DEPARTMENT OF TRANSPORTATION

Building 360 Scanning and Reality Modeling

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Collins Engineers, Inc.

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The ability to collect and utilize large amounts of data is transforming our world. Industries like healthcare, finance, energy, communication, and transportation are finding ways to utilize data to improve people's lives. Processing software and inspection-specific asset management platforms are giving asset owners the ability to utilize this data to accelerate their ability to effectively manage these important assets.

The Building Services Section (BSS) owns and operates over 900 individual buildings at over 250 sites throughout Minnesota. BSS explored ways to collect and process as-built data for their sites and buildings with imaging and scanning technology. The data was collected with spherical cameras, handheld cameras, laser scanners, and drones. This research demonstrates the significant advantages of implementing building and site scanning and shows that the technology has many benefits. This research project identified scanning technologies, processing, and data storage options and documented these workflows. The cost information was analyzed to determine which technologies are cost-effective and how new technologies compare to existing methods.

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Building 360 Scanning and Reality Modeling

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LIST OF ABBREVIATIONS

3D	Three-Dimensional
UAS	Uncrewed Aircraft System
DSLR	Digital Single-Lens Reflex
FAA	Federal Aviation Administration
FPV	First Person View
GCP	Ground Control Point
GPS	Global Positioning System
HDR	High Dynamic Range
LOS	Line of Sight
MNDOT	Minnesota Department of Transportation
MTP	Manual Tie Point
NDE	Non-destructive Evaluation
NDT	Non-destructive Testing
PPE	Personal Protection Equipment
QR	Quick Response (QR Codes)
RPC	Remote Pilot in Command
VO	Visual Observer

EXECUTIVE SUMMARY

The Building Services Section (BSS) owns and operates over 900 individual buildings at over 250 sites throughout Minnesota. This research effort explored ways to collect and process as-built data for their sites and buildings with imaging and scanning technology. The data was collected with spherical cameras, handheld cameras, laser scanners and drones. This research demonstrates the significant advantages to implementing building and site scanning and show that the technology has many benefits. This research project identified scanning technologies, processing and data storage options and documented these workflows. Cost information was analyzed to determine which technologies are cost effective and how new technologies compare to existing methods.

The research team scanned seven different building sites as part of this research and scanned one site twice a year apart. We utilized different hardware and software at different sites to demonstrate the efficiencies and quality each can achieve. We also reviewed different hardware and software platforms available to utilize the data effectively including cloud sharing, virtual reality, and mixed reality. The terms metaverse and artificial intelligence have been popular of late in technology circles and this research demonstrates real world examples of these technologies. We are digitizing our assets and teleporting teams into this virtual world that approximates site visits and by visiting this metaverse teams can realize many of the benefits of a site visit without traveling to the site.

By utilizing digital twins, we are giving team members photographic memory in the form of access to thousands of images of a site or building through photo navigation. Digital twins also give team members the ability to time travel virtually and access data from different time periods to evaluate change over time of a facility. A third significant benefit discovered is the ability to access portions of a building or site that may not be accessible without special access equipment. For instance, team members could inspect a roof virtually without having to climb on top of the building.

Our work identified many benefits of these digital twin workflows including cost efficiencies, improved quality and quantity of data, improved ability to utilize and share data and safety improvements.

CHAPTER 1: INTRODUCTION

1.1 PROJECT OBJECTIVES

The ability to collect and utilize large amounts of data is transforming our world. Industries like healthcare, finance, energy, communication, and transportation are finding ways to utilize data to improve people's lives. Minnesota Department of Transportation (MnDOT) and Collins Engineers, Inc. (Collins) have been utilizing drones and other imaging equipment to collect and process large amounts of data during structure inspections with the goal of improving the quality of bridge inspections and improving safety for both inspectors and the traveling public. Processing software and inspection specific asset management platforms are giving asset owners the ability to utilize this data to accelerate their ability to effectively manage these important assets.

The Building Services Section (BSS) owns and operates over 900 individual buildings at over sites throughout Minnesota. This research effort explored ways to collect and process as-built data for their sites and buildings with imaging and scanning technology. The data was collected with spherical cameras, handheld cameras, laser scanners and drones. This research was designed to demonstrate the advantages to implementing building and site scanning and show that the technology has many benefits. This research project identified scanning technologies, processing and data storage options and documented these workflows. Cost information was analyzed to determine which technologies are cost effective and how new technologies compare to existing methods.

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1.2 RESEARCH METHODOLOGY

The project scope included utilizing existing technology and leveraging our relationships with technology companies and other DOTs to establish building and site scanning workflows. We utilized our existing knowledge of scanning structures while also exploring other newer technologies. It was important to compare not only what is the best technology available but also look at technologies which are cost effective and easily implemented and integrated with existing MnDOT software and processes. These technologies were originally planned to be deployed on a minimum of three MnDOT facilities for the analysis and development of reality models, but seven sites were scanned partially due to the relative ease of collecting and processing data.

Another focus of the project was to not only find ways to acquire and process building and site data but to also find ways to effectively use, store and share the data. Reality modeling can be data-intensive and difficult to share without effective means to view and utilize the data. Many approaches were evaluated including cloud sharing digital twins, virtual reality, and mixed reality.

CHAPTER 2: TECHNOLOGY REVIEW

Technology suitable for collecting data for infrastructure has advanced in recent years and has enable new workflows to manage assets including buildings and building sites. These new technologies include uncrewed aircraft systems, lidar, 360degree cameras. There have also been advancements in software and hardware to post process, host and consume this data. In this chapter we will discuss these technologies and outline how they were used to collect, process, and consume data for this project.

2.1 DATA COLLECTION

2.1.1 Uncrewed Aircraft Systems (UAS)

Uncrewed Aircraft Systems are one of the most effective methods for collecting data. This data collected is typically in the form of photos that are embedded with GPS location information. The advantage of UAS results from the ability to take images from almost any vantage point. Flights can be preprogrammed to complete automated flight or images can be taken manually by the pilot. Recent advances now also include the ability of UAS to use artificial intelligence to determine its own flight paths to collect data after exploring an asset based on the definition of a simple volume by the pilot.

2.1.1.1 Intel Falcon 8+ Drone

The Intel Falcon 8+ UAS is a commercial platform featuring best-in-class redundant hardware, GPS, and sensor package with a high-end image payload. The Intel UAS consists of a rigid frame with 8 rotors, cockpit controller, interchangeable imaging payload mounted on a front center gimbal, and uses propriety Intel software for mission planning and post processing. The battery last for 15 minutes for a typical mission but with the high-resolution sensor this drone can collect a large amount of data per flight. A typical inspection mission can collect 375 42MP images in one flight. This UAS was used extensively throughout Phase IV. Overall, the experience and deliverable created using the Intel Falcon 8+ was the highest quality that has been achieved throughout all four phases of this research project.

The Intel Falcon 8+ features carbon fiber frame construction consisting of 2 rail bars in a V-shape. Each rail houses 4 rotors. At the center of the V is the payload and processing housing. The configuration of rotors allows for flight in wind speeds in excess of 30 mph. Furthermore, the lightweight construction provides best in class weight to payload ratio for excellent flight time. The V-shape provides for an unobstructed field of view from vertical down, 180 degrees to vertical up. The onboard electronic and hardware system features triple redundant flight control with three redundant Internal Measurement Units for quick and reliable data processing of position, altitude and orientation for excellent responsiveness and stability. The 8 rotors, dual batteries, and multiple communication links also offer built-in redundancy for optimal safe operation.

Figure 2.1 Intel Falcon 8+ Commercial Drone

The cockpit controller is the main control interface with the Falcon 8+ platform. The controller features a built in 8-inch touch screen display for imaging and flight planning and a designated 2-inch system information display for system vitals. The controller has two main joysticks similar to traditional UAS platform controls. However, the right joystick has an additional rotational sensor which makes single hand flight control possible at a set altitude. Toggle switches built into the sides of the controller allow for image payload operation with a single hand. With the innovations of this controller, it is possible for a single pilot to flawlessly fly a manual mission at a given altitude while simultaneously operating and manipulating the imaging payload.

Figure 2.2 Intel Falcon 8+ Cockpit Controller

The interchangeable imaging payload of the Falcon 8+ is what sets this UAS apart from other Commercial UAS platforms on the market. Several payloads exist for this platform. Two that stand out specifically are the survey package consisting of a Sony Alpha 7R full frame DSLR camera and the inspection package consisting of a near-infrared and full frame DSLR camera. The Sony Alpha 7R camera contains a full frame 36MP sensor with photography industry leading processing for excellent imaging in all lighting conditions and optimal image color and sharpness characteristics. The inspection package integrates infrared with full frame photography or high-definition video for real time image overlays and the ability to accurately locate and stamp defects in the field.

Intel Mission Control is a proprietary software suite created by Intel for mission planning for the Falcon 8+. The software features several mission types which can each be flown in series and edited to suit any flight condition. The software also allows for importing digital surface models created from higher altitude initial site flights. This provides a detailed background 3D image to plan flight missions.

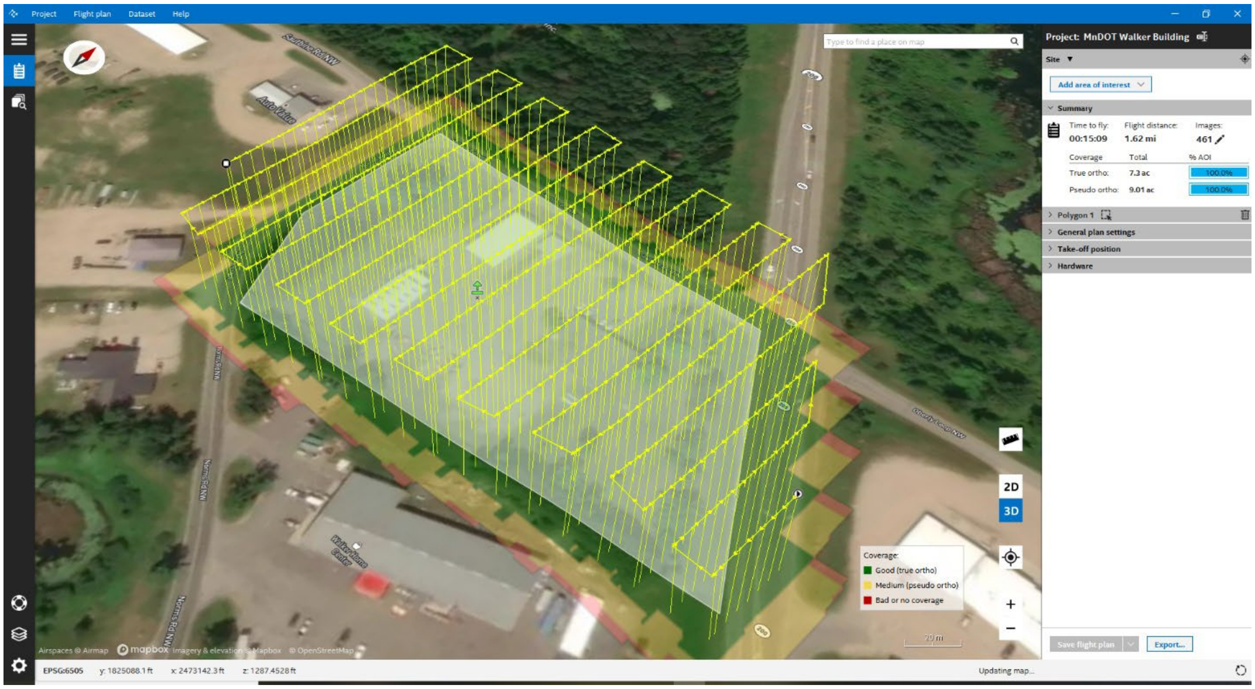

Figure 2.3 Intel Mission Control Flight Plan at Walker Truck Station

The realized benefits of the Intel Falcon 8+ UAS is the high quality, high precision images that allows for optimal inspection through post processing and a platform that is highly redundant, safe, and resilient to wind, electromagnetic, or various other external influences. Some of the realized limitations of the UAS is the high cost and lack of obstacle avoidance. The overall experience with the Intel Falcon 8+ was very positive, and it proved to be a reliable and durable platform for a best-in-class imaging payload.

