of creating a 3D BIM image. Thermographic scans have long been associated with building inspections and commissioning of newly constructed buildings. They can detect energy heat loss, air leaks, and basically provide analysis of how energy is consumed in a building. There are many similarities between the collection and data processing of photos and the process of thermal image data collection. In the study documented by Gonzalez-Jorge et al. (2012) the research of a thermographic scan included processing collected data into a point cloud which allowed the end result to become a 3D model. The fusion of thermographic photos to create a working 3D model with as little data processing as possible was documented by Laguela et al. (2012). The research entailed taking only two photos, two measurements, and processing through a computer algorithm which produced an accurate image. The application of laser scanning, photogrammetry, and thermographic scans for a renovation of a building brings all three processed together to provide an in-depth depiction of the current status of the buildings state (Laguela et al., 2012). As the as-is BIM has been produced with laser scans and photos, the remaining touch is to bring in the thermographic scans and apply them to the BIM. Laguela et al. (2012) documents how the components of bringing in the thermographic BIM images to the table allow the end user to see where there are possible insulation deficiencies in a wall. Introducing the UAV into the thermographic research, Previtali et al. (2013), documents the use of utilizing the UAV to provide the expedient thermal images from a survey of a building exterior and contributing to the overall data collection through BIM. Generating aerial thermal images with a UAV is a powerful contribution to the as-built 3D BIM. Surveying of rooftops now has the ability to detect the geometry of a plane surface, with accuracy, and reconstruct it BIM with knowledge of where there is heat loss happening (Laguela et al. 2014).

2.1 ACCURACY WITH UAV

How accurate can photogrammetry acquisition convey to the end user the visualized models? How accurately does the model need to be to define the 3D model with precision? This section will look at what research has taken place in a collection of photogrammetric data, with regards to accuracy. Terms will be discussed that pertain to the data collection of photographs, and a comparison between laser scanning and photogrammetry will be discussed in order to determine just how accurate these methods of data collection are.

2.2 GROUND CONTROL POINTS

One aspect of obtaining accurate photogrammetric results in a computer model is through Ground Control Points (GCPs). These GCPs can be gained either manually, by using a total station or Differential Global Positioning System (DGPS), or by systematically distributing them throughout the area being surveyed (Eisenbeiß, 2009). In the study by Puschel et al. (2008) the control points were measured with the Global Navigation Satellite System (GNSS) from the network in Switzerland, and worked in conjunction with the Geographic Interface System (GIS), that when combining terrestrial and UAV photographs, they were able to produce accurate and reliable results, within 2.5cm from their photographic survey. These control points are related to the orientation of the structure being surveyed during post processing (Remondino, 2011). Without GCPs in the initial data collection series, the quality and accuracy of the results will improve once they are added into the post processing method (Costa et al., 2016). Another thought is that the closer a photo is taken to the intended target, the better the accuracy is. Daftry et al. (2015) demonstrated that the contrary is true. By taking photos of GCPs at consecutive distances (4, 6, and 10m), the research showed a quantifiable accuracy with their GCPs. The farthest distance had the least amount of mean error (in millimeters) possibly due to the scene completeness the further away the object is.

2.3 TIE POINTS

What are tie points, and how are they related to the accuracy of a survey conducted by a UAV? Tie points are another method that is used to capture and reference the positioning of photos within a computer model during post processing (Remondino et al., 2005). The automatic orientation of tie points can be so overwhelming during the initial photographic capture that the computer may not be able to handle the amount of data, thereby crashing the system. Tie point reduction becomes necessary which decreases the points within a photo but does not damage the accuracy of the end result (Barazzetti et al., 2010).

2.4 STRUCTURE FROM MOTION

In another case, Barazzetti et al. (2010), focused on maintaining accuracy with transferring up-close photographs of small scale statues, and bas-reliefs, through a series of complex algorithms. The study used Structure from Motion (SfM) in a series of photographs that all correspond to a specific object. The photographs are overlaid and, through a computer, an algorithm is displayed with corresponding dimensions to the existing planned BIM model (Golparvar-Fard et al., 2011). Due to the overlapping of photos, the corresponding 3D point clouds are dense and the subsequent images can be processed for use in the as-built project documents. The use of SfM has been utilized in construction projects as documented by Golparvar-Fard et al. (2011), in which the research worked to produce a working as-built of a construction project using cluttered and unordered photos. The point of the SfM is not about how long the computation period takes, but about how accurate the final BIM model is (Wefelscheid et al., 2011). As the technology continues to improve, the further construction workers are able to manipulate photographs through algorithms designed for SfM. Photographs taken with a smartphone or tablet are able to be processed through the SfM method, linked to the as-built design through a server, and brought back to the engineer in the field (Bae et al., 2014).

Free software exists that contain the SfM algorithms vital to the geometric data contained within the photos (Siebert et al., 2014).

2.5 POINT CLOUD DENSITY

The point cloud is the most basic building block of any UAV using photogrammetry. The methods of collection can be different such as Eisenbeiss (2009) using aerial laser scan data and terrestrial images, combined, to produce a very high density point cloud. Terrestrial laser scanner and UAV born imagery can also be compared to point cloud density (Fritz et al., 2013). Point clouds can also be captured with both aerial and terrestrial photogrammetry (Puschel et al., 2008). Obtaining a point cloud from by UAV is an accurate way to obtain a very dense point cloud but can result in a high amount of images with a long computational period (Neitzel and Klonowski, 2011). The terrestrial laser scanner depends on a known set of points that can be set up semi-autonomously in a global coordinate system (Tang, et al. 2010). Targets are set up on the construction site which provides the precision needed for the scanner. The targets can either be typically square with a checkerboard pattern (for ease of identification), or a round sphere. There needs to be at least three set up at different heights and distances for an exact scan to take place.

2.6 LiDAR SCANNING ACCURACY

When terrestrial laser scanning is applied it has the characteristics of a survey with a tripod and the scanner on top, there are also multiple targets that allow for measurements of up to millimeters accuracy (Tang et al. 2010). It is through this process of terrestrial laser scanning that we are able to digitally record the as-is building conditions accurately, and in a specific point in time. The laser scan creates large data sets, or point clouds, that contain a certain density to them. The density of that point cloud tells the story of how detailed the scan is, and if it meets the project requirements for point density (Anil et al. 2011). Essentially, the larger the point cloud, the greater the accuracy the scan is. In another study Boehler and Marbs (2003), studied the accuracy of many different laser scanners going through a whole variety of tests that answered the question as to the major advantages and disadvantages for each type of scanner. The tests relating to the study were about the angular accuracy, range accuracy, resolution, edge effects, surface reflectivity, and environmental considerations.

2.7 COMPARING LASER SCANNING AND PHOTOGRAMMETRY

In other research, there is a move to combine the two methods in order to produce accurate and visually descriptive 3D models. From a terrestrial standpoint, research conducted by, Golparvar-Fard et al. (2011) and Brilakis et al. (2010), compared the accuracy of laser scans and photographs taken of a masonry block and a concrete column. The results indicated that the time, cost, automation, computer storage space, training, and additional project management task for taking photographs worked in its favor. Whereas, the laser scanning was benefiting the accuracy and point density of the objects scanned. The combination of both methods to determine the accuracy of each method on existing buildings and cultural heritage sites was documented by Fassi et al. (2013). At one cultural heritage site, the max deviation between the photographs and laser scan was lower than 1.5cm. At a façade, the max deviation between the two methods was approximately 3-5mm, which can suggest that between the laser scanner and photographs, the level of detail is almost indistinguishable.

2.8 CROSSOVER INDUSTRIES

There seems to be a crossover of industries that are utilizing laser scanning for large portions of earthwork projects. Mining and the geology industry are making use of UAVs for volumetric data in their operations. They are able to gain information about volumes of quarries and mines with dense point clouds that would otherwise contain many occlusions with a traditional terrestrial survey (F. Nex, 2014).

Forestry is another industry that has made use of laser scanning capabilities with a UAV. The forest canopy is of great concern because of the need to understand growth rates, disease and how that affects the forest, and potential for forest fires. The use of LiDAR for determining the large footprint of a forest and especially important is the height at which the UAV flight takes place (Wallace et al. 2012). The height will determine the quantity of the point cloud density. The higher the UAV flight, the less point density will be accumulated and consequently the greater room for error. Another method studied to measure the forest density was to combine the use of a UAV in the photogrammetry sect and take a terrestrial laser scan survey (Fritz et al. 2013). The combination allowed for the tree canopy to be captured with images and computed into a point density data set along with the laser scan that collected what the undergrowth density was. It is this combination of data collecting that brings the full power of the as-is process together. The two point clouds complement each other and produce a stunning result of the entire canopy and undergrowth.

Archaeology and historical heritage site restoration projects are contributing to the use of UAV laser scanning as a means for digital reconstruction.

2.9 UAV

There are many UAV manufacturer companies, and they typically have products that are specific for the action being performed. DJI is one of the most popular manufacturers of UAVs (Figure 2.1). They produce professional, industrial, and consumer (hobbyist) type UAVs (www.dji.com). On the professional side, the Inspire

Figure2.1 DJI Phantom

Pro/Raw focuses on aerial imaging. Whereas, on the industrial side, the Spreading Wings S1000+ (Figure 2.2), or the MG-1 is the latest technology as an octocopter. These UAVs are set up for the experienced pilot who knows

Figur 2.2 Spreading Wings S1000+

how to utilize the advanced flight controller, has the gimbal for a steady camera, and the DSLR camera that can take the 4k images.

Another UAV manufacturing company, Parrot, produces quadcopters, fixed- wing, mini drones, and an assortment of unrelated products. Their most popular UAV is the Parrot Bebop (Figure 2.3) due to the ease of photography it takes; this UAV is not intended for heavy industrial use. GoPro, the action sports camera, has launched into the UAV manufacturing business as well (Figure 2.4). Releasing their version of quadcopters, Karma, is equipped for the GoPro camera Hero4 and 5 (www.gopro.com).

Figure 2.3 Parrot Bebop

Figure Error! No text of specified style in document..4 GoPro Karma

The parts and accessories for the UAVs are part of the experience as well. There will be a need for additional batteries for an extended flight time, instead of the typical 25 minutes. Propellers, motors that provide additional lift, datalink stations, gimbals, controllers, and first person virtual reality (FP), are all different methods that are available to customize and achieve the exact mix of progressive technology for what the job entails.

This research investigated the use of UAVs and their data acquisition methods which include photogrammetry, LiDAR, and thermography in order to provide detailed and accurate 3D images. Within the construction industry, there is a struggle to grasp onto new technologies as they arise. It is because the UAV is an emerging market that the construction industry needs to recognize the power of information that it can bring to the project level, and begin to integrate it alongside the traditional terrestrial methods of data acquisition. The capabilities provided by the UAV are endlessly related to enhancing a culture of safety, quality control, inspections, scheduling, and providing 3D BIM as-built conditions in real time. The construction industry is at a point when, for the first time, real production can be realized by making use of these data acquisition methods. The computer programs available, including BIM, and 4D BIM software can then enhance the data by tracking productivity through scheduling methods.

CHAPTER 3

METHODOLOGY

The primary objective in conducting this research is to present to the reader how UAVs are benefiting the construction industry through data collection. Researching data acquisition methods via literary, peer-reviewed papers included the methods of photogrammetry, LiDAR scanning, and thermography. Not only were the methods of UAV data acquisition studied via literature, but by conducting multiple interviews. The interviews were performed with subjects ranging from professors, to Virtual Design Engineers (VDC), to pilots of UAVs that work in the field. The tools utilized in collecting this data were by way of a web conferencing system, email, and in person. The summaries of the interviews will be within this section and will provide a brief overview of any critical findings.

Why was this done using this approach?

The anticipated results are that the use of the UAV on a construction site does indeed benefit the GC. The expectation is that the GC will be able to use this technology, such as the photogrammetry method, LiDAR scanning, and thermography to create as-built 3D BIM images and use those images to provide the owner with information that would not have otherwise been available.

For this research, we explored the emerging uses of UAV technology in the industry. There are projects being implemented by private industry in the Seattle area that are collecting data with UAVs, however, to access a company willing to share their trade secrets is difficult without truly knowing somebody within that body. Interviewing people that have written and published works relating to this technology is forefront because it is an easier course to take than say, conducting a time intensive study on a two-year high rise building. Most subjects were easy to start the dialogue with, but the scheduling of the interviews was not the easiest to accomplish. This method of data collection was used to accomplish a dialogue with industry professionals that are, right now, in the forefront of the UAV data collection industry.

Five interviews were conducted with each person having their own expertise in the field. The response ratio for interviews was ten companies/individuals were contacted, and five responded for the interview. The following shall determine why each participant was chosen for their knowledge and how it can be applied to the overall thesis.

Professor 1:

Professor 1 was chosen because of his extensive knowledge base of utilizing photogrammetry on construction sites. He has co-written chapters in books, written journal articles, conference proceedings, and lectures. Topics range from the topic of robotics, UAVs, data acquisition, and 4D BIM and how they apply to large scale construction projects. He has developed his own photogrammetric software and continued to improve the solutions for the past ten years. His experience goes back about four years ago with UAV solutions on construction projects.