Recognized benefits of using the Intel Falcon 8+ UAS:

- Ability to view vertically up and down
- Option of pre-programmed flight or interactive flight (manual flight controls)
- Most advanced flight planning software on the market for complex 3D flights
- High-Resolution high-quality images
- Ability to fly without GPS signal
- Up to 15 minutes of usable flight time
- Ability to collect a large amount of data in a short period of time
- Hardware and software are both resilient and reliable

Recognized limitations of the Falcon 8+ drone:

- Not suited for flight indoors
- Size of drone and controller makes it difficult to transport easily in the case

2.1.1.2 Intel Falcon 8+ Drone

The Skydio 2 is manufactured by Skydio as displayed in the image below is the second UAS platform made produced by Skydio. The Skydio 2 was initially marketed to adventure enthusiasts for cinematic use but has also been developed with inspection specific enterprise features includes the ability to use obstacle avoidance with a shorter 1-foot range. The environment in which this UAS was created requires autonomous flight through dense wooded areas and AI (Artificial Intelligence) capable of real-time navigation around obstacles. To accomplish this, the Skydio has a state-of-the-art obstacle avoidance and object sensing technology. Skydio produces and develops UAS in the United States.

Figure 2.4 Skydio 2

The Skydio's autonomy system and navigation camera system consists of a high-speed video processor and an on-board camera payload which create a real-time point cloud of the world around it. The onboard processor can create over 1 million points per second at a rate of 500 iterations per second. The camera payload for navigation consists of 6 cameras in a triangular configuration on the top and bottom. Each camera is a 4k Sony sensor with a super fisheye lens (200-degree field of view) creating a 360degree coverage of the environment around the camera. The generation of a 3D real-time point cloud in conjunction with AI based autonomous flight makes the Skydio an ideal candidate for flying in close proximity to structures and in confined spaces.

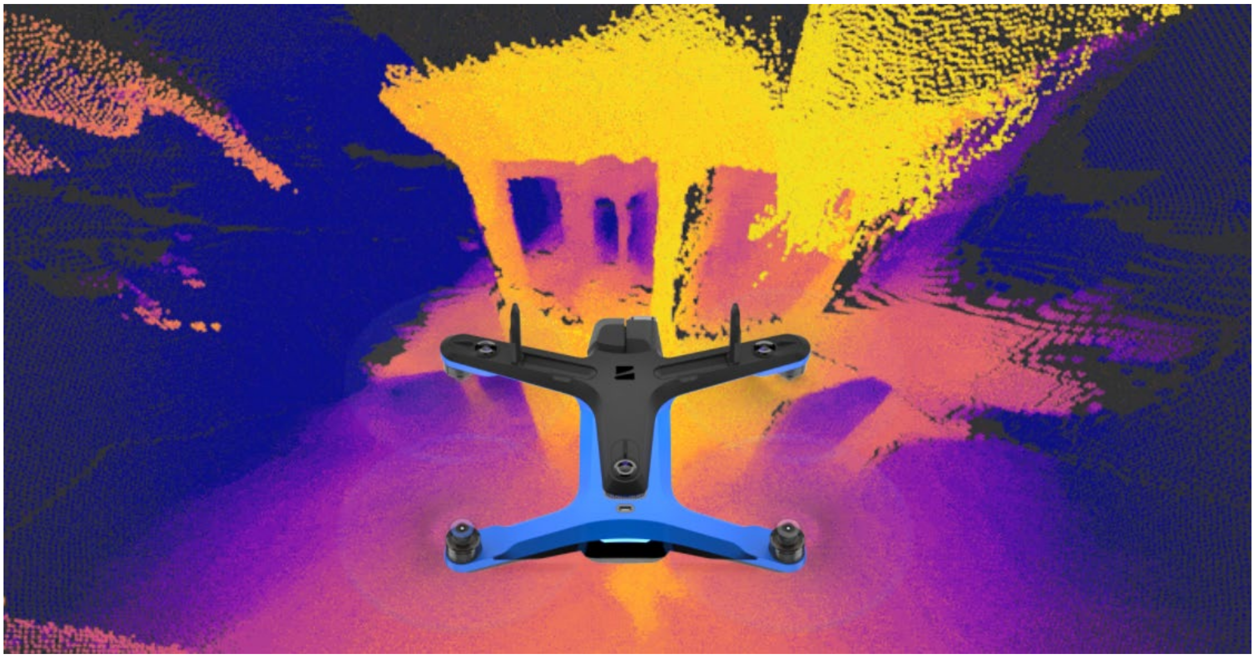

Figure 2.5 Skydio 2 Generated Point Cloud Environment for Obstacle Avoidance

Figure 2.6 Skydio 2 Flying in Tight Area Using Obstacle Avoidance

The onboard primary camera system consists of a Sony 12.3MP sensor capable of 12MP HDR still-photos or 4k HDR video. While this resolution of imagery is on the lower end of professional cameras, the ability to fly within inches of an object or surface makes the 12MP sensor more than adequate for building and site data collection. The following are some benefits and limitations of the Skydio 2 that have been recognized as a result of this study.

Recognized benefits of the Skydio 2:

Approximate price tag of $3,000 USD (Jan. 2022) Which includes the hard case and additional batteries. Enterprise features cost and additional $1,500 per year and the 3D scan tool is an additional $1,500 per year.

- 3D point cloud-based obstacle avoidance
- Rigid frame construction provides for a more rugged and reliable platform
- 4k HDR video capabilities allows for ideal images in all lighting conditions
- GPS receiver for accurate position data, image tagging, and stabilization
- 23-minute battery life
- 3D scan artificial intelligence data collection

Recognized limitations of the Skydio 2:

- Low resolution primary camera makes the UAS less than ideal for large area mapping
- No onboard lighting for internal confined space inspection
- Any moisture collection on the navigation cameras will prohibit flight

The results of exploring the use of collision-tolerant and obstacle avoidance UASs in building inspection were positive. The relative ease of use and minimal set up make the collision-tolerant and obstacle avoidance UASs a great addition to an inspector's toolbox. The Skydio 2 is certainly a tool for inspectors, which will help image buildings and building sites at a relatively low cost.

Figure 2.7 Skydio Collecting Data on MnROAD Research Building

The Skydio 2 drone platform has the ability to collect data using artificial intelligence through the use of the 3D Scan application. This application generally works by having the pilot define a volume in which an asset that needs to be scanned exists. Along with some resolution or distance to object setting the Skydio drone explores the volume, determines the physical dimensions and configuration of the object to be mapped and calculates the optimal flight patterns to collect data for a 3D model.

Figure 2.8 Skydio Collecting Data on MnROAD Research Building

2.1.2 Terrestrial Imaging

While UAS is one of the most effective ways to gather data traditional point and shoot, DSLR and phone cameras can also be used. Unmanned Aircraft Systems are one of the effective methods for collecting data. This data collected is typically in the form of photos that are located with GPS. The advantage of UAS results from the ability to take images from almost any vantage point. Flights can be preprogrammed to complete automated flights or images can be taken manually by the pilot. Recent advances now also include the ability of UAS to use artificial intelligence to determine its own flight paths to collect data after exploring an asset based on the definition of a simple volume by the pilot.

Figure 2.9 Point and Shoot Digital Camera for Photogrammetry

Using traditional cameras is natural to inspectors and thus, can be implemented with a relatively low additional cost for equipment. Photos taken using any modern digital camera can be an input for post processing software, however the deliverables greatly improved if the camera has the following features:

- GPS Location Enabled: Creates a geo-located image to assist post processing software to order and match images for a model or map.
- High resolution sensor: A camera having a 12MP or greater will allow for a model to be generated and can greatly enhance. In most cases the better resolution, the better the model.
- HDR (High Dynamic Range) Still Imagery: HDR provides excellent photography in all lighting conditions. Often with terrestrial imagery, sky, sun, or backgrounds are captured while obscuring the focus on dark elements such under soffits. HDR imagery assists in consistent image lighting, reducing instances of over or under exposure and saturation.
- Water / Dust / Impact Resistant: Inspection conditions are often in wet, dirty, and tough environments. Waterproof, shockproof, and dustproof camera features provide inspectors a durable and reliable platform with the potential use of underwater imagery for submerged element modeling.

Figure 2.10 DSLR Digital Camera for Photogrammetry

Less traditional to inspectors is DSLR (digital single-lens reflex) cameras. DSLR cameras are commercial grade, high resolution digital cameras. The benefits of these platforms are very high-resolution sensors, typically 36MP or more, which yields images that can display small defects from relatively far distances. The user input settings create better quality images in low light conditions or high-speed photography but requires the user to have a significant understanding of photography. GPS enabled feature are not as common in DSLR cameras and they are much less durable in wet or rough environments, which limits their use in inspections.   A variety of aftermarket lenses such as wide angle or optical zoom options are available for these cameras, but not all are recognized by the post processing software. The use and type of a DSLR camera and lenses should be determined and vetted through post processing software prior to implementing in the field.

The largest change and increasing potential in photography platforms is smart phones or tablets. Many phone/tablet producers are making their cameras and image processing focal points in their list of features. The significant ease of use, requiring very little knowledge of traditional photography, makes smart phone or tablet imaging a very reliable deliverable. Additionally, smart phones and tablets continue to have increased resolution sensors which compete with or exceed the ability of point and shoot cameras. Most modern smart phones and tablets have excellent GPS signal and are durable and resilient to wet or tough conditions. Most inspectors carry some version of a smartphone and, in lieu of other technologies, can use these for quick on-site imaging. Some smartphones and tablets are introducing (Feb 2020) LiDAR and other imaging payloads as a supplement to their onboard imaging payload which will further set these data acquisition tools apart from the traditional point and shoot cameras.

2.1.3 Lidar Scanning

Lidar and laser scanning are additional popular technologies that can be used to scan and model exterior and interior spaces. These technologies tend to be more expensive but produce quality professional-level results. MnDOT currently owns a GeoSLAM handheld lidar unit and our team captured data on two buildings as part of this project.

LiDAR is a remote sensing technology which uses the pulse from a laser to collect measurements. LiDAR is an acronym of Light Detection and Ranging, also known as laser scanning or 3D scanning. SLAM stands for simultaneous localization and mapping. Combining these technologies provides the ability to 3D scan indoor spaces.

Figure 2.11 GeoSLAM Mobile Scanner

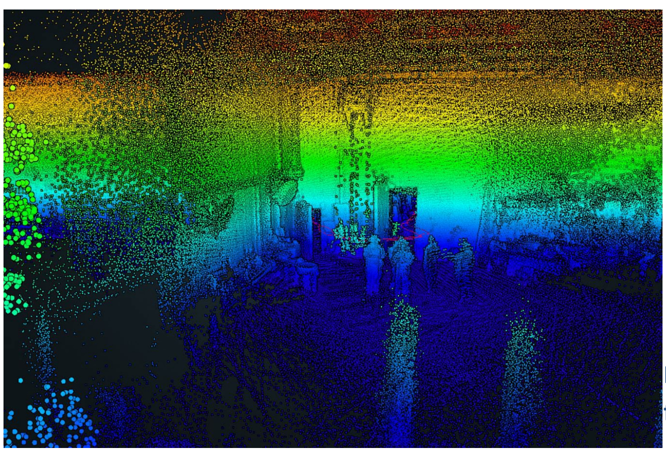

Figure 2.12 Pointcloud Derived from GeoSLAM

2.1.4 360 Degree Cameras

There are numerous 360degree cameras now on the market that can capture 360 video and images of interior spaces. These cameras can be used simply to create imagery for reference or can take images to be processed into 3D models. These cameras are generally cheap and easy to use and implement.

Professional level 360 imaging equipment also exists that can scan interior spaces into 3D models. Matterport is one example, and the technology is popular in both the real estate industry and commercial-type applications. With either professional or consumer level equipment, measurements can be made, and floor plans extracted.

Figure 2.12 Ricoh Theta Z1 360 Camera

Figure 2.13 Matterport Scan from Ricoh Theta Images

2.1.5 Ground Control

AeroPoints are drone-specific aerial targets that record their own position using GPS, which is processed and corrected to ensure survey-grade accuracy. The benefit of this technology is that inspectors do not need the traditional base and rover surveyors to mark benchmarks prior to flying and these serve as both the GPS collector and the image target in one package. The use of these smart targets greatly increases the accuracy of data from +\- 6-foot accuracy to sub-inch accuracy.

Figure 2.14 Propeller Aeropoint UAS Survey Target

2.1.6 QR Codes

QR Codes (Quick Response Codes) is an adaptation of traditional 1-dimensional bar codes. QR codes contain a 2D matrix of pixels which are unique and can contain location or identification information. Placing QR codes on targets in various places during a data collection onsite prior to imaging can greatly increase the efficiency of processing and quality of the final product. QR code images are publicly available and were implemented during Phase IV. The size of the QR code was examined to determine the optimum target for a camera resolution at a given distance. Application of QR codes to different mediums were explored to test the durability, reflectivity, ease of application, and longevity of each installation. The type of target and method of adherence was proven to be independent of the specific material and environment; however, the application of QR codes was proven to work in nearly any location or condition.

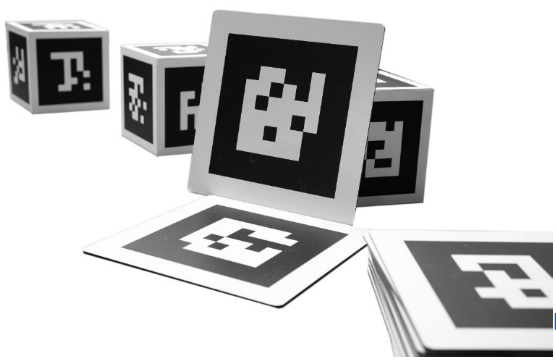

Figure 2.15 QR Code Targets

If the software is uncertain about surfaces or areas, it may produce a model that is incorrect and requires an engineer to enter Manual Tie Points (MTPs) in the model to improve model accuracy and clarity. This method is generally used after the first step is processed where the user can focus on areas of concern. Once an area is identified to improve, the user cycles through the images calibrated within the chosen area to manually mark or adjust key points. This process can be very tedious and time consuming on large structures.

After placing the QR codes throughout the area to be imaged in conspicuous locations, the user can proceed as normal with acquiring UAS or Terrestrial Imagery for a model. Contextcapture is the post processing software, and it will automatically find these QR codes and create manual tie points from them which aids in the processing.

Figure 2.16 Code Target Adhered to Salt Shed Wall

2.1.7 Mixed Reality

he Minnesota Department of Transportation Bridge Inspection Group and Collins Engineers have been working with Bentley Systems and Microsoft in developing software for the Microsoft HoloLens 2 to be able to perform virtual inspections using mixed reality. A 3D reality model can be loaded on a Hololens headset, and the user can not only view the virtual building or building site in a hologram but can also make measurements, add notes, add, and classify defects and denote elements. Utilizing mixed reality can allow users to populate or review inspection data from their office and allows for the sharing of site data with experts in other locations.

Figure 2.17 Microsoft Hololens 2 headset

Figure 2.18 Holographic Overall Site View of Walker Truck Station from HoloLens 2

Figure 2.19 Holographic View of Walker Truck Station Building from HoloLens 2

2.1.8 Virtual Reality

Models can also be viewed in a virtual reality environment with the Oculus Quest VR headset or similar. Specifically, Matterport models can be viewed using this hardware through a web browser within the

Oculus system. Us. virtual reality can give users a sense of scale not available by viewing models with a computer screen alone.

Figure 2.20 Oculus Quest 2 VR Headset

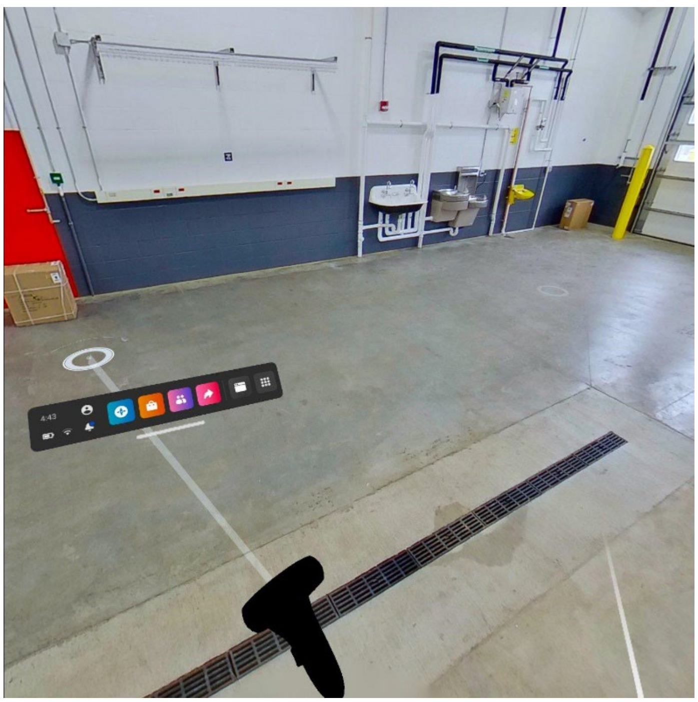

Figure 2.21 Mixed Reality Virtual Tour with Oculus VR Headset

2.2 DATA PROCESSING

2.2.1 Post Processing Software

After data is collected in the field in the form of images, GPS tags, ground control and manual tie points the next step is to process that data into deliverables. These deliverables can be in many formats including 3D reality models, 2D orthomosaics and 2D orthoplanes all of which can be geometrically and geospatially correct on the order of sub-centimeter accuracy. These outputs can be used locally or shared with others via cloud platforms. Many software platforms exist to create deliverables and our study is not intended to give recommendations on specific software but, to discuss and compare in general terms the features that are beneficial to team members. Post processing software is as important as the drone hardware and often gets overlooked in the process. Our team used Pix4D and Contextcapture to process reality models and used Fuji Film Infrastructure Photo Analysis and Contextcapture Insights for artificial intelligence applications.

Data collection is the first step in the workflow with data processing being the next step. Data that is collected in the field generally needs to be processed into deliverables that can include 3D point clouds, 3D meshes, orthomosaic maps, and orthoplanes. The software processing are typically referred to as reality modeling and the deliverables are described as digital twins.

Reality modeling software transforms 2D images from drones or terrestrial cameras into 2D and 3D deliverables. The software works by analyzing the input images to identify common points between images. Trigonometry is used along with camera lens information to create a 3D model of the area where the images were taken. Images need to be taken with very high overlap of between 70-80%. While reality modeling is considered a new technology the processes are based on photogrammetry which is a technology that is well established and used in the civil industry for many years. This ensures there are common points in many images. The term reality modeling derives from the process of turning images into a model that approximates reality visually, dimensionally and if ground control is used geospatially as well.

All reality modeling software packages are very computer resource intensive and utilizing computers with high end processors and memory is desirable to decrease processing times which can vary from hours to days to process larger models. We processed data for this research effort in Contextcapture, Pix4D, GeoSLAM, and Matterport.

2.2.1.1 Contextcapture

Contextcapture is developed by Bentley Systems and is a high-end reality modeling software that can process images and ground control into digital twins. The software produces point clouds, meshes and orthomosaics. Contextcapture excels at producing high quality models of complex 3D assets. This software can process locally and, on the cloud, and models can be shared via the cloud platform Contextshare.

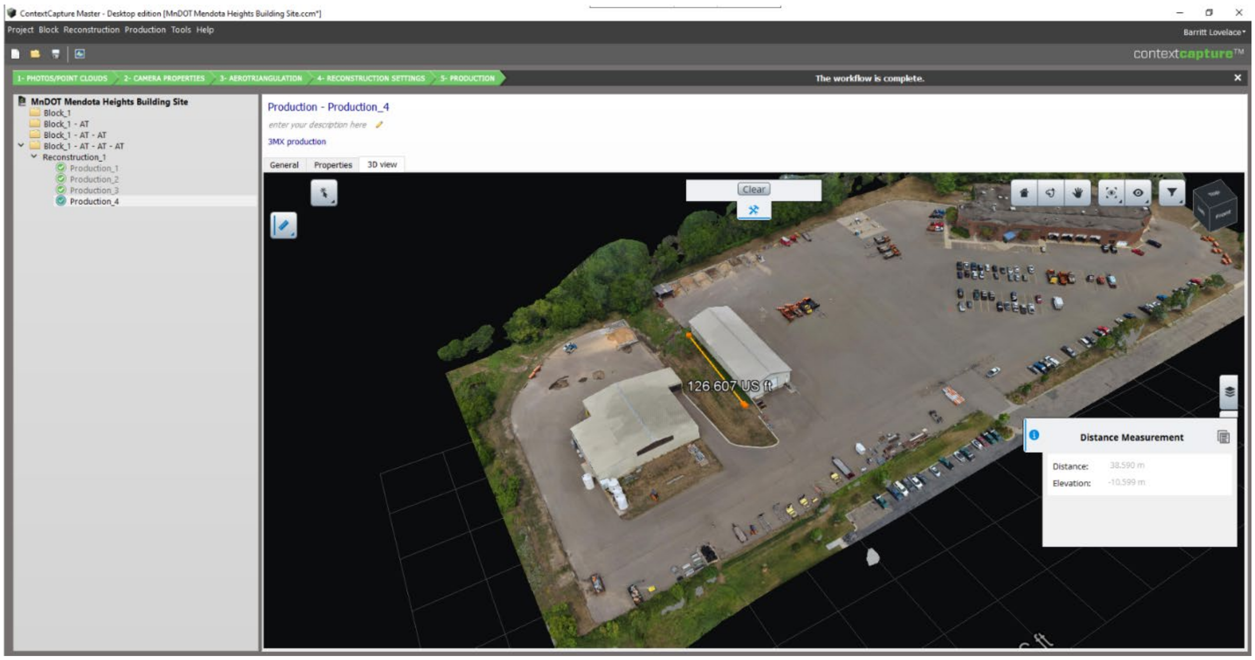

Figure 2.22 Contextcapture Model of Mendota Heights Site

2.2.1.2 Pix4D

Pix4D is developed by the company Pix4D and is a popular reality modeling software that can process images and ground control into digital twins. The software produces point clouds, meshes and orthomosaics. Pix4D excels at site maps but struggles with complex 3D asset modeling. This software can process locally and, on the cloud, and models can be shared via the cloud platform.