The interview consisted of a series of semi- structured questions with topics ranging from photogrammetry and LiDAR software to more detailed information in regards to what happens with the data once it is collected and processed. Other subjects that were discussed correlated to current problems with the data acquisition and what future solutions are being researched and developed. This information could be used as a means to reiterate what the current state of research is doing in the construction industry, as well as compare to what other researchers are doing in the realm of photogrammetry and LiDAR.

Professor 1 discussed the use of photogrammetry and UAVs on a construction site and likened the image capturing software as a commodity resource. There are many companies that are offering solutions and the cost of said solutions are becoming less and less. There are many ways to capture images of a construction site and a UAV is just one method. Taking images with a smartphone, still cameras to create a timelapse, and developing autonomous ground robots are just a few of the ways that photographs of construction sites can be taken to be processed into a 3D image point cloud.

4D BIM was another aspect that was discussed in detail in conjunction with photogrammetry. This tool has been available for the past twenty years, but only recently, in the past five to six years has it been applied. Typically, it is used as a means to check the quality of a schedule, but is an "underexplored" method. This is mainly due to working with the schedule on a weekly basis and many companies just don't have the capabilities to staff that type of position, especially if it is a two year or shorter duration project. A good Superintendant can walk through a two year project, however, on a larger and more complex project, 4D becomes more desirable. What this becomes is a mechanism that automatically updates the 4D BIM image in such a way that after a weekly update meeting, a Subcontractor can look on their smartphone, pull up that 4D BIM and visually see what task they have committed to and where the location is.

During the interview, there were a few unexpected thoughts that came to be presented. One was that the use of LiDAR scanning can be overused on a project, in that, the data is not as "easily scalable as images and videos are." The purpose, in its most basic form, is the "visual asset management platform," and this is regardless if it is a photographic image or LiDAR. Another thought was that the point cloud density is not as important as previously thought. Being the backbone of the image the point cloud provides the abilities to measure volumes, areas, lengths, and angles in an image. If the density is not as complete, the option is to go back to original photograph, but if it is complete, then there are many options for measurement. Lastly, the control point markers are not necessarily required to generate the point cloud. If they are available, then the point cloud can be an actual representation of the as-built process and can be used for QA/QC documentation. If they are not available, then the point cloud will have to be manually brought over to the BIM image and brought into alignment.

This interview was conducted via a web conferencing system called, gotomeeting.com, which makes it possible to log into the system through a laptop, or call in. This made it imperative to listen and steer the interview in a direction that made sense and not just read off questions that didn't make sense in the context of the discussion, but added value to the topic. Timing of the interview was an issue due to the different time zones.

To conclude this interview is that photogrammetry is a well established method of data acquisition on construction projects. It's a matter of what we do with that data and how it is processed that becomes the issue. If it is being used as a visual asset tool, then the point cloud density and control markers are two things to be mindful about. Planning, and scheduling are other things to be thinking about when processing images. When planning a flight, ensure that there is no clutter, or try to minimize any occlusions that may occur. If scheduling is a complex issue, then perhaps 4D is a method that needs to be discussed to be implemented into the BIM. The information shared throughout this interview shall be compared to the current literature to determine if there are any inconsistencies throughout.

Professor 2:

Professor 2 was selected because of his expertise in utilizing UAVs for thermographic data acquisition of buildings. He has been conducted extensive research, at an academic level, for six years in the photogrammetric processing of thermographic data for building inspections, using LiDAR for BIM, and analyzing geographic information with UAV systems.

This interview took place via an email questionnaire due to the difficulty in scheduling an online web conference, as well as multiple time zones to deal with too. Because of utilizing this email questionnaire, the answers are sparse and straight forward. However, the information to draw on does have value in regards to the timeliness of flights, data acquisition, and economic benefits that UAVs can provide a construction project.

In the questionnaire he submits answers concerning his use of UAVs are the DJI Phantom, Mikrocopter, and multicopter which are then used for photogrammetry and surveying purposes.

When taking photographic images they are mainly used in autonomous mode for surveying prior to construction and in manual mode for inspections during construction activities. When surveying forestry applications, he uses LiDAR scanning. When answering for the point cloud density, he relates that the point cloud density is not that critical, however, they do provide reliable geometric capabilities for survey drawings. The cost of the entire operation can be decreased when utilizing a UAV because there is no need for a manned operation, and also the risk is decreased to the operators of manned flights of high structures.

A couple interesting points concerning the answers to the questionnaire are that the point cloud density is not as critical as previously thought, and the different methods of data acquisition can be combined. This is assuming that data acquired from thermography, LiDAR, and photographic images can be combined to present a powerful BIM.

The circumstances about this interview are the location, scheduling and time zones. The interviewee was willing to participate on a web conference tool, but it just was not possible to connect because of different schedules. The interview questionnaire was emailed in hopes of spurring a result, which it did, but very minimally as one could imagine. Despite the short answers, there is a knowledge base that it is coming from and can be interpreted from there.

The takeaway of this interview will be that the point cloud of any data acquisition is not as critical as previously thought, the different methods of collecting data can be combined, and the economic benefits to utilizing UAVs are decreased cost and risk.

Professor 3:

Professor 3 was chosen for interview because of her knowledge base of thermographic data analysis with UAVs. Her experience has been in the academic research field for seven years. She has co-written, and written, upwards of fifty articles which includes chapters in books, and conference papers. This information provided can be utilized to compare and contrast what is currently being researched.

The topics that were discussed directly relate to the data acquisition of UAVs on construction projects. The interviews topics ranged from what type of products are used for data acquisition, to the software as it applies to creating the 3D BIM, and the intricacies of the different methods of data collection. She discussed about using a Sony NEX 7 camera for the 3D modeling and terrain models, as well as the Hokuyo LiDAR scanner. The camera is well received for its use in 3D modeling, due to its cost and variety of applications. However, with the Hokuyo, it was assumed to be on the low end of available products, but it really depends on the GPS and IMU to provide the 2D scanned results. Accuracy with the LiDAR is still within the vicinity of 2-5cm. As of right now, LiDAR is not reliable, they break down and have issues, but the industry is trying to break the mold and is making a push to change over to LiDAR.

When discussing the software, she uses commercially available programs (AgiSoft Photoscan, Pix4D) for photogrammetric processing, and for LiDAR her colleagues have created a custom software program. The only reputable, commercially available software for LiDAR, is coming from the manufacturers of the scanners themselves. The programs are all improving.

The method of UAV thermographic imaging was discussed, and how the process is similar to photogrammetry. The issue is that the imagery collected by the thermographic camera is terrible because low the pixilation rate. So, the technique to rectify that is to overlay the thermal images on the LiDAR or photographic images thereby obtaining the geometry and texture.

During the interview there were issues that arose, that are worthwhile to note that can perhaps make in impact. There are opportunities to thermal scan rooflines, and access areas that may have seemed impossible before. Utilizing a backpack system that can process information and easily transport is an item that is being developed and researched as a means for UAV accessibility. Lastly, UAV thermal scanning is to be used as a more reliable method of maintaining a built building for energy assessment.

In conclusion, this interview discussed the major methods of data acquisition with a UAV, and looked at the products, software, and intricacies associated with these methods. The takeaway from this interview is that the thermographic method of data collection with a UAV can be worthwhile for energy assessments by processing the information as photogrammetric data and then overlaying the thermal data on the BIM. This interview can be relevant to actual applications of thermal imaging in the field and what the best, most economical use of this type of data acquisition will be.

Company Alpha:

Company Alpha was selected for interview because of the extensive background, 15 years, in structural engineering and virtual design. Utilizing 3D BIM and terrestrial laser scanning as a typical procedure for procuring data on a construction project added to the depth of knowledge of what is typical for engineering to be doing with data acquisition at the project level. The information provided by Co. Alpha can be viewed as a company that is new to utilizing UAVs on construction projects. Although terrestrial laser scanning is being heavily used as a means for acquiring as-built data, the UAV has not been a part of that process. Their experience has been for photographic images once the project has closed out. This interview can provide insight into what an introductory companies views are regarding using the UAV for data acquisition on construction projects.

Most of the experience has been related to utilizing terrestrial laser scanners, so the discussion surrounded the methods, products, and timeliness of data acquisition that way. But, when discussing UAVs the discussion revolved around UAV growth in construction, industry adaptability, and economic benefits. By conducting laser scanning terrestrially, there is a very highly detailed point cloud created, and the limitation is that it can be very time consuming to process all that information. But, what you get is the ability to give an object an identity, such as a main duct, and then with that pixilated image, import into Revit, or similar program, making it possible to draw over those scans. The amount of scans depends on the circumstances of the project. If they are starting a renovation, they will scan at the beginning. If they have multiple concrete pours, they will scan before the pour to document the rebar layout, where the sleeves are located, and general conditions of the site.

The use of UAVs on their construction site was subcontracted out, and a video was taken as a way to show the owner what has been done, as well as use the video for marketing purposes. She definitely believes that in the future the construction industry be working with UAVs, but right now the market is in a “testing out” stage. That is, the industry doesn’t know how to use the technology yet, and as long as it shows improvements, then more and more companies are likely to get on board. Safety is a big issue, and putting an UAV in a situation that otherwise would be a person, can be a big benefit. Co. Alpha is perfect for this study because they have knowledge that UAVs exist, and have had minimal exposure to what they can do on a jobsite. In this case, the UAV was used for taking a video, but during the interview there was an information exchange that led to a light-bulb moment. Something to the effect of not knowing that the UAV could collect photographic images, or take LiDAR and create an accurate 3D BIM. During the interview this became a new way of looking at the industry and the potential for new uses started to spark more interest in the process.

The big takeaway from this interview is that the industry, as a whole, isn’t ready to adapt with this new technology because it is unproven, and the return of investment has not been established as of yet. Otherwise, the future use of this technology seems to be wide open for interpretation. This information can be used as a means to understand where intro level companies are at concerning the use of UAV data acquisition on construction projects.

Company Bravo:

Company Bravo was selected for interview because of their expertise in the field of flying UAVs on construction projects. They also fly UAVs for inspection of bridges, wind turbines, solar fields, and have extensive experience with photogrammetry, LiDAR, and thermography. They work directly with the GC on construction sites, and understand what data the client is looking for and how to achieve said results. This information can be valuable to individuals and researchers alike who are interested in the realities of field work and UAV data acquisition.

During this interview, some of the topics discussed were about the types of UAVs they have used, what type of data acquisition (photographic, LiDAR, etc.) have they used previously, computer software, and how they view the future impacts UAVs will have on construction sites. Co. Bravo utilizes all types of UAVs, but depending on what the clients needs are, they can accommodate. For instance, if there is a lot of ground to cover, heavier payload, and they need longer flight times, the fixed wing UAV will be used to obtain the data. Otherwise, if they are looking at visual inspections, vertical structures, and a more detailed imagery, the multi rotor UAV is how they proceed.

Photogrammetry was discussed as a valuable asset to a construction site that collects data that is unlike any other method that has been used prior. As of right now, the industry is on the cusp of accomplishing survey grade accuracy (3cm), but the typical accuracy is in the 4cm range. This can be the difference between an exterior concrete foundation falling, or not. It is the opinion of Co. Bravo that this is why there is still a struggle of the old way of doing things to today's generation that are more willing to change. Talking about the ground control points, the point was made that the ground survey crew still needs to be conducting their work, and that the UAV survey is a complement to that work. The GCPs need to be in place for a greater accuracy, and if they are not, there needs to be a real-time positioning, GPS, and reference station for a decently accurate survey. Discussing the software associated with photogrammetry, the company utilizes Pix4D and Photoscan. Pix4D just released its BIM platform which has generated excitement throughout, but another aspect is the accuracy to which they will allow. Pix4D will allow the results to be as accurate as possible, whereas the Photoscan software will limit the software accuracy.

LiDAR was also discussed as a means for UAV data acquisition. Co. Bravo utilizes the Riegl scanner, and is able to obtain a very accurate 2cm scan. They mostly use the LiDAR for civil, earthwork type projects, including roadways. One of the many challenges in working with LiDAR is how to obtain a point density that will have the 3D image as an end result. It depends on the Hertz cycle of the scanner and the speed at which the UAV is flown. It is possible adjust the Hz cycle of the scanner and adjust the UAV speed to collect the correct amount of point cloud data. LiDAR is not going to go away anytime soon, and it will only have an increase of attention due to the automotive industry integrating LiDAR into their driverless systems. Another issue regarding LiDAR is the ability to combine the photogrammetry and LiDAR data as a means to compare the data or create a better image with the data. Co. Bravo was surprised when combining the files to find how accurate photogrammetry has become when compared to LiDAR.

Thermography was discussed as a method to create 3D BIM. But, Co. Bravo did not find that creating a thermographic 3D image was beneficial to the journeyman facilities manager. The process is to obtain the thermal 3D BIM is the same as for photogrammetry. The images are pared down and the software creates the geometry. The real interest lies in the use for inspections of structures, such as roofs, building envelopes, wind turbines, and solar panels. The company gets more value from real time inspections of those types of areas.

In the real time use of UAVs for any type of data collection there are limitations and procedures that need to take place prior to any flying can take place. One limitation discussed was the FAA regulations that enforce how the commercial applications of UAVs can take place. Part 107 (See Appendix I) superseded Exemption 333 as a means to speed the licensing process up and allow for more commercial UAV activities to take place. It is still a 90-120 day licensing process, and the Federal Gov't is still tightly regulating where a UAV can fly. An operator needs to obtain a Certificate of Waiver (COW) to fly in areas other than what is regulated. Another limitation is the weather, which comes as no surprise. The UAV can be water proofed, but to a certain degree. Then, once all these limiting issues are completed, the flight itself on a construction site needs to be planned and mandated by the GC in order to provide a culture of safety for all workers. So, talking and planning with the Superintendent and Safety Officer prior to flying are of vital importance, and plus there needs to be communication to ensure they are ready for a scan of work completed, that there isn't material in the way, or any last minute changes.

As for the future of continued UAV use, there are already major corporations that have a drone initiative, and are pushing the envelope forward in that regards. It's an adoption that upper level executives have a keen sense that the UAV can play an integral part of marketing. The newer generation will embrace the technology, however, the underlying argument that is not being discussed is that there isn't as much value with UAVs as the major corporations are leading on. This is another tool in the belt of data acquisition, and as fast as the equipment is being produced, it is already outdated. This makes it difficult for a company to sink any money into their equipment without the fear of having outmoded gear. So, it really just becomes a causality dilemma, and in general a disruptive process as companies grow.

A couple of the major findings through this interview are related to the findings of accuracy through photogrammetry and LiDAR. The other finding is the autonomy of flight for data collection. Accuracy relating to photogrammetry is on the cusp of survey grade accuracy (3cm), but the best accuracy Co. Bravo is finding is in the 4-6cm range. This is also depending on the software being used as well to help obtain the most accurate data as possible. LiDAR, on the other hand, is far more accurate in that they are able to achieve a UAV survey with 2cm accuracy. Discussing the autonomy of flights, Co. Bravo prefers autonomy because humans cannot fly as good as a computer, and the computer knows exactly where it took the photograph and can take into account the overlap. The waypoint file is uploaded into the UAV and the computer takes over from there. The UAV will be manually assisted to the starting point, and a switch is flipped, then the UAV starts its mission.

This was the only in-person interview conducted, and by far the most informative. This is due, in part, to the ability to read expressions and mannerisms during the interview. It's easier to direct the flow of an interview, and more comfortable, which then helps in creating a trust with dialogue. The structure of the interview did have pre-set questions, but the ability to ask really good follow up questions was enhanced because of the face-to-face interview.

Overall, this interview consisted of a solid discussion following all topics relating to UAVs. The interview went over photogrammetry, LiDAR, and thermographic processes and solutions. The discussion entailed the equipment utilized, flight planning on construction sites, and what the future holds technologically and economically for companies within the UAV industry. The information as a whole can be compared and contrasted to the current literature research that is available in order to determine if there are any inconsistencies related to data acquisition.

CHAPTER 4

DATA ANALYSIS

This chapter will examine the results of the data which are presented. The data was collected and processed in response to the question posed in Chapter 1 of this thesis. There were goals that directed the analysis of this data, and they were to build the baseline knowledge of the technology that the UAV can use as a means to collect data. The other goal was to verify how accuracy is accomplished through the use of equipment and technology by clarifying its ability to be used in the field. For the most part, these goals have been obtained. But, because the field of UAV data acquisition is emerging within the construction industry, the literature and investigations were sparse.

1.0 INTERVIEWS

Five interviews were conducted, and those interviews were conducted in a semi-structured survey, phenomenological study, in which the purpose was to understand the experiences of that person in order to infer what their typical experience is (Lester, 1999). The response ratio of the ten individual/companies contacted, only five decided to interview. The interviews were conducted via three methods. One method was through an online conferencing tool that promotes online communication through file sharing with multiple parties and the ability to call in or connect through a computer (GoToMeeting.com). Another method was an emailed questionnaire, and lastly, an in-person interview.

. Figure 4.1 shows the data collection methods, photogrammetry, laser scanning, and thermography and their interdependent nature depend on the accuracy of what the data they are collecting is, and how it performs.

The first step in analyzing the data will be to evaluate the interviewee's answers Then directly compare that data with information provided by literary research. Lastly, the data will be input into graphical visualizations in order to provide a better understanding of UAV data acquisition on construction projects.

1.1 PHOTOGRAMMETRIC ACCURACY

Accuracy is, by far, the most important element in any data survey, whether it be photogrammetric, LiDAR, or thermographic. Within this research, photogrammetry happens to have the most literature written about the use of UAVs and data collection. Table 4.1 shows the relevant literature on the topic of accuracy as it pertains to photogrammetry and it includes the responses from the interviewee's Professor 1 and Company Bravo. The interviews that are not mentioned on this table did not include information in regards to photogrammetric accuracy because of either lack of knowledge, or expertise on the subject. Table 4.1 shows, in detail, how the authors summarily executed their plans to obtain

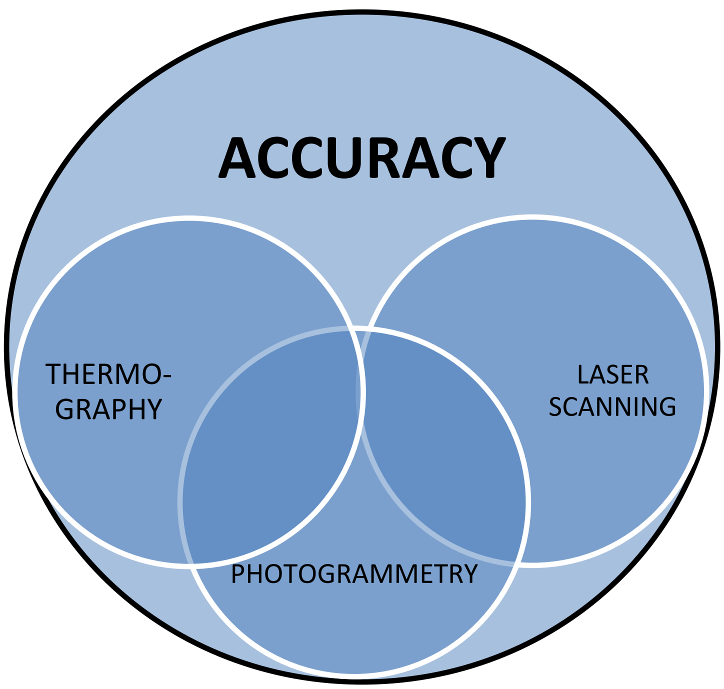

Figure 4.1 Diagram depicting how Accuracy encompasses all methods of data acquisition

accuracy through the use of photogrammetry. In one instance, it was proven that the higher the flying altitude, the lower the accuracy of the data collected (Fritz et al., 2013). In another, the author combined two different methods, photogrammetry, and LiDAR, which improved the accuracy of the data to within 1.5cm (Nielson and Holley, 2014). Another study overlaid the LiDAR and photogrammetric data in order to discover the maximum difference between the two sets were 3cm. This method of data collection and processing is in line with what Professor 1 had discussed. By combining methods it is possible to create a more accurate model than just with one (photogrammetry). Starting with the BIM image and overlaying the photogrammetric images over, allows the algorithm to recognize the geometry before it is captured.

Company Bravo had a different viewpoint, in that the application of purely a photogrammetric pursuit of accurate data will not allow for the LOD required for survey accuracy. Co. Bravo's view is that the technology is very nearly at the point where it can be reliable enough to be used as a sole survey mechanism. But, for that change to happen, the industry as a whole needs to view the UAV as not just a tool in the chest, but as a reliable data acquiring mechanism that can produce highly accurate images. As Co. Bravo stated when asked

Table 4.1 Literature reference and the summary of how accuracy was illustrated in the research with photogrammetry. Summary of Interviews portrayal of accuracy.

LITERATURE	DEFINITION	INTERVIEW
Fritz et al. 2013	Accuracy decreased the higher the altitude is of the UAV	**Professor 1: Increasing accuracy by using BIM prior to the data collection and then align the photogrammetry to the BIM. Algorithm understands the geometry before it is captured.**
Achille et al. 2015	Photogrammetric data was combined with laser to provide an accurate survey. Overlay of the data sets had a maximum difference of 3cm.	**Company Bravo: On the cusp of reaching survey accuracy (under 3cm) with photogrammetry. 4cm is the best they have seen. Higher point density does not necessarily mean better accuracy. The photograph requires (3) points and (3) photos for triangulation.**
Barazzetti et al. 2010	Improves the location of SIFT and SURF components by reintroducing the Least Squares Matching algorithm (LSM).	
Costa and Mendes, 2015	Lack of visual content reduces accuracy, whereas obtaining and adding GCPs can increase accuracy. Higher Point Density has higher accuracy. Multi scale images have better accuracy but longer processing time.	
Eisenbeiss, 2009	Those UAVs with no GPS/INS will have low accuracy; GPS and consumer grade INS will have moderate accuracy; Lastly, DGPS with navigational and tactical grade INS will have the highest accuracy.	
Feifei et al., 2012	4 combined camera depends on 2 items that reduce error: 1. strong stability of the mechanical structure and 2. exposure control circuit. Low altitude aerial photographs.	
Neitzel and Klonowski, 2011	Results from software give different density and completeness. The software used is dependent from the accuracy.	
Remondino et al. 2011	Utilizing several different methods of algorithms called MicMac and PMVS	
Seibert and Teizer, 2014	Measuring an earthwork site, the RTS took fewer points and the UAV took more, and the assumption is that the UAV is more accurate	
Wefelscheid et at. 2011	Bundle adjustments to detect loop closures lowers computational costs. High resolution leads to better accuracy. Forstner interest point detector and SIFT combined to locate keypoints.	
Yamazaki et al, 2015	Both ground and aerial images combined to produce most accurate 3D models	
Nex and Remondino, 2014	DGPS and INS with direct geo-referencing, good accuracy. Low end navigation with SLAM can produce good results too.	
Laliberte et al. 2010	Orthorectified image mosaics with high accuracy. For rangeland monitoring the 83-88% is acceptable.	
Freimuth and Konig, 2015	High resolution photos produce high accuracy, however requires extensive monitoring for 4D BIM	
Nielson and Holley, 2014	Combination of photogrammetric and LiDAR methods to produce exterior window mullions with accuracy to 1.5cm.	
Eschmann et al. 2012	Algorithms, along with GPS and IMUs create high level of accuracy	
Barfuss et al. 2012	Misalignment with RGB imagery in processing is a factor	
Hakala et al. 2013	Higher accuracy with UAV due to flying heights. Combining insitu irradiance with image measurements would provide best results.	

about the continued use of UAVs on construction sites, the response was:

> "We're seeing a generation shift and managers construction managers superintendents there very welcoming to technology. Someone who's been doing project management for 40 years, they have their systems and they don't want to change their systems."

1.2 PHOTOGRAMMETRY AND 3D BIM

Analysis of the literature provided insight as to the purpose of why this data was being acquired (see Table 4.2). Table 4.2 summarizes what the literature is doing to accomplish the creating of a 3D BIM image. The interviews are summarized in order to best understand what the actual field is doing to procure the 3D images as a final product. Regardless of the industry being provided with the data for their modeling, the power of the visualized model is what each industry is striving towards. It doesn't matter if the UAV is capturing data to calculate volumes in an earthworks project, or the data capture of buildings succumbed to natural disasters (Seibert and Tiezer, 2014; Yamazaki et al., 2015). The purpose is the complete capture of the data point clouds and their processing into the model "for detailed information and quick response times" (Eisenbeiss, 2009). As Professor 1 states that the "3D point cloud is the backbone of the image [and] gives you the capabilities to measure the image." The image is what people want to see and interact with, and it's the point cloud that gives the user the geometry behind the photograph. As it was stated in the previous section, the accuracy of the images is not in the survey accurate realm as of yet. But, the measurements of images can, and is being, conducted, and should be encouraged. But, there must be a caveat concerning the nature of said accuracy due to their limitations.

In analyzing the data obtained by literature and interviews it became apparent that the only difference between conducting a cultural heritage site survey, inspections, terrain modeling, and construction site surveys are the recurrence of the flight surveys.

Table 4.2 Literature reference and the summary of how 3D BIM was illustrated in the research by photogrammetry. Summary of Interviews portrayal of 3D BIM.

LITERATURE	DEFINITION	INTERVIEW
Achille et al. 2015	Cultural Heritage Documentation	**Professor 1: 3D point cloud is backbone of the image that gives you the capabilities to measure the image. Bring point cloud into alignment with BIM**
Barazzetti et al. 2010	Create 3D images in an automatic way from objects with sets of unoriented and markerless terrestrial images	**Company Bravo: Fly week after week and develop a working timeline in a 3D model of your construction project.**
Costa and Mendes, 2015	3D mapping of construction sites and terrain to develop processes	
Eisenbeiss, 2009	Application of 3D images from UAV for detailed information and quick response times.	
Feifei et al. 2012	4 combined cameras overlapping for rapid 3D modeling	
Wang et al. 2004	3D model from single image.	
Neitzel and Klonowski, 2011	georeferenced 3D point cloud utilizing different software	
Remondino et al. 2011	Develop 3D models for contouring, DSM/DTM	
Seibert and Teizer, 2014	Earthwork site 3D modelling for volumetric data computations	
Wefelscheid et at. 2011	Development of a 3D building with a new method called Variance Descriptor Analysis (VDA)to detect loop closures	
Yamazaki et al, 2015	3D images of buildings damaged in natural disasters to show the detailed damage.	
Nex and Remondino, 2014	3D mapping of terrain	
Wen and Kang, 2014	3D building model into scene and generate Augmented Reality view based on that model	
Kima et al. 2015	Earthwork 3D model	
Freimuth and Konig, 2015	Semi-autonomous UAV to create 3D BIM	
Nielson and Holley, 2014	Inspected high rise structure with photographs overlayed onto the BIM	
Eschmann et al. 2012	3D model created to inspect concrete walls with automatic detections of cracks, spalls	
Gillins et al. 2016	3D point clouds for inspections of bridges	
Hakala et al. 2013	Fabry-Perot interferometer to collect spectal imaging for poor conditions	

Company Bravo conducts weekly flights on construction projects in order to obtain clear historical documentation, in a timeline manner, that allows the user to visually see the progress made in a 3D BIM. Professor 1 discussed that the recurrence of surveys really just depends on the context of the construction project. It could be once a week or every day. The point Professor 1 was making is how do we limit the additional tasks added to the Project Managers (PM) daily activities without creating such a burden? The liability and cost could be outsourced to a Subcontractor, thereby eliminating the task from the PM activity. There are multiple companies available that can accomplish the data acquisition and processing, such as DroneDeploy or SkyCatch websites.