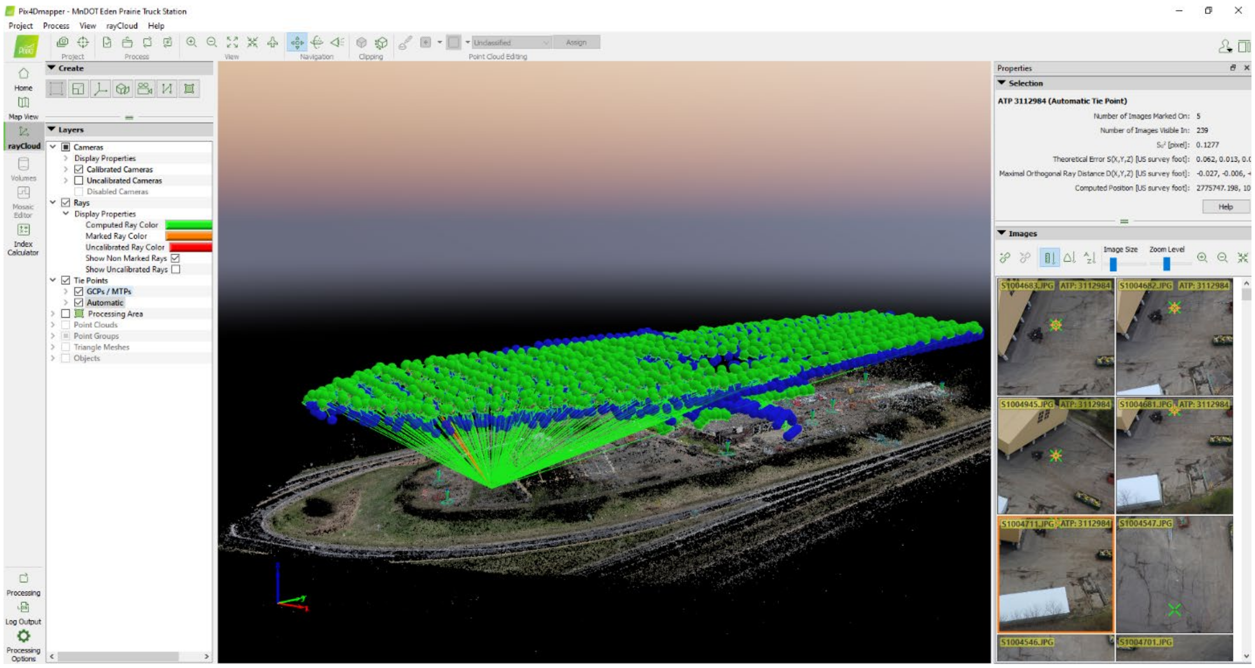

Figure 2.23 Pix4D Post Processing of Eden Prairie Truck Station

2.2.1.3 GeoSLAM Hub

GeoSLAM Hub is a software developed specifically for the GeoSLAM mobile lidar products. This software post processes the data into point clouds. Not strictly a reality modeling software it does not produce point clouds or meshes that resemble the physical asset other than in shape. It does have a method for connecting images taken from GoPro camera video that is attached to the unit while scanning. Data can be exported into building layouts.

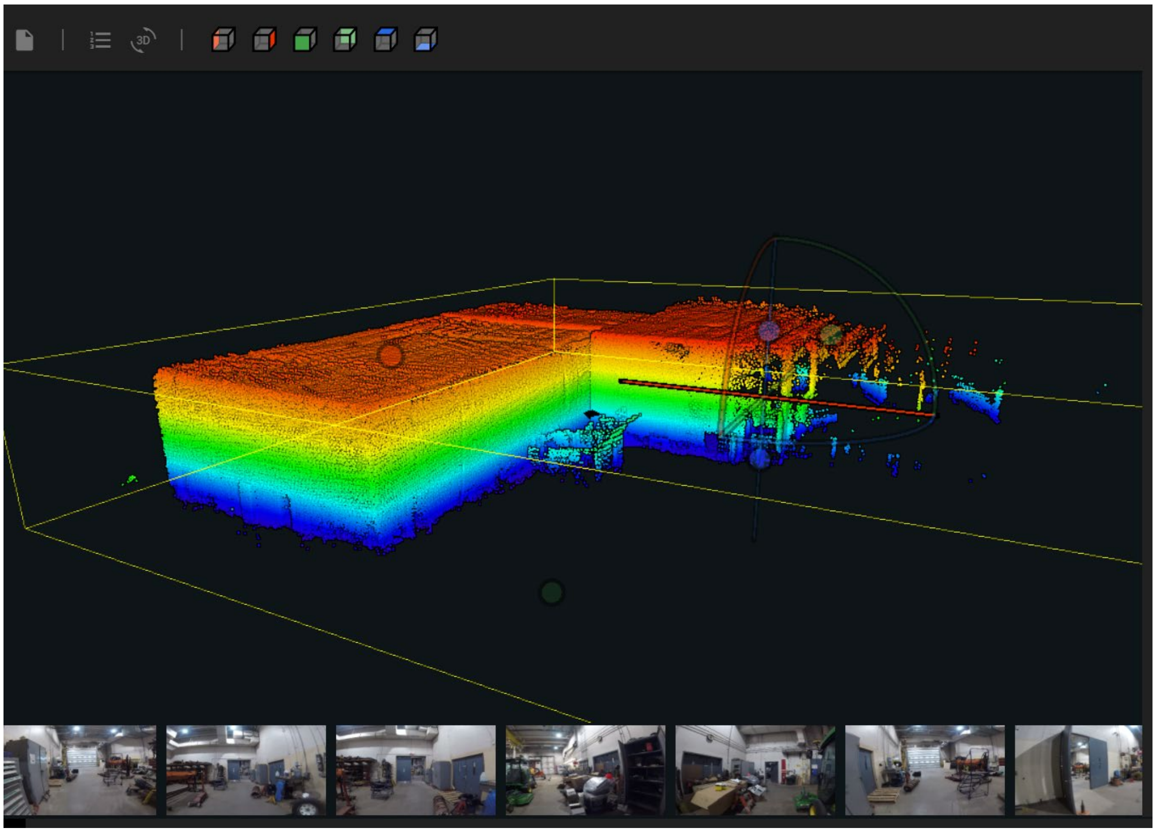

Figure 2.24 GeoSLAM Post Processing Software

2.2.1.4 Matterport

Matterport is a cloud-based processing software that processes images taken through the Matterport application on a phone or tablet computer and processes those images and shares the results on a cloud platform. The platform is popular within the real estate industry and is often used to show houses in a virtual format. The technology also lends itself well to our application which is more commercial. The models can be easily viewed via the cloud platform and measurements can be taken of the spaces as needed. This software is also not strictly a reality modeling software but has many of the same components. The software was very easy to use in scanning a building can be done quickly and results available within a short period of time. Schematic floor plans can be downloaded of the spaces for use in a CAD environment. Spaces can also be viewed in a virtual reality environment via an Oculus Quest headset.

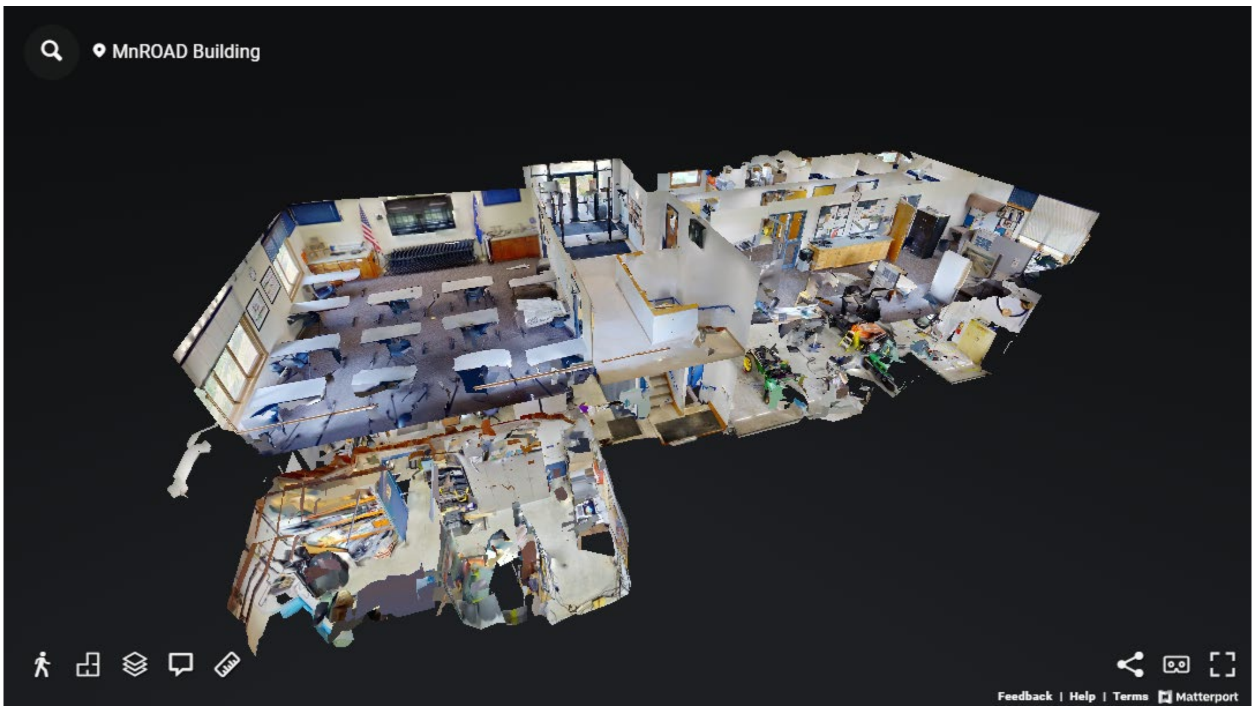

Figure 2.25 Matterport Dollhouse View of MnROAD Research Facility

2.2.2 Post Processing Hardware

Post processing the data into 2D and 3D deliverables is a computer hardware intensive process. Processing large models can sometimes take 1-2 days of processing time. In order to improve the process, the data for this research effort was processed on high end computers with fast processers, graphics processing units and hard drives. These computers are very similar to high end gaming computers. Many of the post processing software packaged mentioned previously can process models via a cloud as well so that local processing resources are not needed. These computers cost approximately $5,000.

Figure 2.26 High End Processing Computer Setup

2.3 DATA SHARING

2.3.1 Cloud Sharing

Cloud sharing platforms are available from Contextcapture, Pix4D and Matterport. The ability to share digital twins via a web based environment is a game changer and allows anyone with permission from any location to access and utilize these models with only a computer and browser. Users can view the models in several formats including 2D orthomosaics, 3D point clouds and 3D meshes. Matterport allows viewing of the 3D images of the interiors similar to Google Streetview. Matterport also shows a schmatic type 3D model of the building. Users can take measurements and use photo navigation features to view original images of areas simple by clicking on that area.