1.3 PHOTOGRAMMETRY AND INDUSTRY

There has been a surge of industries that are catching onto the use of UAVs as a prosperous business model. The analysis conducted of the literature and interviews is

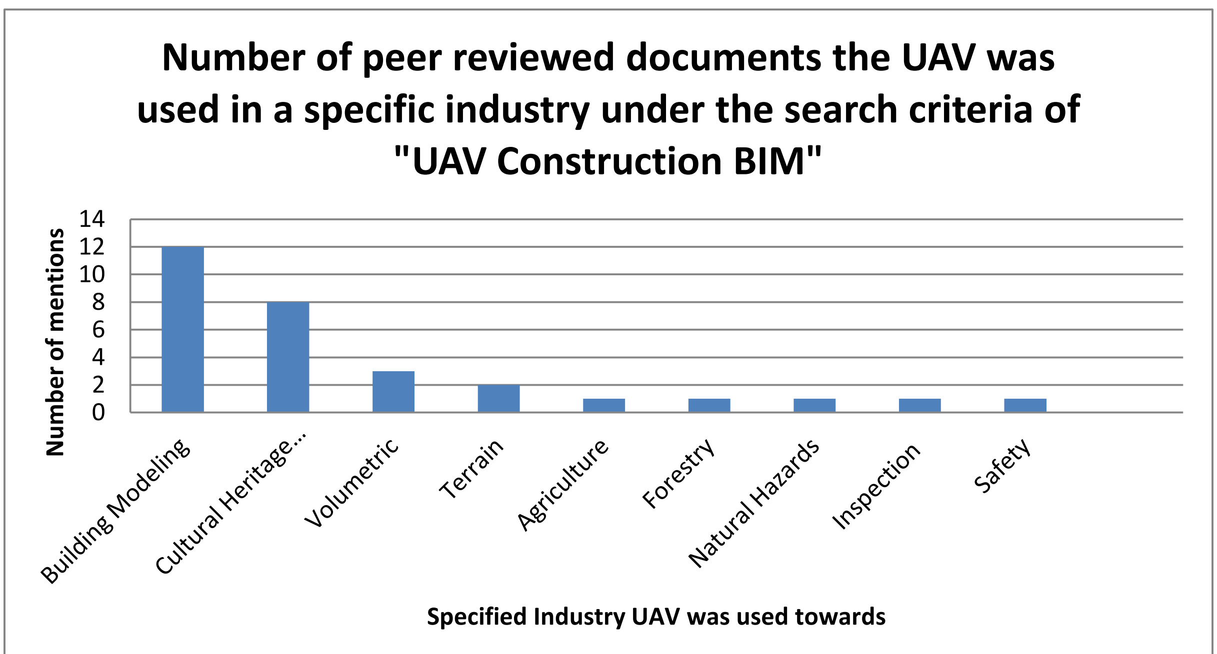

Figure 4.1 Industry use of UAVs

summarized in Figure 4.1. The data comes from literature that was researched under the context of the Google Scholar search engine: "UAV construction BIM." Of course, for example, there are many more papers written about safety with UAVs in the construction industry, but the limitation of "BIM" resulted in a lower hit ratio. This shows where the core of the industry and current research is taking place under those specific search terms.

Cultural Heritage Documentation is being studied and researched by parties interested in documenting areas of historical significance, such as Pava, in Sienna, Italy (Eisenbeiss, 2009). Or, documenting sculptures in Honduras and Sanctuaries in Vietnam (Barazzetti et al., 2010). The use of photogrammetry to digitally record historical sites is a practice that has improved greatly within the short amount of time. As the equipment and software solutions improve, the surveying accuracy also improves at more and more complex areas, as shown in the application at the Neptune Temple in Paestum, Italy (Nex and Remondino, 2014).

Building modeling is another area in the analysis of literature that was noted. This area of study includes buildings that have been destroyed (Yamazaki et al., 2015), buildings that are being built (Costa and Mendes, 2015), buildings that require inspections for concrete defects (Eschmann et al., 2012), and experiments conducted with different camera arrays (Wang et al., 2004; Feifei et al., 2012). It is within these areas, Cultural Heritage and Building Modeling, that the construction industry can gain the most information from because the surveys are related to buildings, structures, and statues that have been built and require 3D imaging for documentation purposes.

There are many other industries related to this analysis of literature. Under the category of Volume is the relationship of earthwork sites, mining, and anything related to excavation. These surveys are conducted on roadway projects (Seibert and Teizer, 2014;

Barfuss et al., 2012), landfill volumes (Neitzel and Klonowski, 2011), and mining projects (Eisenbeiss, 2009). This data from the literature can direct large scale construction projects to obtain quantitative information for volumes of earthwork. The remaining industries such as forestry and agriculture all have their own takeaways which can be utilized by the construction industry. For instance, if there is a need to build on a green field and a tree count is required, what better way to obtain data than by UAV in lieu of walking through the area and manually counting each tree?

1.4 PHOTOGRAMMETRY AND CAMERAS

This analysis contains information regarding the type of camera the literature used as well as the interviewees. The literature was researched on Google Scholar under the

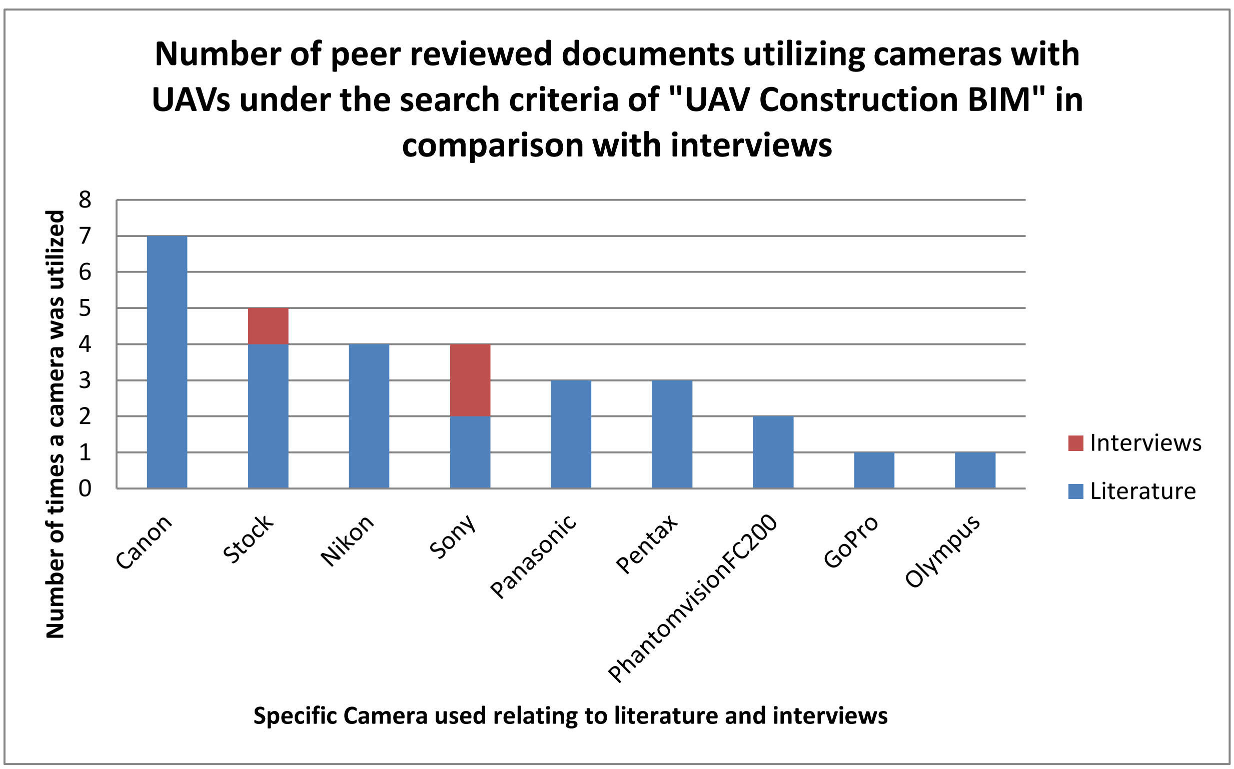

Figure 4.2 Cameras used by UAVs for data acquisition

criteria of "UAV construction BIM." This limitation of search criteria brought many papers utilizing photogrammetry for BIM purposes, and the types of equipment utilized for that objective. Looking at Figure 4.2 the research shows that as far as high-end cameras being used for data collection, they aren't. A basic Canon camera that delivers high- resolution, quality photos can set you back about $500 USD (on the low end). The cameras need to be DSLR as they provide high- quality resolution and a response speed of about 4 frames per second (fps). The UAVs that provide stock cameras, such as the DJI Phantom are also widely used, but they are more widely used for the inspection, and safety side of the construction industry (Gheisari et al., 2014; Irizarry and Costa, 2016; Gillins et al., 2016). The camera that Company Bravo uses is a Sony 6000 and has a CMOS sensor which is proven to be one of the best survey cameras on the market. One of the reasons Company Bravo does not go out and invest in the most expensive equipment is because in a few months time, the equipment will be outdated, and they do not want to continually purchase expensive equipment. In the world of cameras, it pays to know a good product and do the due diligence to understand what you are getting. It is not always the case that the most expensive item will give you better results.

1.5 PHOTOGRAMMETRY AND SOFTWARE

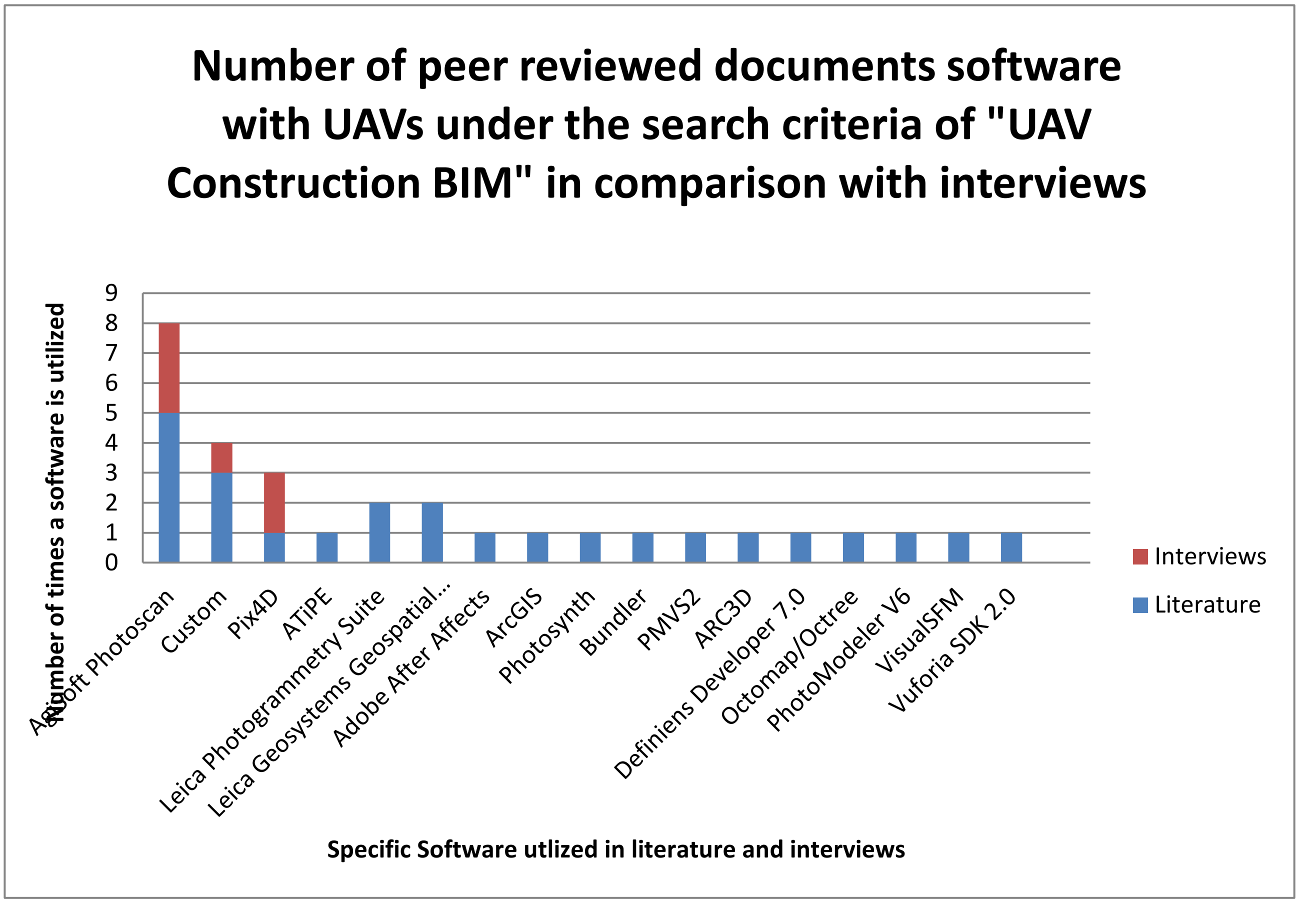

Figure 4.3 Software used to process photogrammetric data acquired by UAV

This analysis combines the literature and interviews conducted. All, but one, of the interviewees, were willing to discuss the software that is used to process photogrammetric data. The use of the software is as varied and all over the place as any emerging market would be. In this category of analysis, the commercially available software is truly dependent on the cost associated with the program. In Figure 4.3 the most used software is the AgiSoft Photoscan, and that was found not only from the literature but by the interviewees. Through a Google Scholar search, the term “UAV construction BIM” was used to find the relevant literature that applied to this research. Closely following the commercial product is the custom built software, then Pix4D after that. Leica offers software utilized for roadways called Leica Geosystem, which is made for contouring and volume calculations (Barfuss et al., 2012). Leica Photogrammetry Suite was also noted to be used for building modeling and historical sites (Feifei et al., 2012; Eisenbeiss, 2009). The remaining list of software packages is what's happening with this emerging technology. As the commercial software develops and becomes more and more confident with reliability towards accuracy, there will be a shift to those software developers that are leading the market in that area.

Looking at the data acquired through literature reveals that the software provided by AgiSoft Photoscan, or Photoscan, is chosen by those conducting cultural heritage type documentations (Achille et al., 2015; Nex and Remondino, 2014; Seibert and Teizer, 2014, Yamazaki et al., 2015). Other literature compared how the software of Photoscan did with their case study (Neitzel and Klownoski, 2011). The recommendation was for larger uploads

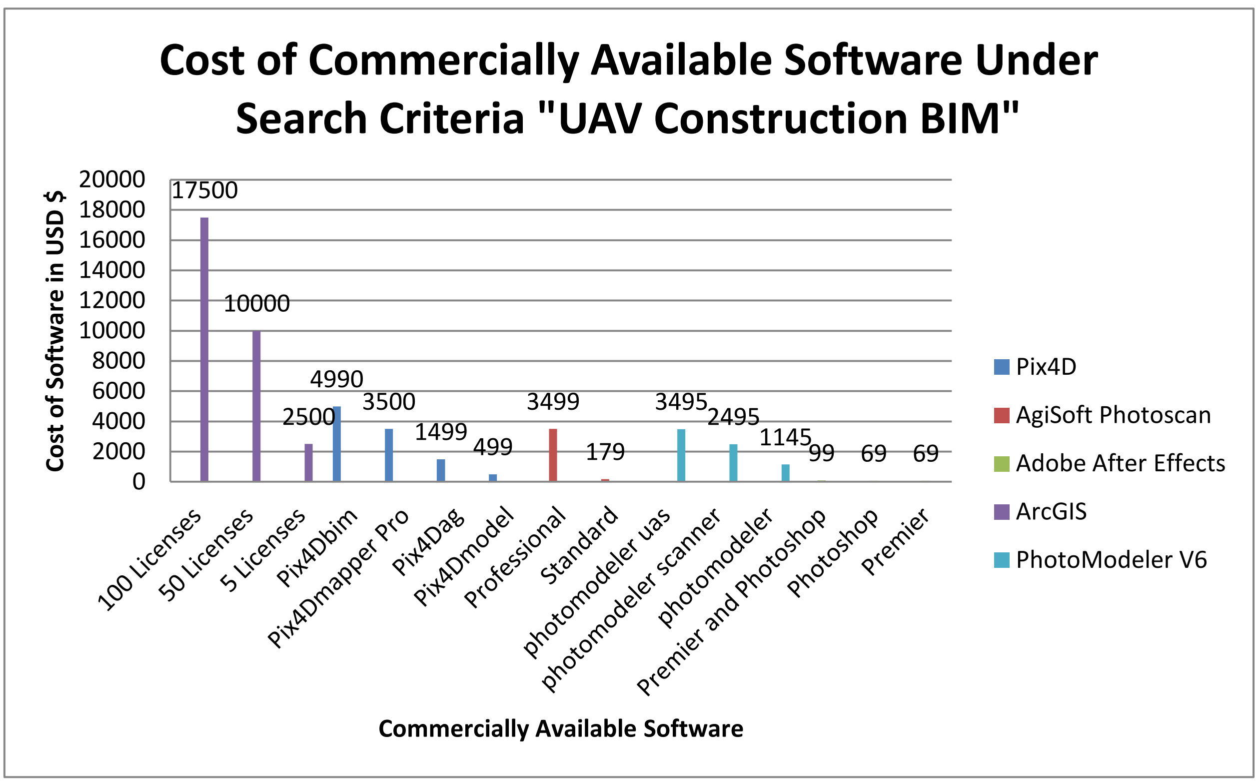

Figure 4.4 Cost associated with Commercial Software Programs for Data Processing

of photographs, 100 images and more, to have a 64-bit system and at least 6 gigabytes of RAM. Looking at the website to understand the draw of this software, they provide all the professional tools that would enable high-quality 3D image processing in a Professional Edition and a Standard Edition (http://www.agisoft.com/).

It was noted by Company Bravo that the software developed by Pix4D is willing to take the accuracy to zero, but the Photoscan software will not guarantee that degree of accuracy in their processing. This is perhaps why Pix4D can demand a higher licensing fee. Pix4D also provides a variety of packages to choose from that are distinct to the type of industrial work being conducted. Figure 4.4 analyses distinct commercial software packages and their associated cost. The highest cost was established by Trimble's ArcGIS software that only sells their software in license increments. Evaluating Pix4D shows the distinct software packages available per industry, and the cost associated shows where the value lies. The BIM package is the highest cost, then Mapper Pro, Agriculture, and the basic 3D modeling. These licenses are available on two computers (such as a desktop and laptop). Photos can is next in cost and available package options with a Professional package and a Standard (which is very limited compared to the Pro package). Down the list is Photomodeler, which contains three types of competitive packages, closely relating to the software provided by Pix4D and Photoscan. The UAS software package is the most costly of the three. Lastly, Adobe After Effects is the least costly option but severely limited as it is primarily for photoshopping images and image manipulation.

1.6 PHOTOGRAMMETRY CONCLUSION

Through analyzing the data set forth, it is possible to deduce that accuracy can be met through the use of the right equipment and software that is available. Accuracy doesn't depend on the most expensive equipment or software packages available, but on the knowledge of what is required, and the wisdom that comes with experience. Obtaining photographic data by flying at lower altitudes, by combining terrestrial and aerial data, by acquiring the correct camera, and using the best software are all items that will ensure that accuracy will be met.

LITERATURE	DEFINITION	INTERVIEW
Roca et al. 2014	Accuracy is tied to the GPS and INS. Horizontal and Vertical measurements are also important for the frequency provided as well as distance.	**Professor 3: The laser scanner itself has about a 2-5cm accuracy, but they aren't too reliable yet, they break down, they have problems.**
Wallace et al. 2012	Scan angles and flying height drastically affect the accuracy. Increased point density improves accuracy.	**Company Alpha: If you need 100% accuracy, then do not rely on the laser scanner, but on a manual basis, by hand.**
Langerwisch et al. 2016	Accuracy was an issue due to the interface of the quadcopter not being precise enough. A smartphone was installed on the copter to capture the orientation.	**Company Bravo: The as-built technology is not as accurate as it seems to be. You just won't find the centimeter grade accuracy. With LiDAR the pulse is on a Hertz cycle. The speed of the Hz and UAV are dependent on each other to change the point density. Compared photogrammetry and LiDAR and photogrammetry was almost as accurate as the LiDAR.**
Kaul et al. 2016	To ensure accuracy, a terrestrial laser scan was conducted and then an aerial. Accuracy depends on the callibration of the device in hand. Vertical accuracy is higher than horizontal due to the data collected beneath the UAV.	

Table 4.3 Literature reference and the summary of how accuracy was maintained by LiDAR. Summary of Interviews portrayal of accuracy.

2.0 LASER SCANNING ACCURACY

Accuracy with UAVs utilizing LiDAR scanning has become a focus due to an increased demand within a multitude of industries. Table 4.3 shows the literature and interviews conducted as they are related to how accuracy is achieved through the use of LiDAR. There are certain aspects concerning the LiDAR achieving accuracy, and one of them is how strong the GPS and INS signal strength is. The higher grade DGPS will achieve a greater level of accuracy than a regular GPS signal (Roca et al., 2014). As well as a tactical or navigational grade INS will reach the highest accuracy available. Discussing the actual LiDAR performance with Company Bravo, it is related to the Hertz cycle of the LiDAR pulse itself. The two components of LiDAR Hz and UAV speed are interrelated with each other in that the point density will change depending on the speed at which the UAV is flying and the Hz cycle at which the LiDAR scanner is programmed for. Of course, the scanner can be programmed to increase or decrease its Hz cycle depending on the circumstances of the job. The literature confirmed this by attesting to the accuracy being most dependent on the horizontal and vertical angles being captured (Wallace et al., 2012; Kaul et al., 2016). It was shown that there is a higher point density (better accuracy) directly beneath the UAV than on the horizontal parts of the data (Kaul et al., 2016).

However, not all are smitten by this technology. Professor 3 and Company Alpha do have their reserves as they are not convinced this technology is at a point where it has achieved precision. It is not reliable yet, and the scanners break down frequently according to Professor 3. Company Alpha would rather depend on data acquired by hand than by LiDAR if they wanted 100% accuracy in their measurements.

2.1 LIDAR AND 3D BIM

The purpose of collecting the data via LiDAR scanning has been analyzed by the literature written and interviews conducted. The literature shows how the data was collected, what algorithms were used to accomplish the acquisition, and what the end results are (Table 4.4). In one experiment the UAV was flown over, in one direction, of a building to scan for the roofline profile and then flown in a lower position, perpendicular to the first scan. This process was conducted in order to determine the measured accuracy of

LITERATURE	DEFINE	INTERVIEW
Roca et al. 2014	(2) methodologies to capture data. 1. acquired roof data and positioning per the DTM, and subsequent walls per the GIS 3D format. 2. flying low to capture roof and walls with more detailed information.	**Professor 1: Overuse of scans to as-built pre-concrete pours which document the rebar, conduits, etc.**
Wallace et al. 2012	Surveyed for growth prediction models. The lower heights provided more coverage.	**Professor 3: When creating 3D models, the GPS and IMU needs to work very well to provide correct information.**
Langerwisch et al. 2016	3D models in urban environments consist of ground and aerial LiDAR scanning. Proposes a 6D SLAM technique and a ICP mapping stack algorithm to reduce the point cloud density from the combined surveys.	**Company Alpha: Utilize laser scans for documentation of pre-construction activities, for renovation.**
Kaul et al. 2016	Proposes a continuous time 3D SLAM algorithm to conpensate for the motion created by the UAV.	

Table 4.4 Literature and the summary of how 3D BIM was illustrated in the research, collected by LiDAR. Summary of Interviews portrayal of how 3D BIM and LiDAR are connected.

the roof and walls by flight direction (Roca et al., 2014). It was determined that both the width and depth of the building was different with a 21.2% deviation of volume.

A big problem with the UAV is the movement while scanning. In terrestrial laser scanning, everything is stationary which is why millimeter accuracy is possible. Algorithms have been created as a means to compensate for this movement during the scanning process. There is the SLAM algorithm that compensates for this motion by taking and recording GPS coordinates every second (Kaul et al., 2016). Another algorithm created to compensate for the UAVs movement is the 6D SLAM (Langerwisch et al., 2016). This takes the combined point cloud density created from terrestrial LiDAR and aerial LiDAR surveys and reduces the overlap, thereby decreasing the amount of point cloud data and the time needed to process the information.

According to Professor 1, there is a potential issue of overusing the UAV LiDAR scans for pre- concrete pour activities. If it is an everyday activity it could become a task that puts a burden on the team oriented to handle the acquisition and processing of data. Regardless of the burden, it is a vital step to document the exact locations of MEP, and rebar in a pre-pour area.