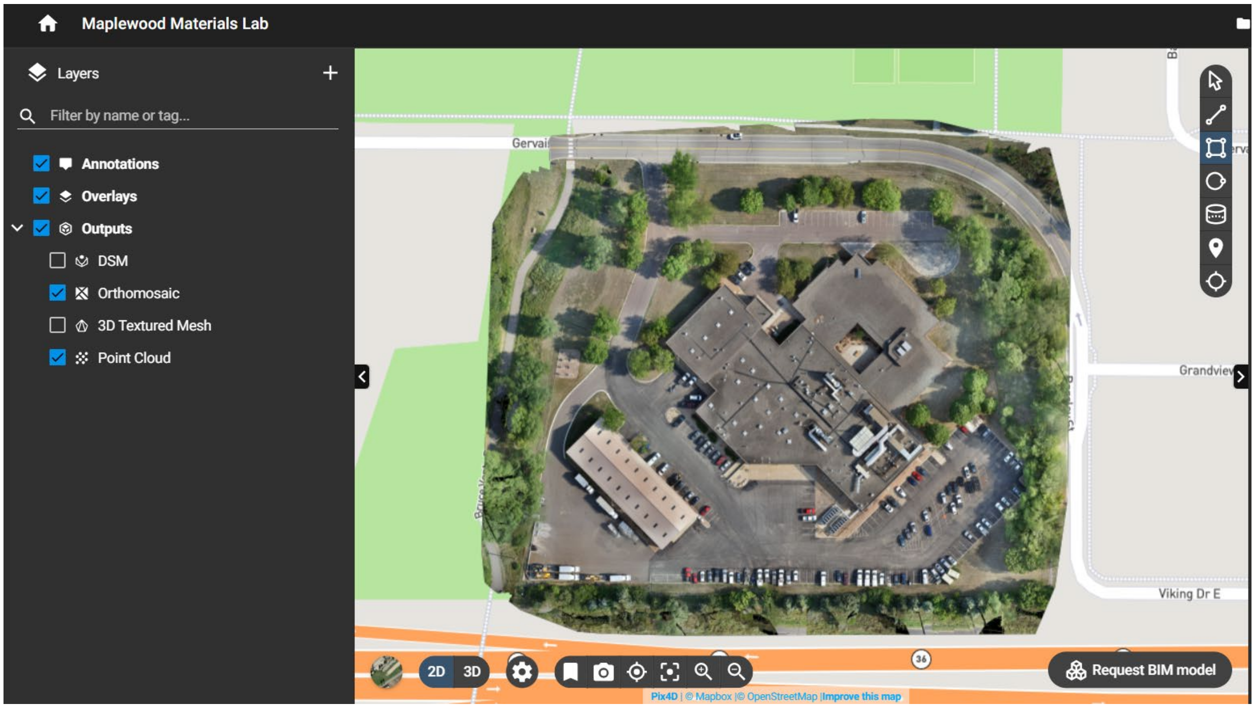

Figure 2.27 **Pix4D Orthomosaic Cloud Sharing**

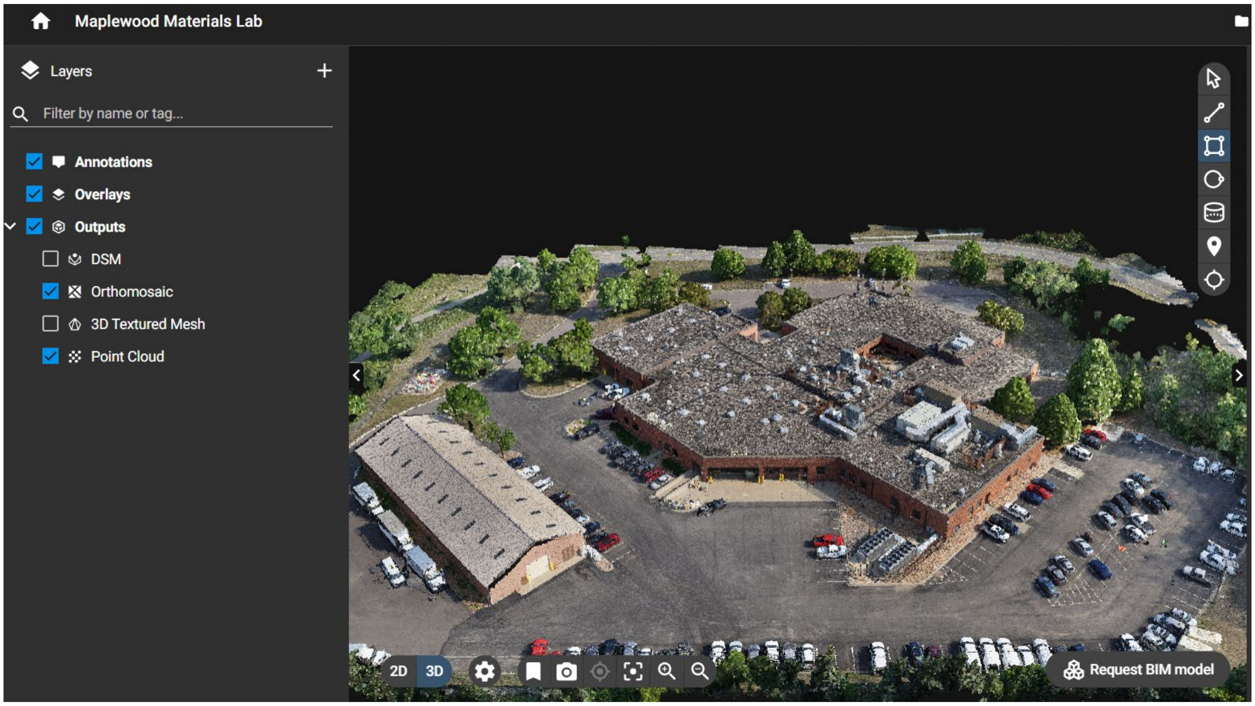

Figure 2.28 **Pix4D Point Cloud Web Sharing**

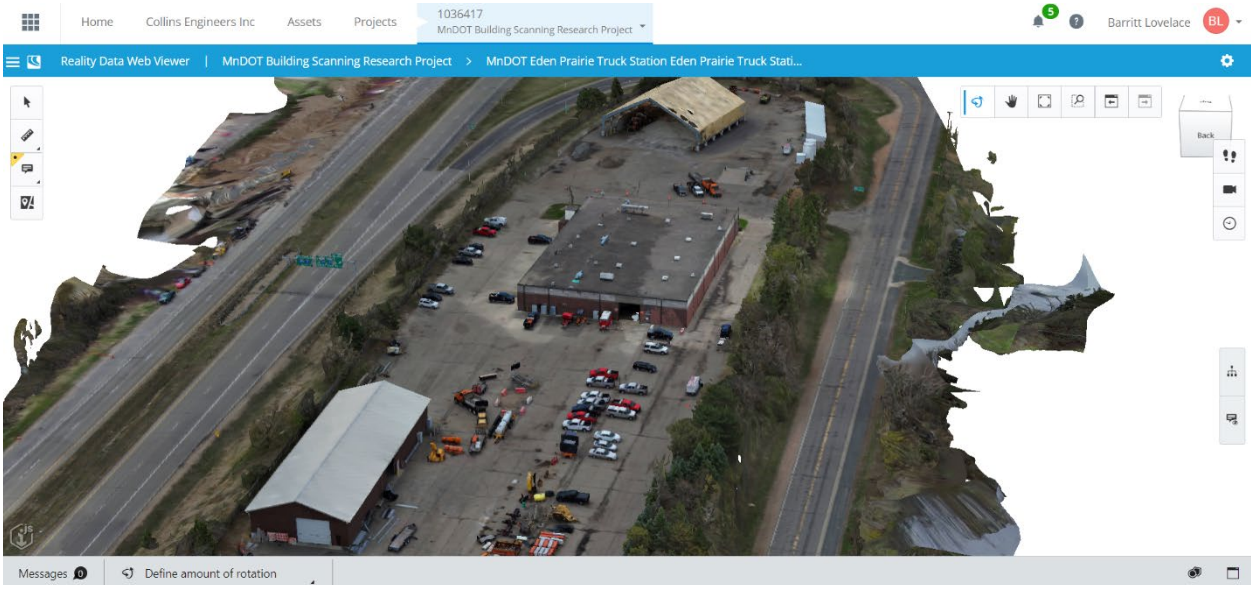

Figure 2.29 **Contextshare 3D Mesh Cloud Sharing**

CHAPTER 3: BUILDING AND BUILDING SITES

3.1 DATA COLLECTION AND DELIVERABLES

As part of this research effort data was collected at seven MnDOT sites. A combination of different technologies and software were used at each site to compare workflows and results as summarized below:

	Data Collected					Data Processed		
Building Site	**Intel**	**Sky dio**	**Skydio 3D Scan**	**Matterport**	**GeoSLAM**	**Matterport Interior**	**Pix4D**	**Bentley (Login Required)**
Walker Truck Station	Yes	Yes		Yes		Link	Link	Bentley Cloud Services
Brine Building	Yes	Yes		Yes		Link	Link	Bentley Cloud Services
Unheated Storage	Yes	Yes		Yes		Link	Link	Bentley Cloud Services
Unheated Storage 2	Yes	Yes		Yes		Link	Link	Bentley Cloud Services
Chaska Truck Station	Yes						Link	Bentley Cloud Services
Eden Prairie Truck Station		Yes	Yes				Link	Bentley Cloud Services
MnROAD Research	Yes, 2X	Yes	Yes	Yes		Link	Link	
MnROAD 2021 Site						_	Link	
MnROAD 2022 Site						_	_	
MnROAD 2022 Building						Link	_	Bentley Cloud Services
Cedar Truck Station					Yes			
Maplewood Material Lab	Yes						Link	Bentley Cloud Services
Mendota Truck Station		Yes					Link	Bentley Cloud Services

Table 3.1 Building Sit Scanning Data Summary

3.1.1 Walker Truck Station

The Walker Truck Station is located in Walker Minnesota and the main building is relatively new opening in 2019. The site consists of a main building, salt shed and three accessory buildings. Data of the overall site was collected with both the Intel Falcon 8+ and the Skydio two drone and was post processing in Contextcapture and Pix4D. Aeropoint automatic ground control targets were used for the overall site data collection and modeling. The interior was captured with a 360 Degree camera with Matterport to capture the building interiors. The entire data collection took one person less than a full day to collect. A video summary of the data collection and post processing can be found here.

3.1.1.1 Data Collection

Data Collected

- Intel Falcon 8+ Drone Overall Site
- Skydio 2 Drone overall Site
- Matterport Interiors (4 buildings)

Figure 3.1 Building Site Scanning Data Summary

3.1.1.2 Processed Data

Data was processed in Pix4D, Contextcapture and the interior 360degree images were processed in Matterport. The Intel Falcon 8+ images produced the most detailed models as expected with its 36 MP DSLR camera. The Skydio 2 still produced good results, but the 12 MP camera makes it more difficult to get comparable results without flying at a much lower altitude than the Intel Falcon 8+. Contextcapture generated significantly better results even with the same Intel Falcon 8+ images. The figures below compare and contrast the differences in model quality between drones and processing software.

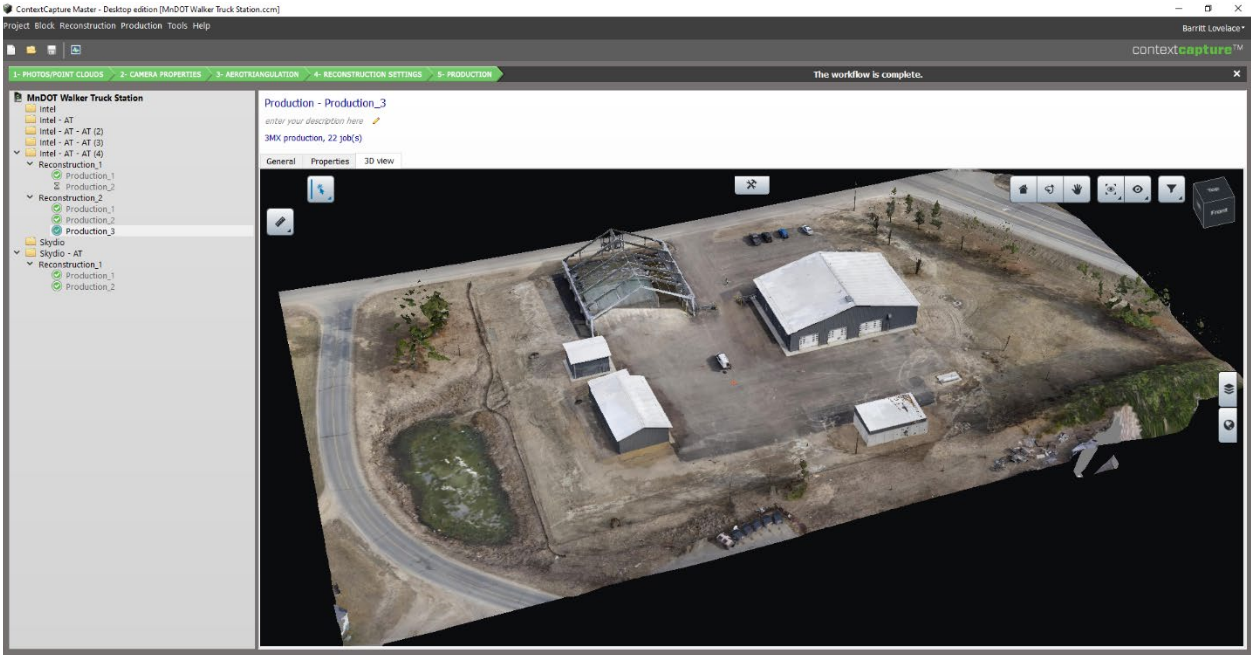

Figure 3.2 Contextcapture Model of Walker Truck Station Site

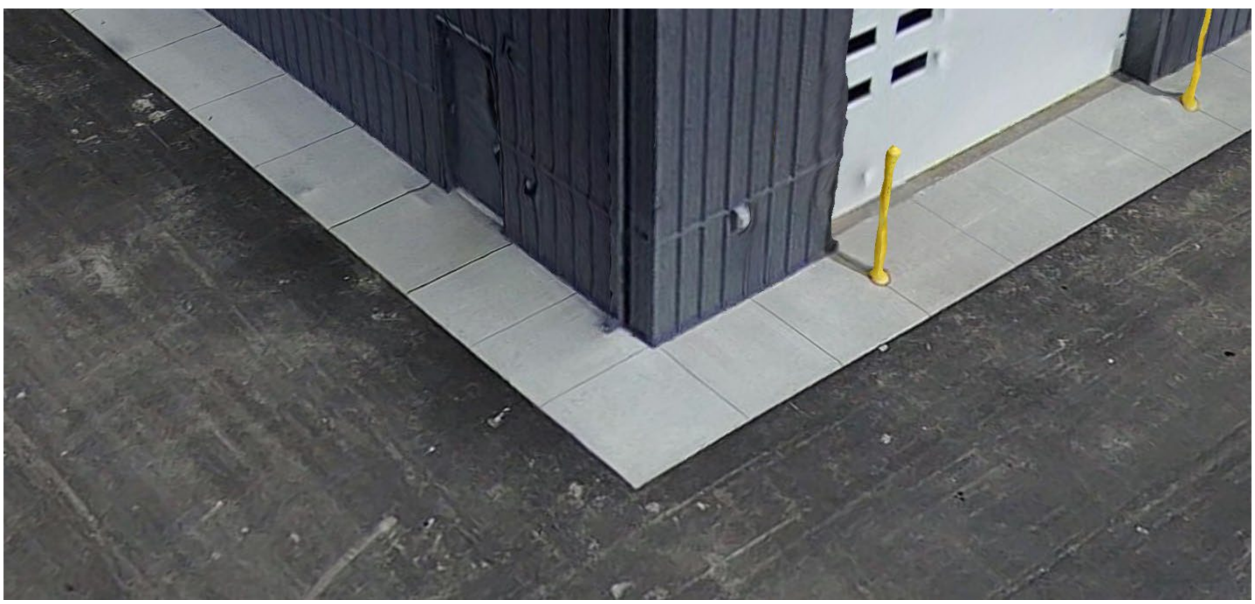

Figure 3.3 Close Up of Contextcapture Model using Skydio 2 Input Images

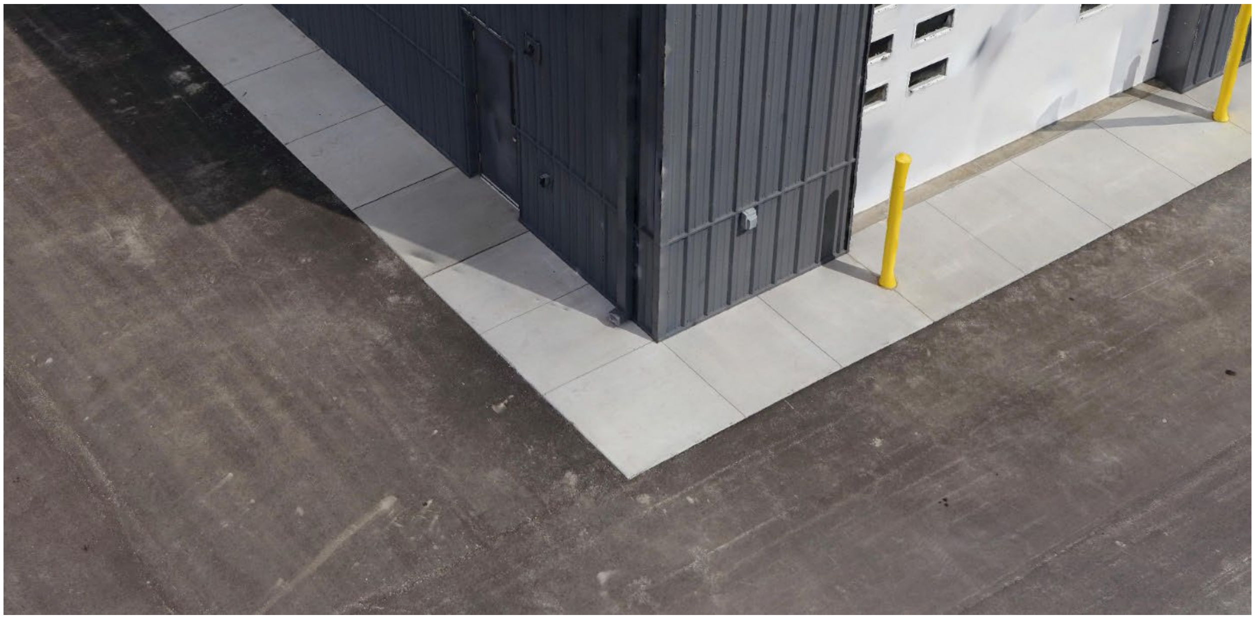

Figure 3.4 **Close Up of Contextcapture Model using Intel Falcon 8+ Input Images**