2.2 LIDAR AND INDUSTRY

Investigating the literature and interviews revealed what industries are interested in the use of UAVs and LiDAR technology. The largest use of LiDAR being used for a specific industry is being that of building modeling, with forestry, and terrain being the smallest percentage (Figure 4.5). This literature was found through the use of the Google Scholar search engine, and the search criteria was "UAV LiDAR Construction." This isn't to say that other industries aren't utilizing UAVs with LiDAR, but that through a saturated literature

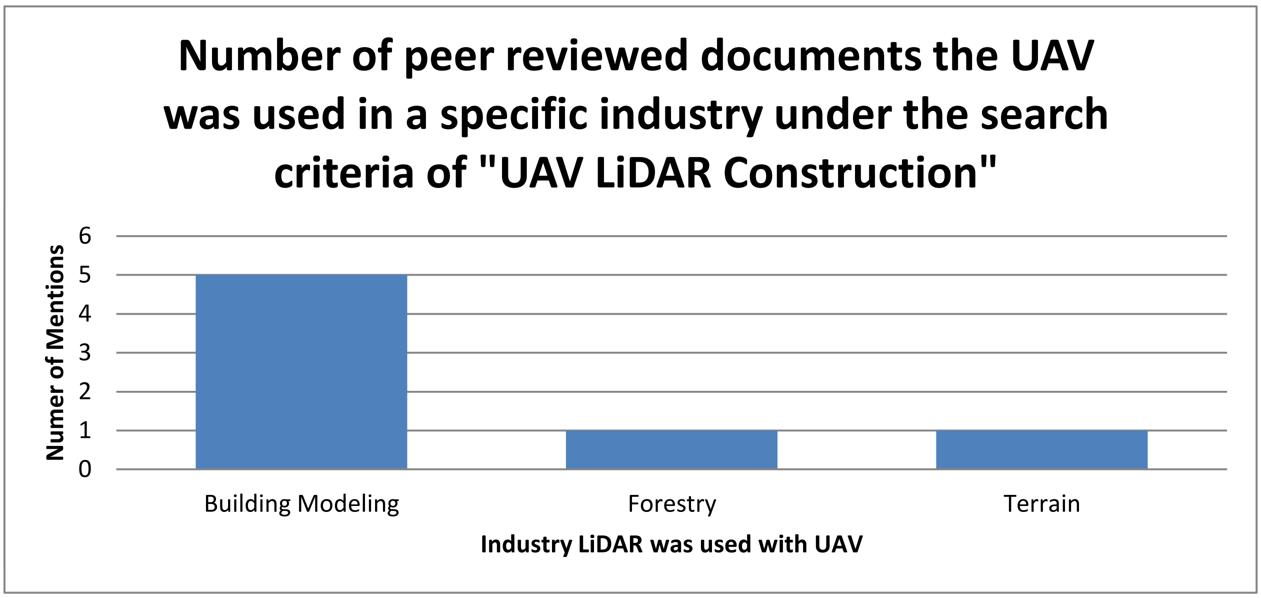

Figure 4.5 LiDAR scanning by industry

review, it became apparent that within the confines of the construction industry it simply has not been developed. There are applications that other industries are applying that can cross over to the construction industry. For example, in the forestry arena, the interest is growth, biomass, and disease which the LiDAR is capable of detecting and processing (Wallace et al., 2012). The research studied how the flight height affects the accuracy as well as the angle of scanning, and horizontal accuracy. These issues are not distinct to the forestry industry and can directly cross over to the construction industry.

2.3 LIDAR SCANNERS

There are multiple companies that produce the LiDAR scanners, and within the literature and interviews, it became apparent that Hokuyo was the most often used scanner (Figure 4.6). Using the Google Scholar search engine, the search criteria for “UAV LiDAR Construction” brought up multiple research papers. Ibeo, Leica, and Riegl were also used, but not in a significant way. The Hokuyo brand is known as being on the not-too-expensive side of scanners which may indicate why it is the most widely used. Hokuyo also has approximately seventeen different models available that provide distinctive capabilities. The Hokuyo UTM-30-LX is the prevalent model because it has a large scanning range (30m and 270d), and can be used at higher speeds, which makes it perfect for a UAV. The cost is also what makes it so attractive to potential users. At approximately $4,825 this is very

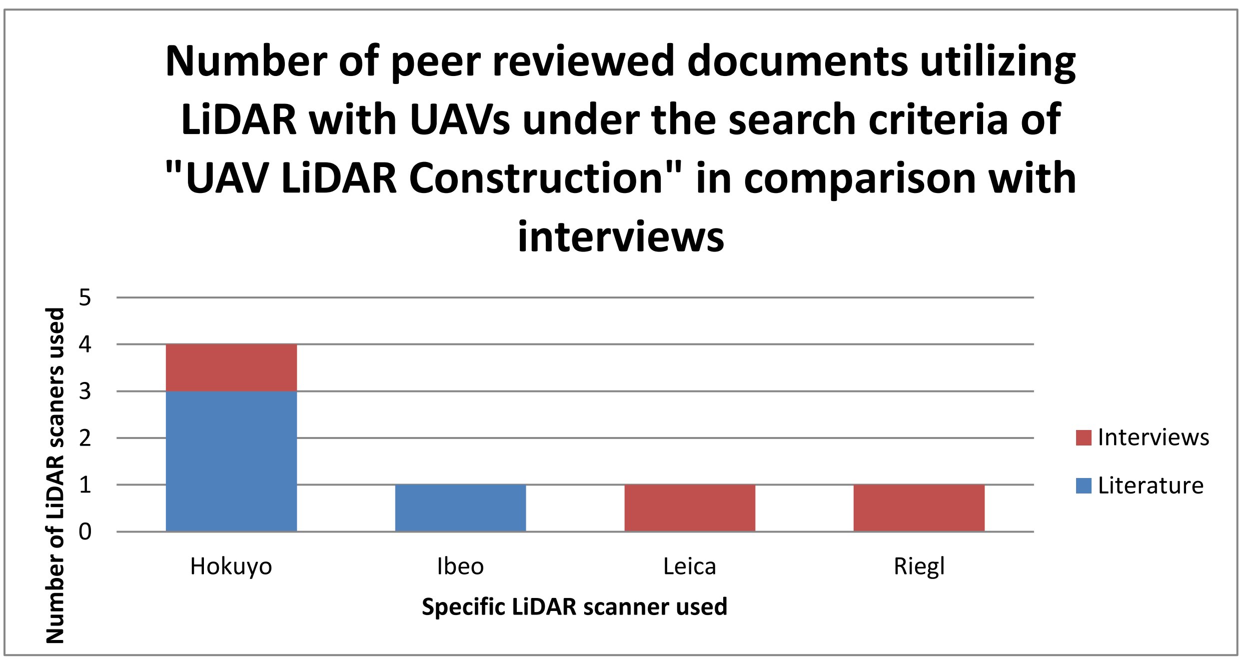

Figure 4.6 Product Brand of LiDAR scanner used for data acquisition

competitive with other manufacturers. The only downside is that Hokuyo does not offer their own software to complement their product.

The other models, Ibeo, Leica, and Riegl, are rapidly moving upward, as they not only provide a product but their own software to go with the equipment. So, it becomes a package deal that leads to less hassle for the user. The cost of these products is difficult to find on their websites, which can only mean one thing: If you have to ask, you can't afford it. There seems to be exclusivity about the cost and use of these products due to the fact that it is not simple to find on the web pages or a word search.

2.4 LIDAR SOFTWARE

Investigating this technology has led to understanding that the available software is just as varied as the photogrammetry software. Through literature investigation and interviews, it became apparent that there were three software programs being used for building modeling, and one for forestry (Figure 4.7). Software utilized for LiDAR processing on construction projects was found on the Google Scholar search engine with the criteria of "UAV LiDAR Construction." Green Building XML (gbXML) was utilized on the 3D BIM because it has capabilities related to energy modeling (Roca et al., 2014). Furthermore, the capabilities presented in gbXML are interoperable between CAD based models and other software for the sake of energy designers, architects, and engineers (www.gbxml.org).

The batwing UAV was utilizing a custom system that was configured as a single entity (Kaul et al., 2016). The custom configuration was vital to this research because of the two data sets that were required to be joined. There was a handheld LiDAR dataset as well as the batwing.

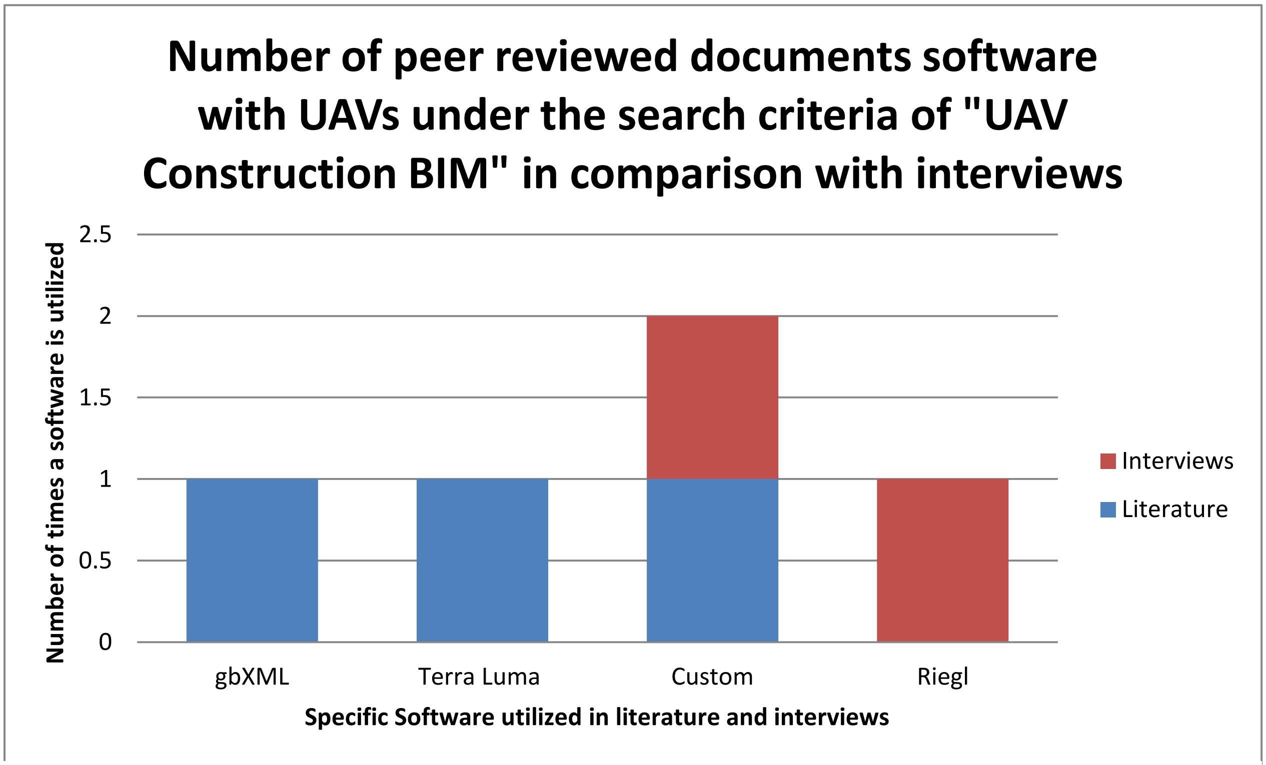

Figure 4.7 Software used to process data acquired by LiDAR

TerraLuma is another system that was utilized for the acquisition of forestry data. Used in conjunction with Ibeo Lux, the combination of the TerraLuma built UAV provided for a mapping system that was capable of providing the data for proper forest management.

From the discussion with Professor 3, and Companies Alpha and Bravo, the LiDAR software is comprised of a system that works in conjunction with the UAV. Typically, the maker of the UAV will provide the LiDAR scanner and software as a total package. This is the case in the interview with Company Bravo. They have a Rigel's system that encompasses all aspects of the data acquisition process. Looking at Rigel's website, they offer products and software for a wide range of applications, including terrestrial, aerial, and mobile (http://www.riegl.com/nc/products/).

2.5 LIDAR CONCLUSION

This analysis looked at the accuracy brought about by LiDAR data acquisition. The investigation also looked at the capabilities of 3D BIM, the different industries using LiDAR, types of LiDAR scanners, and software provided for LiDAR. The question remains as to the requirements for accuracy, and if they are being met in the field. Is there a better way to acquire the LiDAR data via UAV per the literature research and interviews? Is it possible to conclude that data acquisition by UAV LiDAR alone will not suffice for the type of accuracy that needs to be met? This is being asked because, through interviewing it became apparent that LiDAR scanners are not reliable enough yet to be utilized on their own for survey accuracy. But, they can provide enough information to produce 3D BIMs within the 2-5cm range. If used in combination with terrestrial laser scanning, the coverage is much more thorough.

3.0 THERMOGRAPHY AND ACCURACY

The data provided by the current literature available on the topic of thermography, UAVs, and construction has not been researched extensively. There are experts in the field who have provided enough data for what thermography can offer the construction industry. Specifically, the data is related to overlaying the thermographic photographs on top of an already created 3D model. This provides the user with a 3D BIM in a thermographic way that shows energy heat loss, air leakage, moisture buildup, etc. (Maureillo et al., 2015). Laser scans or photogrammetric data are combined with the thermographic information in a

LITERATURE	DEFINITION	INTERVIEW
Laguela et al. 2014	Combine laser scans with thermographic data to accurately locate defects.	**Professor 3: Process is just like photogrammetry but the results are much worse because the cameras are not high quality. So, the thermographic data overlays the photogrammetric or laser scanned data.**
Mauriello et al. 2015	Found value in the creating of an accurate building model because it can be transported to other tools, creates faster analysis of data, etc.	**Company Bravo: The use of thermal images have been to view abnormalities in roofs, wind turbine motor housing, or solar panels for examples.**
Bison et al. 2012	Implement photogrammetric data with the overlay of thermographics and position them accurately. The point is not the extreme accuracy with thermographcis, but simplified version that is compatible.	

way that lines them up and provides images that are not the most extreme (Laguela et al., 2014; Bison et al., 2012). Through conducting interviews, it also became apparent that the thermographic process was not meant to produce extreme accuracy, as was pointed out by Professor 3. Professor 3 noted that the images taken by thermal cameras are not at all high quality and are not meant to be. Company Bravo had only experienced using the thermal cameras for inspections at roofs, wind turbines, and solar fields.