Figure 3.5 Close Up of Pix4D Model using Intel Falcon 8+ Input Images

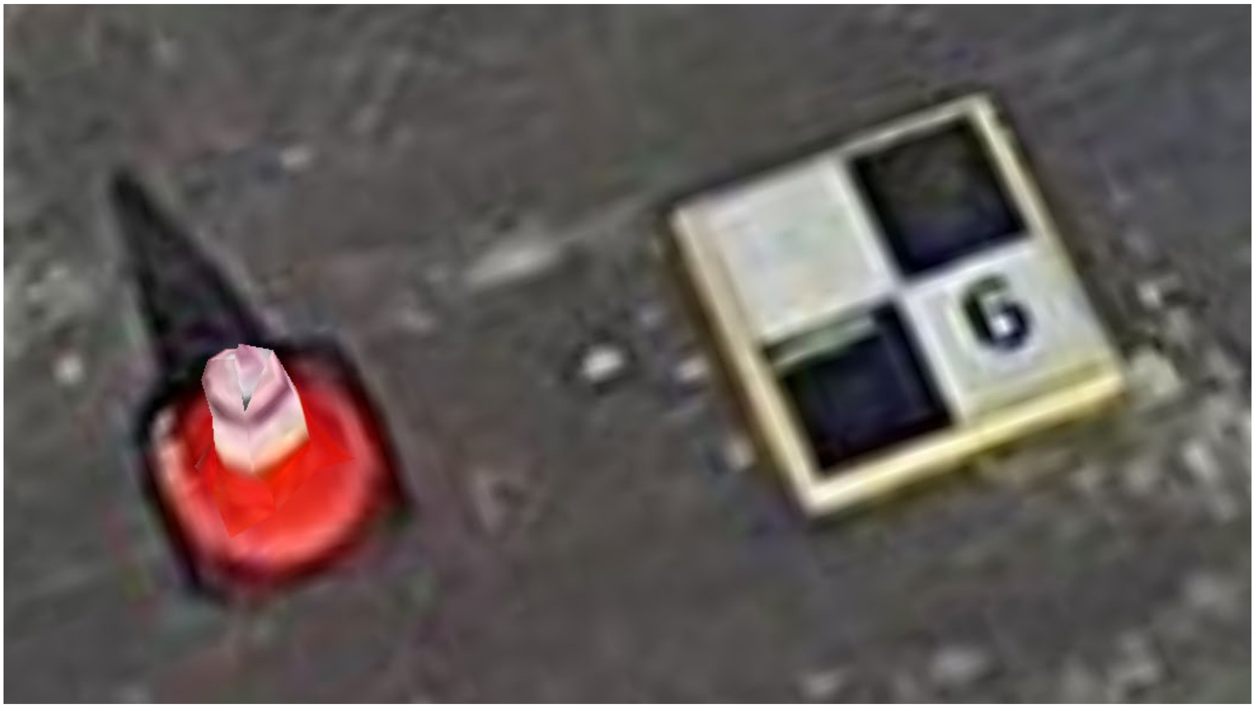

Figure 3.6 **Close Up of Contextcapture Model using Skydio 2 Input Images**

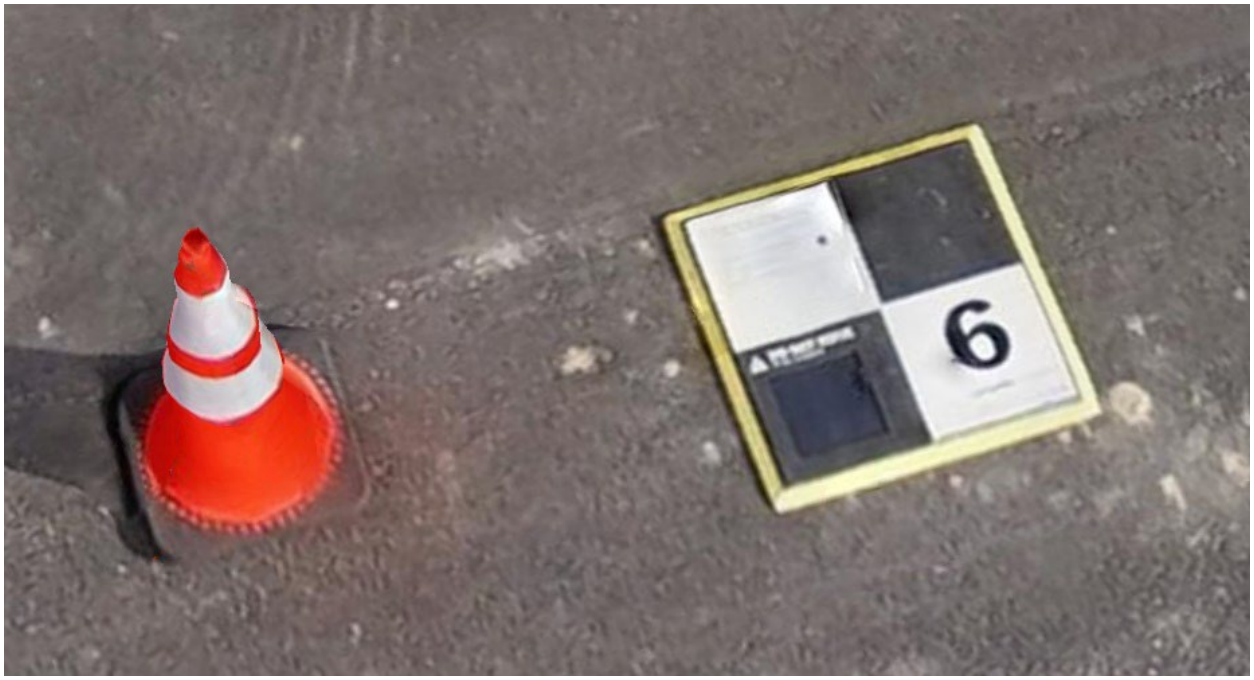

Figure 3.7 Close Up of Contextcapture Model using Intel Falcon 8+ Input Images

Figure 3.8 Close Up of Pix4D Model using Intel Falcon 8+ Input Images

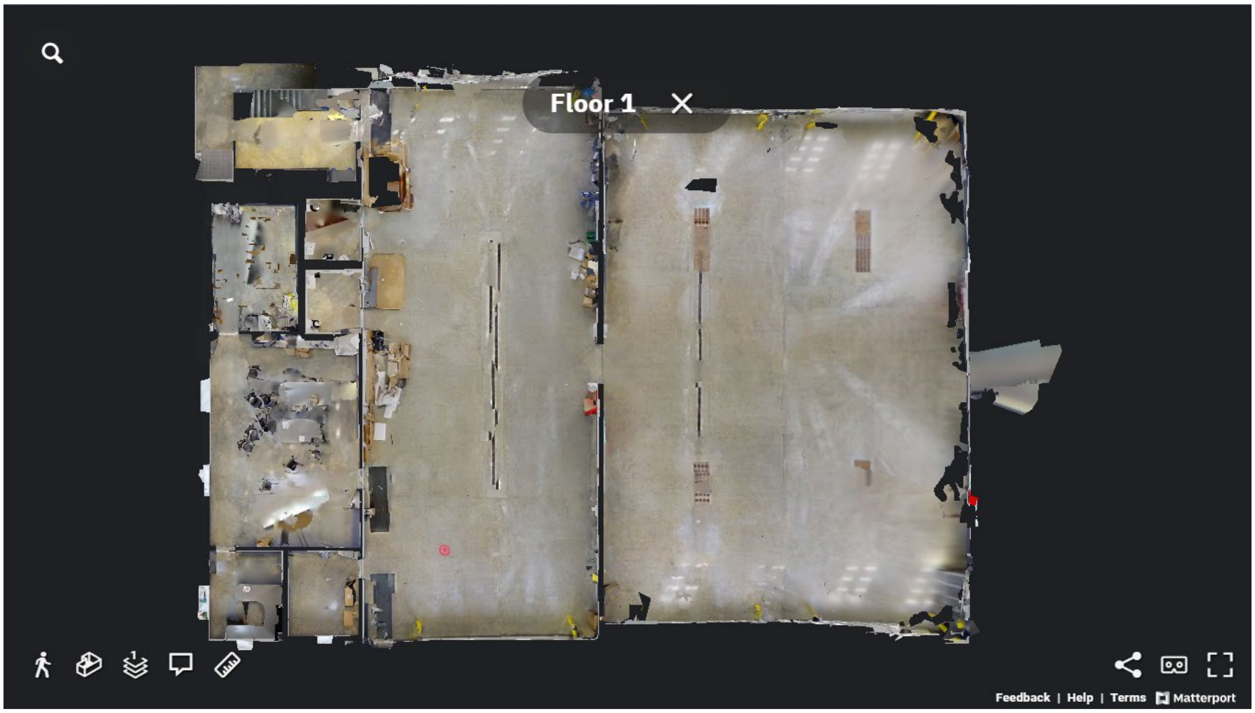

Figure 3.9 Matterport Building Layout View

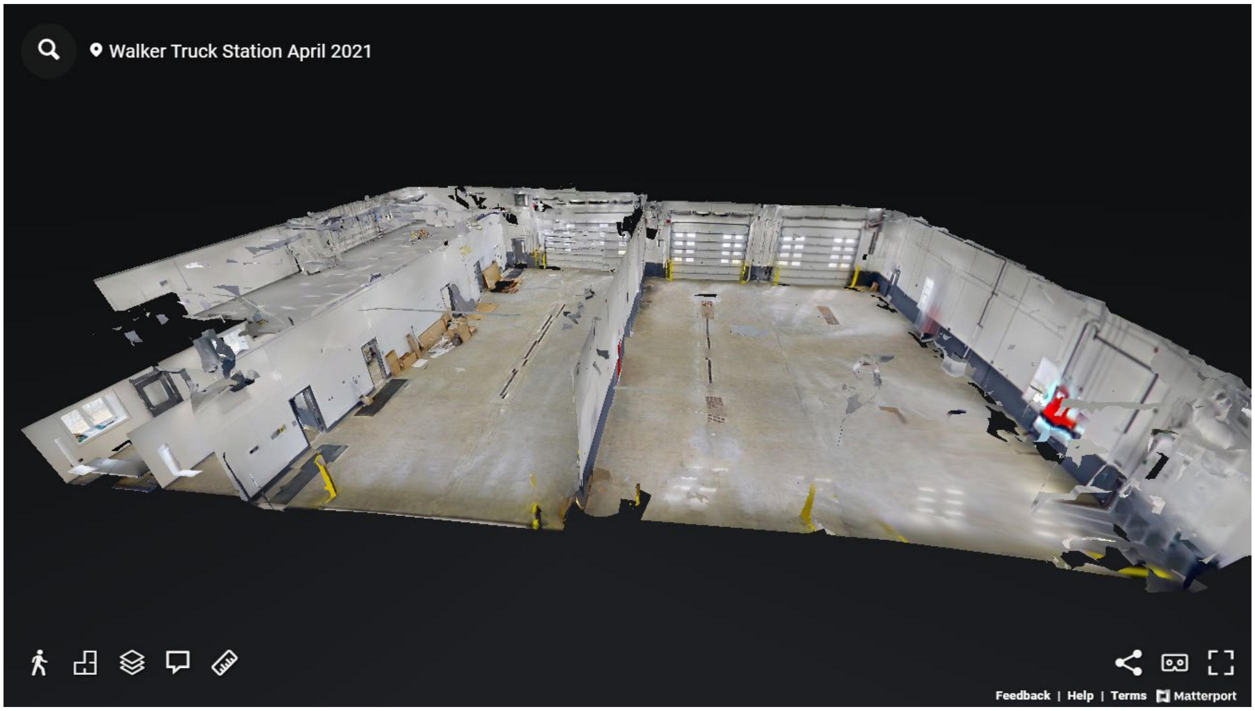

Figure 3.10 Matterport Dollhouse View of Building

3.1.1.3 Data Sharing

Models of the Walker Truck Station Site were shared on the Pix4D Cloud, Contextshare and Matterport. These models can be viewed by anyone with a web browser and the proper link and credentials. The Contextshare models were also shared in mixed reality via the Microsoft Hololens 2 headset and the Matterport interior models can be viewed in virtual reality with the Oculus Quest headset. Examples are show below and links can be found in the table at the beginning of this section.