3.1 THERMOGRAPHIC 3D BIM

LITERATURE	DEFININITION	INTERVIEW
Laguela et al. 2014	3D models extracted by aerial oblique thermographic imagery.	**Company Bravo: Tested the 3D modeling with thermal imaging, but for normal building uses, it didn't prove its value.**
Mauriello et al. 2015	Automated 3D model with a thermal overlay.	
Bison et al. 2012	Output is the 3D model based on the existing building model. Goal is a simplified model with each pixel representing temperature, heat flux, absorption, and coefficient.	

Table 4.6 Literature and the summary of how thermographic data and 3D BIM were illustrated in the research. Summary of Interviews portrayal thermography and 3D BIM.

The research regarding what the industry is doing with the 3D imaging process is very much so related to the accuracy section. The primary example being that the researchers were taking thermographic photographs by UAV and then overlaying them on the already made 3D model (Laguela et al., 2014; Mauriello et al., 2015; Bison et al., 2012). The product of this overlay is the representation of each pixel as “temperature, heat flux, absorption, and coefficient.” (Bison et al., 2012).

Company Bravo practiced this method of overlaying the thermographic photographs on a 3D model and, although it showed the building envelope, the value of providing this

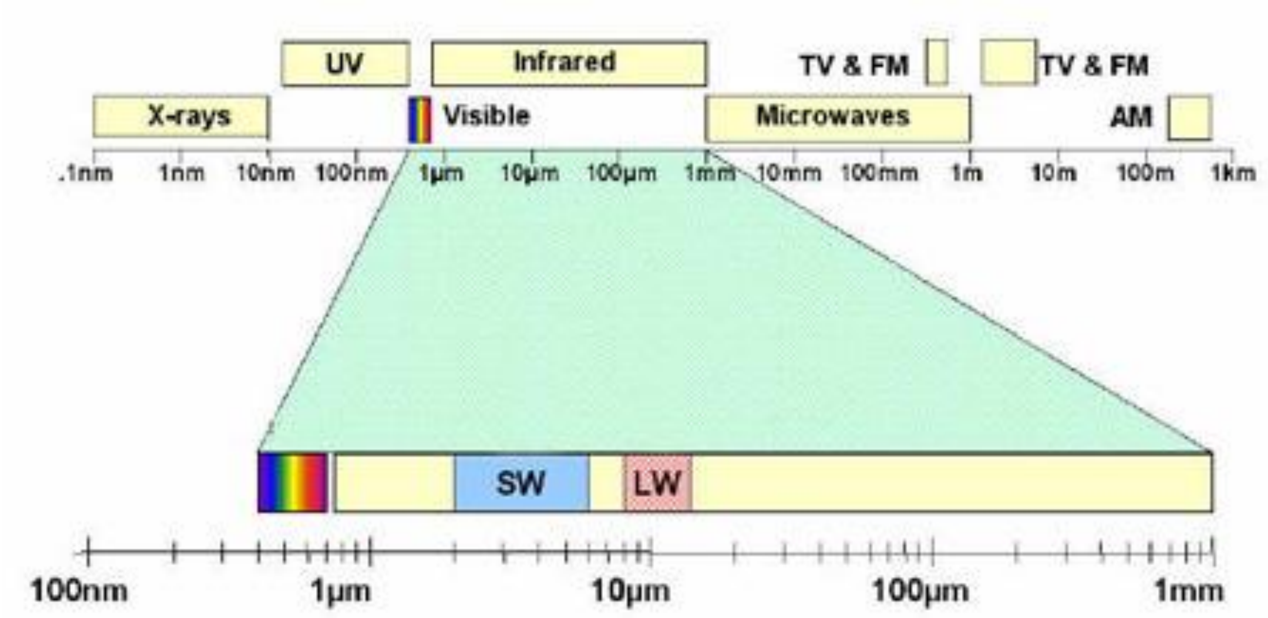

Figure 4.8 Image taken from solutionsdirectonline.com shows the relationship of Short Wave (SW) and Long Wave (LW) on the spectral scale.

information to a client wasn’t sufficient to justify the added expense.

3.2 THERMOGRAPHIC CAMERAS

The cameras utilized in the literature research were the Xenics Gobi 384, Parrot Camera (stock), and the FLIR Systems SC 660. Xenics Infrared Solutions manufactures multiple types of IR cameras in the Short Wave (SW) and Long Wave (LW) range, along with everything in between (Figure 4.8). The Gobi 384 contains a Long Wave camera (Figure 4.9) that operates at 7 µm to 14 µm on the wavelength scale which is best suited for electrical testing and exterior inspection (http://www.iranalyzers.com/operatingprinciples.htm). The Xenics Gobi 384 (Image 1.0) has interchangeable lenses and filter attachments, multiple data ports, and Xenics provided computer software programs. Other things to note concerning this product is the spectral band that can pick up anywhere between 8 μm to 14 μm, and the number of pixels is 384 x 288. The weight is low enough to not make an impact on the flight of a UAV.

The FLIR System SC660 (Figure 4.10) is a higher end thermal camera that offers a pixel

Figure 4.10 FLIR System SC660

Figure 4.9 Xenics Gobi 38

detector of 640 x 480, and a spectral range of 7.5 μm to 13 μm. The cost of this camera is higher due to the "SC", which gives it a scientific rating. This camera is simply for the research aspect of data acquisition and is not for flight on a UAV. This camera is strictly for terrestrial data acquisition.

Utilizing the Parrot Drone stock camera and applying a thermal filter to the photographs in Adobe After Affects which is more for the look of a thermal image than the actual use of a thermal camera (Mauriello et al., 2015). This was for the experiment and overall reaction to thermal imaging of a building.

The cost of the Gobi is undetermined at this point as the price is not able to be found on the website or on a seller website, such as amazon.com. In order to obtain the pricing for this product, the manufacturer needs to be contacted for any further information regarding the products. During an amazon.com search for a general idea on how expensive these products are, the low end, meaning a handheld product made by FLIR will cost approximately $1,135. The higher end FLIR, handheld thermal IR camera will cost roughly $12,450. The FLIR System SC 660 will be somewhere on the higher end due to its rating as a scientific camera and because it provides more capabilities, such as higher pixels (meaning better accuracy) than a Xenics camera would provide.

3.3 THERMOGRAPHIC AND SOFTWARE

Within this analysis of what type of software is being used in the literature and interviews concluded that, as with the other data acquisition methods the software is as varied in its use as anything. The research shows that ArcGIS, PhotoModeler, MatLab, Adobe After Affects, and SketchUp are the software programs that were utilized in the thermographic data processing. As it was discussed in the previous 3D BIM section, the thermal images are simply photographs and are treated to the same photogrammetric process as any digital photographs would be. The commercial programs are utilized for the processing of the thermal images, then overlaid with the 3D image. But, there is a program called MatLab that isn't at all common, and the application of that program was unique (Bison et al., 2012). Developing the script in MatLab was on the fly and the researcher needed to find methods that preserved making the wall "their geometric and radiometric characteristics."(Bison et al., 2012). The survey success was

Table 4.7 Literature reference and the equipment and software utilized in the research of thermography

EQUIPMENT	SOFTWARE	LITERATURE
Xenics Gobi 384	ArcGIS, Sketchup	Laguela et al. 2014
Parrot video camera	Adobe After Affects	Mauriello et al. 2015
FLIR Systems SC660	PhotoModeler, MatLab	Bison et al. 2012

granted by the use of markers that were able to be seen by both thermal and visual cameras, and subsequently processed.

3.4 THERMOGRAPHIC CONCLUSION

To conclude this discussion on the aspects of UAV data acquisition with thermographic data, the analysis presented included the use of thermographic images in 3D BIM, how accuracy is obtained, what types of cameras are used, and what software accompanies this process. Due to the limited literature and knowledge presented by the interviewee's it is difficult to conclude that this method of data acquisition has any bearing on the construction industry whatsoever. Through this analysis, it is possible to determine that as the current state is presented, the level of accuracy is just not where it needs to be if any level of survey accuracy is to be used. The primary use of this data is not to provide any extreme level of accuracy, but to provide data that shows building defects and areas that contain heat loss, or air leakage.

4.0 DATA ANALYSIS CONCLUSION

To conclude the data analysis, this process investigated the literature researched concerning the UAV, their use, and their methods of data acquisition. The investigation also performed interviews with industry professionals and professors, whom are experts in their fields. Through the course of exploring this topic, the questions as to how accuracy is achieved with each of the methods mentioned above were asked, and it is possible to arrive at a solution as to how to achieve a better accuracy. By combining the elements of each method there are opportunities to arrive at a closer, more detailed 3D BIM image. Combining terrestrial photogrammetrics with aerial, or terrestrial LiDAR with aerial data is one possibility to achieve said accuracy. Any other combination such as LiDAR and photogrammetry will also produce high quality results. Thermography is the only other solution that does not have the high resolution cameras that can provide the results needed for an accurate 3D model. But, the thermographic intent is more of a visual representation, rather than as an as-built document. Equipment and software are the other solutions as they are a major contribution to the effort of data acquisition. But a caveat; all equipment (cameras, scanners, software) are not all made equal, and it is not always the case that the more expensive equipment will provide the more high quality and accurate results.

CHAPTER 5

DISCUSSION

There are several points to note concerning the results of the research conducted in the case of assessing the technology used by UAVs in the construction industry. The first of these points considers the validity of the assumption that the technology UAVs are using is beneficial to the industry. Clearly, the use of UAVs is limited to cases that have the specialized parameters set in place, or are homogeneous. This assumption will only hold in a very small amount of real cases. The other assumption that may be difficult to fulfill, is the one concerning the technology that is highly accurate at portraying as-built 3D models. The value would be realistic for data acquired by LiDAR but in the case of photogrammetry may be less accurate.

The technologies of photogrammetry, LiDAR, and thermography have been used previously to demonstrate their usefulness in the construction industry. Not all GCs have the ability to provide the data processing required for the acquisition of photo images, LiDAR, or thermographic scans. This type of data acquisition could take a whole additional person to perform these tasks internally, or the hiring of a subcontractor to absorb the liability. Wen and Kang (2014) found that in the additional manpower required was more heavily burdensome on the CCTV cameras throughout the job site, meaning that if there is maintenance or additional coverage needed, the additional manpower needed is unproductive when the UAV can give real-time surveillance of the entire project site. The manpower that it takes to collect the data on a construction site is of little consequence to the time and cost associated with the data collection sequence. Vacanas et al. (2015) also concluded that the "UAV can…achieve a more effective collection of records," when updating infrastructure for project management purposes. This is all with the intention and purpose that the project has set up the data collection process and is without limitations in the acquisition of data. However, the cost associated with such startup is subjective due to the equipment, licensing, and manpower costs that fluctuate with the market.

More limitations are present that will deter the GC from performing data collection practices on a construction site, and that is the current legislation. In the United States, the FAA passed Part 107 which sets into motion an exam commercial UAV pilots can take in order to attain a license (Dorr and Duquette, 2016). This licensing has enabled thousands of people to legally pursue an endeavor in a new and rising industry. Some of the Part 107 rules can limit where the UAV can legally be flown (see Appendix II).

One of the important aspects is that whoever is collecting the data and processing has the best available software that can provide the accuracy needed to fulfill the engineering requirements. This is, of course, depending on whether the project is simply taking photographs for visual inspections, or creating full 3D BIM images for use in the as-built documents. The software has to be there in order to provide that level of accuracy for the client's needs. It was discussed in the interviews how the Pix4D currently provided the better accuracy than the Agisoft Photoscan software. Costa et al. (2016) concluded through experiments with the Pix4D software that the hardware, software, and environment need to be addressed for better 3D mapping results. Neitzel and Landowska (2011) found that through software experiments, multiple commercial programs were compared and contrasted with each other, and concluded that deviations in accuracy can be attributed to the applied software. Essentially, not all commercially available programs are the same, and you get what you pay for. Purchasing top of the line, professional packages will get you the most sophisticated and accurate software.

Custom software packages that are not commercial are another aspect that this research has revealed to be of importance. The research of Goparvar-Fard et al. (2011) found that the custom software of integrating time into the 3D as-built has the ability to enhance many aspects of the construction progress, and by utilizing a custom built 4D BIM software, it was found that better information was being provided to the project team. Freimuth and Konig (2016) indicated that the occlusions and clutter can be automatically detected in order to provide a robust aerial image, thereby furthering the custom software not yet available on the commercial market.

The technology available that collects data on construction projects is on the cusp of reaching real survey accuracy. Photogrammetry has been compared to the accuracy and precision that has been acquired from LiDAR data based on volumetric or 3D visual imagery. Siebert and Teizer (2014) concluded that, comparing an aerial survey acquiring photogrammetric data versus a terrestrial robotic total station not only saved time but created a more dense point cloud. The data acquisition by UAV can provide a competitive approach to collecting data and conversion to 3D BIM. The combining of terrestrial and aerial imagery with photographs is another method that can produce a higher accuracy than just one or the other. The same goes for LiDAR data acquisition; one terrestrial and one aerial combined to produce an accurate 3D image (Fritz et al., 2013; Puschel et al., 2008). The accuracy of the combined method can be created as one file through a .LAS file. The photographic images can be processed to a .LAS, and the LiDAR also to a .LAS. The two files can then be combined as one in order to create the 3D BIM.

There were also unexpected results, which were related to the concerns of privacy and UAVs in the air. It is so easy to be consumed by the technology that drives the UAV that it can be forgotten how the general populace believes the UAV to be an invasion of privacy.

Acquiring data on a vertical high-rise, in a downtown, densely populated area, the UAV can have an intimidating presence that people can feel threatened by. This relationship with a flying camera is one of the reasons why the FAA pulled the reigns in on allowing commercial use and createed an entire license for the UAV. Another unexpected result was the use of thermographic scanners to create a 3D BIM. The geometry of the building must be both LiDAR scanned, or photographed, and the thermographic images are to be laid over that geometry. However, the thermographic images are not as precise as needed to solely rely on that data.

What is the significance of this research? What does it tell us about what is going on, and where we are headed? It has been said that the construction industry is lacking sorely behind other industries in the productivity arena. Why is this, and how can this be rectified? This research helps to underline the current status of research that is being conducted with technology as a means to put it on the table. Because the use of UAVs is on the cutting edge of what is happening in the industry, there really isn't that much research as to what is out there. For professional Virtual Designers, Architects, or GCs there is a lack of awareness of what the UAV capabilities can accomplish on a construction project. Other industries, such as forestry and agriculture, have acquired a taste for the use of UAVs, and construction is again, showing up late to the game. The desire to improve the technologies within the industry, and make advancements with as-built conditions can become an industry standard with the right approach to data acquisition. UAVs may be that tool in the shed that can provide the information required to produce the BIMs needed for a look-ahead decision making process.

This is a significant area of research because:

1. The construction industry sorely lacks in productivity

2. This can help determine where our current technology lies
3. This can help determine what our next steps are in the industry.
4. We learned what technology is being used by the UAV for data acquisition.
5. We learned what is being done with it.

There were a few limitations throughout this study, and one major limitation is the fact that this study is only capturing this technology in a specific point in time. The technologies represented within this thesis are changing rapidly, which makes it difficult to truly portray the peak of what the tech is doing in present form. Another aspect limiting the study was the response ratio of interviews. Some professionals did respond with ease and openness in discussing their work, while others were unresponsive or did not want to discuss their methods. Another limitation to the study, which was more of a wish list, was for an UAV to conduct experiments with. With the correct equipment there could have been actual experiments conducted with the technology and accuracy judged and comparisons made.

CHAPTER 6

CONCLUSION

The aim of this research was to look into and determine how the technology is being used by UAVs in the current state of the construction industry. Part of the technology reviewed was related to the photogrammetric, LiDAR, thermography, and combinations of those technologies. Interviews were conducted to discuss the latest procedures with the industry professionals, as well with professors who are developing the technologies. These findings through interviewing and researching peer-reviewed literature allowed for an in-depth view of what the current state of technology is with respect to UAVs. Because this is such a new arena that is just starting to become widespread, there are not that many published papers regarding UAVs in the construction industry. If there are papers, they are mainly published within the last two years, or so. In the upcoming years, the increase of documentation will be exponential.

The findings of the literature and the interviews found that there is a wide array of equipment and software on the market for photogrammetric data acquisition. But, the products become thin when discussing LiDAR and thermography for use on construction projects. This is due to either the rapidly growing market, where the technology outpaces its usefulness and cost becomes a major factor, or there just hasn’t been enough interest within construction to provide the research. From the interviews that were conducted, there does seem to be an interest, and a curiosity to see if the industry will latch itself onto the UAV as a main player of data acquisition. However, the UAV will not be the only method of data acquisition, as combining terrestrial and aerial methods can provide a more powerful, robust imagery of a building under construction.

Yes, other industries are beginning to lean heavily on the use of UAVs, and the significance of this research is that it is being brought to awareness for industry professionals. Even discussing with professors about this technology, not only gave insight as to where the current state is, but also, as to the direction of the technology.

The limitations of this research involved working with a technology that is changing rapidly, and the focus was to understand the state of the art technology..There is more research that is needed to understand applications of these technologies on construction job sites.

Looking at furthering the research in the UAV, augmented reality (AR) realm will enhance the technology being used already. Continuing with increasing the accuracy of photographs and LiDAR data needs to be studied further, specifically in the construction industry. Utilizing that data and implementing it with 4D data is already an area being researched for its effectiveness in planning and scheduling of long-term projects. UAVs need to have a greater, in-depth study on long-term projects for their data acquisition in all regards. The research that can be looked at further is the autonomy of UAVs on the exterior, and more importantly, the interior. Another area that can be explored further is the use of ground robots as a means for autonomous data acquisition. So, it’s not just UAVs that are being studied for their data acquisition methods. There are a lot of tools in the shed that can accomplish the same results, and the UAV is just one of many.

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Appendix

Appendix I – Summary of Operational Limits Within Part 107

- Unmanned aircraft must weigh less than 55 lbs. (25 kg)
- Visual line-of-sight (VLOS) only; the unmanned aircraft must remain within VLOS of the remote pilot in command and the person manipulating the flight controls of the small UAS. Alternatively, the unmanned aircraft must remain within VLOS of the visual observer.
- At all times the small unmanned aircraft must remain close enough to the remote pilot in command and the person manipulating the flight controls of the small UAS for those people to be capable of seeing the aircraft with vision unaided by any device other than corrective lenses.
- Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle.
- Daylight-only operations or civil twilight (30 minutes before official sunrise to 30 minutes after official sunset, local time) with appropriate anti-collision lighting.
- Must yield right of way to other aircraft.
- May use visual observer (VO) but not required.
- First-person view camera cannot satisfy “see-and-avoid” requirement but can be used as long as requirement is satisfied in other ways.
- Maximum groundspeed of 100 mph (87 knots).
- Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a structure.
- Minimum weather visibility of 3 miles from control station.
- Operations in Class B, C, D and E airspace are allowed with the required ATC permission.
- Operations in Class G airspace are allowed without ATC permission.
- No person may act as a remote pilot in command or VO for more than one unmanned aircraft operation at one time.
- No operations from a moving aircraft.
- No operations from a moving vehicle unless the operation is over a sparsely populated area.
- No careless or reckless operations.
- No carriage of hazardous materials.
- Requires preflight inspection by the remote pilot in command.
- A person may not operate a small unmanned aircraft if he or she knows or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS.
- Foreign-registered small unmanned aircraft are allowed to operate under part 107 if they satisfy the requirements of part 375.

- External load operations are allowed if the object being carried by the unmanned aircraft is securely attached and does not adversely affect the flight characteristics or controllability of the aircraft.
- Transportation of property for compensation or hire allowed provided that
  o The aircraft, including its attached systems, payload and cargo weigh less than 55 pounds total;
  o The flight is conducted within visual line of sight and not from a moving vehicle or aircraft; and
  o The flight occurs wholly within the bounds of a State and does not involve transport between (1) Hawaii and another place in Hawaii through airspace outside Hawaii; (2) the District of Columbia and another place in the District of Columbia; or (3) a territory or possession of the United States and another place in the same territory or possession.
- Most of the restrictions discussed above are waivable if the applicant demonstrates that his or her operation can safely be conducted under the terms of a certificate of waiver

Appendix II – Drones used with LiDAR, Thermographic Cameras, or Cameras; Type of Computer Programs for Processing; Reference; Industry

DRONE COMPANY	DRONE MODEL	LIDAR	MODEL	THERMOGRAPHIC CAMERA	SPECTRAL CAMERA	CAMERA	MODEL	COMPUTER PROGRAMS	REFERENCE	INDUSTRY
HiSystems GmbH	Okto XL	Hokuyo	UTM-30LX					gbXML	Roca et al. 2014	Building Modeling
TerraLuma	Oktocopter	Ibeo	Lux						Wallace et al. 2012	Rangeland Monitoring
Microdrone	MD4-1000	Hokuyo						Survey Planner	Langerwisch et al. 2016	Building Modeling
Skybit Systems	Eagle Quadcopter	Hokuyo	UTM-30LX-F						Kaul et al. 2016	Safety
Mikrocopter	Okto XL			Xenics Gobi 384				Agisoft Photoscan	Laguela et al. 2014	Natural Disaster - Buildings
Parrot	AR 2.0			Parrot video camera					Mauriello et al. 2015	Terrain
	Helicopter UAV				FPI				Hakala et al. 2013	Forestry
HiSystems GmbH	MK Okto2					Panasonic	Lumix G3	VisualSFM	Fritz et al. 2013	Forestry
Eos Fly	Octocopter					Canon EOS	650D	AgiSoft Photoscan	Achille et al. 2015	Building Modeling
	RC Helicopter					Nikon	D200	ATiPE (custom)	Barazzetti et al. 2010	Building Architecture
Surveycopter	Mini RC Helicopter					Nikon	D2Xs	ATiPE (custom)	Barazzetti et al. 2010	Cultural Heritage Documentation
	Quad Micro UAV					Pentax	Optio A40	ATiPE (custom)	Barazzetti et al. 2010	Cultural Heritage Documentation
DJI	Phantom 2 Vision +					PHANTOMVISIONFC200		Pix4D	Costa and Mendes, 2015	Terrain, Building Modeling
3D Robotics	Iris +					GoPro	Hero4	Pix4D	Costa and Mendes, 2015	Terrain, Building Modeling
	Mini-UAV Helicopter					Canon	D60	Commercial Software: Leica Photogrammetry Suite V8.9 (LPS)	Eisenbeiss, 2009	Cultural Heritage Documentation
	Mini-UAV Helicopter					Nikon	D2Xs	Leica Geosystems	Eisenbeiss, 2009	Cultural Heritage Documentation
	Mini-UAV Helicopter					Nikon	D2Xs	In House Software: BUN; SAT-PP V1.0	Eisenbeiss, 2009	Cultural Heritage Documentation
	Copter 1B					Nikon	D2Xs	LPS; SAT-PP V1.0	Eisenbeiss, 2009	Natural Hazards
Microdrones	MD4-200					Panasonic	Lumix FX35	PhotoModeler V6	Eisenbeiss, 2009	Gravel Pit Volume
	Copter 1B					Canon	D20	SAT-PP	Eisenbeiss, 2009	Agriculture
	FKC-1 - Blimp					Canon EOS	5D Mark II	LPS V9.1; SAT-PP V1.0	Feifei et al., 2012	City Modeling
	Fixed Wing					Canon EOS	5D Mark II	LPS V90; ISDM; SAT-PP V 1.0	Feifei et al., 2012	City Modeling
	UAVRS-II					Nikon	D100		Wang et al. 2004	Building Modeling w/Single Image
HiSystems GmbH	MK Okto					Canon Digital	100 IS		Neitzel and Klonowski, 2011	Comparison of software, landfill
	Microdrone					Pentax	Optio A40		Remondino et al. 2011	Survey
Mikrocopter	Quad XL					Sony	NEX-5N	Comparison of Commercial Software: Photosynth, Bundler, PMVS2, Photoscan, ARC3D	Seibert and Teizer, 2014	Cultural Heritage Documentation
Ascending Technologies	Falcon 8 Octocopter					Panasonic	Lumix GFI		Wefelscheid et at. 2011	Excavation
DJI	Phantom 2 Vision +					PHANTOMVISIONFC200		ATiPE	Yamazaki et al, 2015	Building Model
Microdrone	MD4-1000					Olympus	E-P1		Nex and Remondino, 2014	Thermographic Building Model
Microdrone	MD4-200					Pentax	Optio A40	AgiSoft Photoscan	Nex and Remondino, 2014	Cultural Heritage Documentation
MLB Co.	Bat 3 - Fixed Wing					Canon SD	900	ArcGis	Laliberte et al. 2010	City Modeling
						Sony	NEX-5R	Definiens Developer 7.0	Wen and Kang, 2014	Agriculture
	Mini-UAV					N/A			Kim et al. 2015	Building Modeling
	N/A					N/A		Custom	Freimuth and Konig	Excavation
Aibot	X6					N/A		Vuforia SDK 2.0	Nielson and Holley, 2014	Building Modeling
Mikrocopter	MAV					Canon Powershot	SX220 HS		Eschmann et al. 2012	Building Modeling
DJI	Phantom 3 Pro					Stock camera		Corel Photo-Paint	Gillins et al. 2016	Thermographic Building Model
DJI	Phantom 2 Vision +					Stock Camera		Octomap/Octree	Irizarry and Costa, 2016	Inspections
Parrot	AR.Drone					Stock Camera		Adobe After Affects	Gheisari et al. 2014	Visual Assets
Parrot	AR.Drone					Stock Camera			Irizarry and Gheisari 2012	Safety