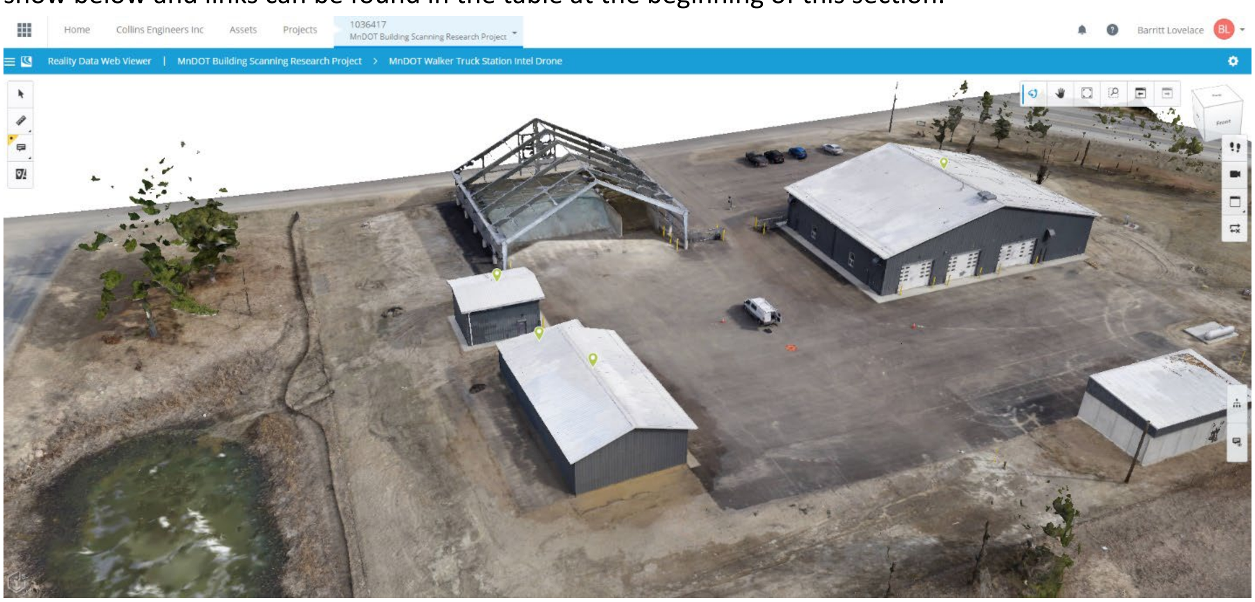

Figure 3.11 Contextshare Cloud Model of Walker Truck Station Site

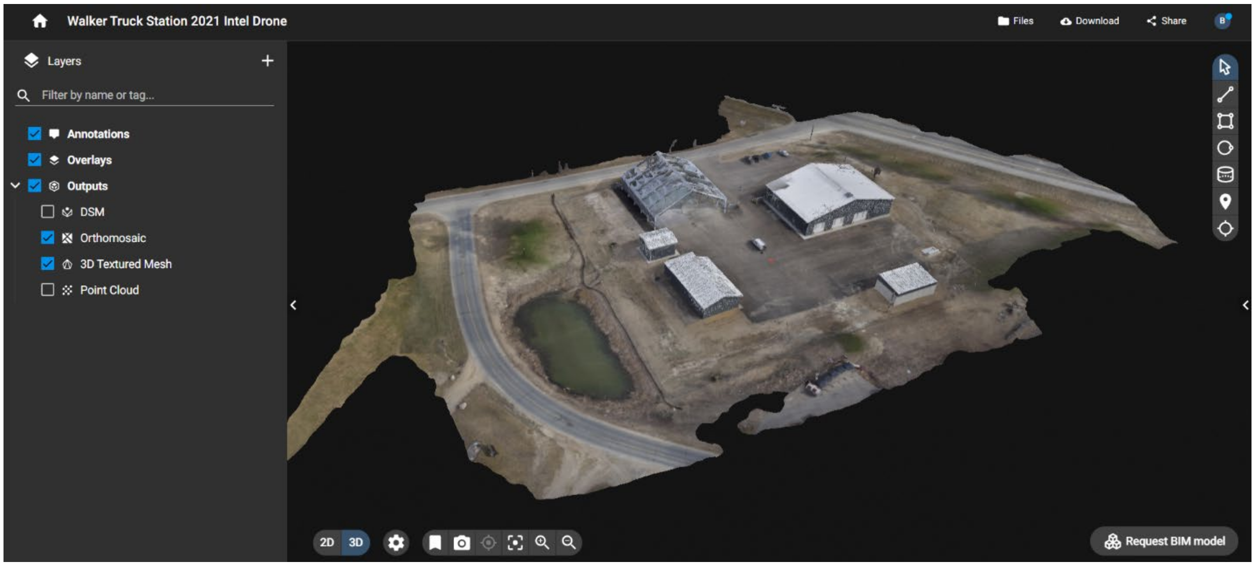

Figure 3.12 Pix4D Cloud Model of Walker Truck Station Site

Figure 3.13 Microsoft Hololens 2 Screenshot of overall Walker Truck Station Site

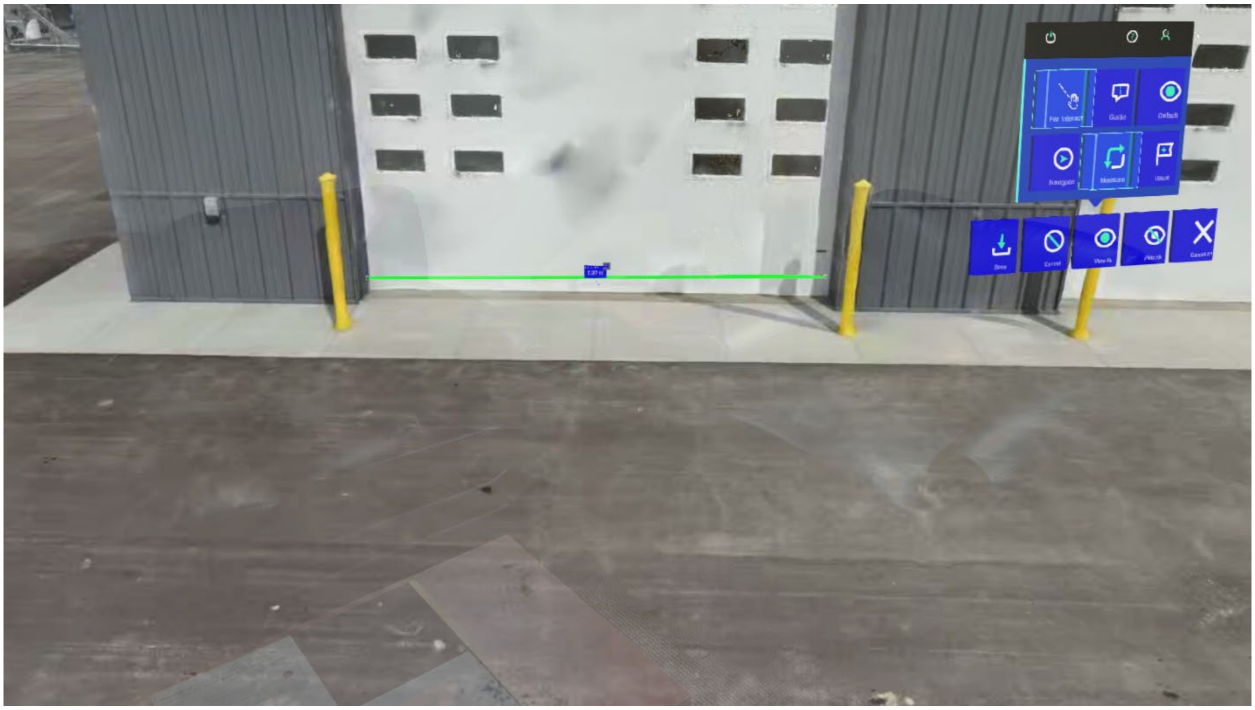

Figure 3.14 Microsoft Hololens 2 Screenshot of Walker Truck Station Site

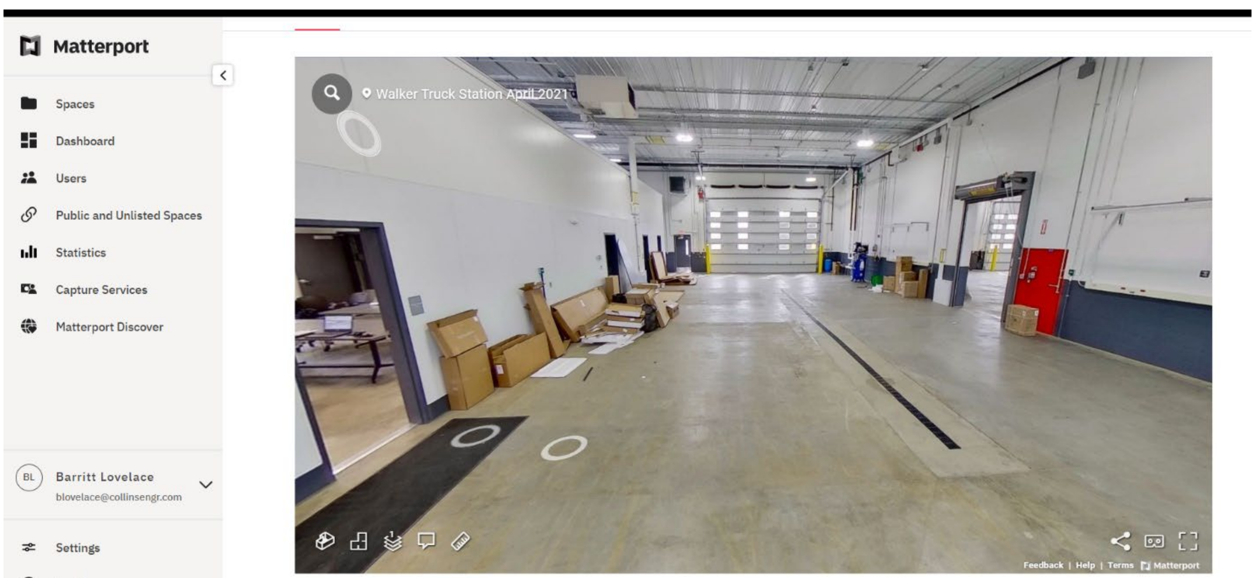

Figure 3.15 Matterport Screenshot of Walker Truck Station Site

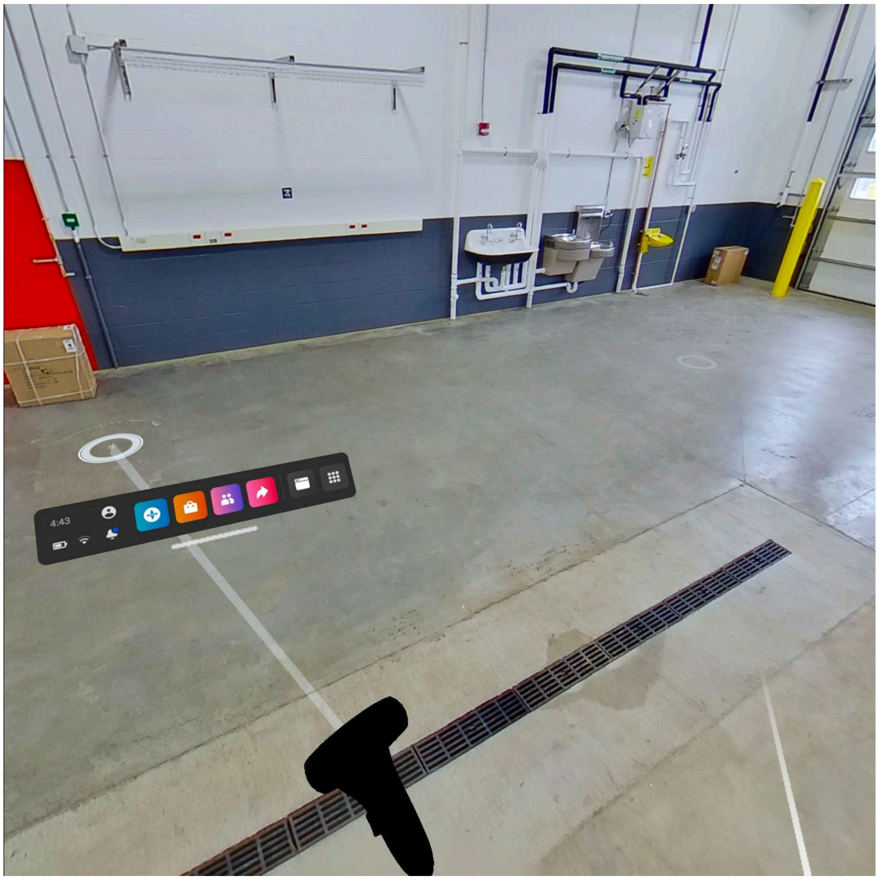

Figure 3.16 Matterport Virtual Reality Screenshot of Walker Truck Station Site

3.1.2 Chaska Truck Station

The Chaska Truck Station is located in Chaska, Minnesota. The site consists of a main building, salt shed and three accessory buildings. Data of the overall site was collected with the Intel Falcon 8+ drone and was post processing in Contextcapture and Pix4D. Aeropoint automatic ground control targets were used for the overall site data collection and modeling. The entire data collection took one person 3 hours to collect.

3.1.2.1 Data Collection

Data Collected

- Intel Falcon 8+ Drone Overall Site

Figure 3.17 Intel Falcon 8+ Drone Collecting Data Over the Chaska Truck Station

3.1.2.2 Processed Data

Data was processed in Pix4D, Contextcapture. The Intel Falcon 8+ images produced detailed models as expected with its 36 MP DSLR camera. Contextcapture generated significantly better results than Pix4D even with the same Intel Falcon 8+ images. We flew the drone inside the salt shed and can use the models to generate stockpile volumes within the models. The figures below compare and contrast the differences in model quality between processing software packages.

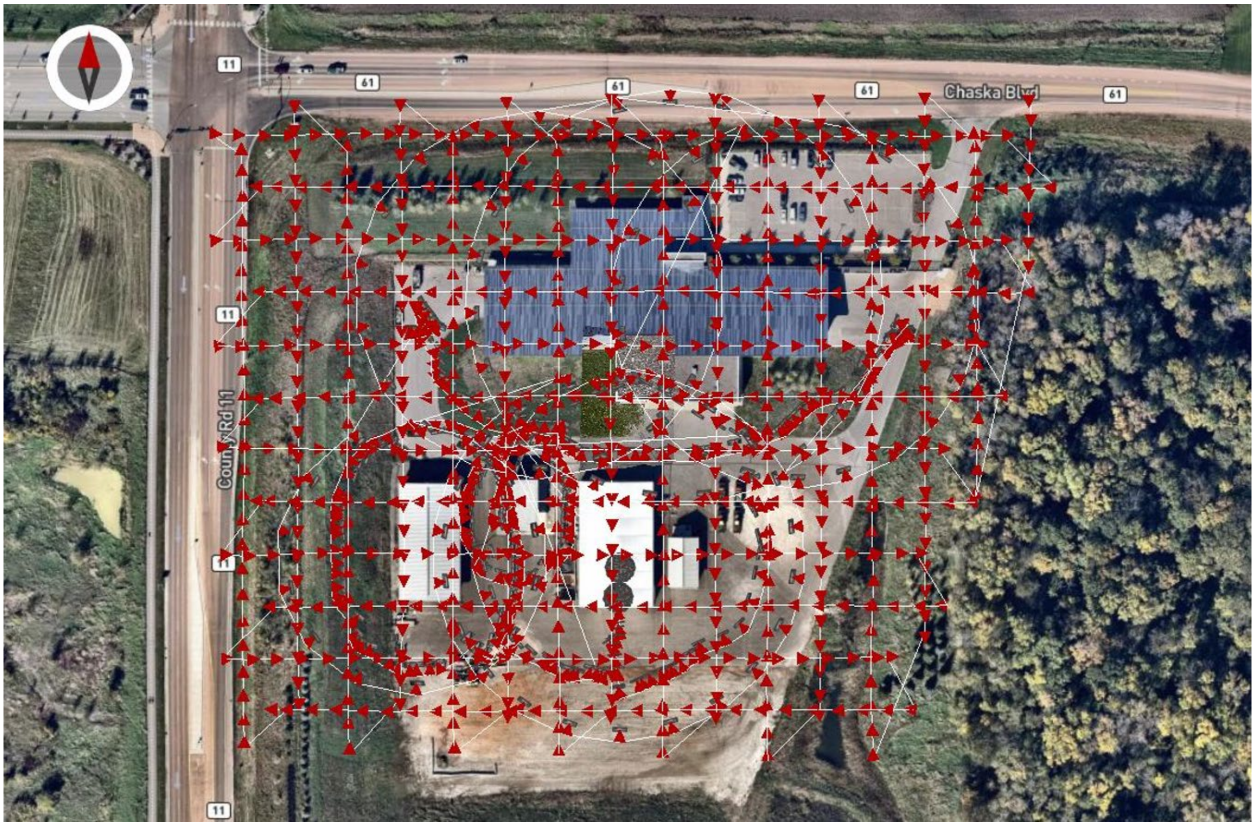

Figure 3.18 Intel Falcon 8+ Flight Plan Results

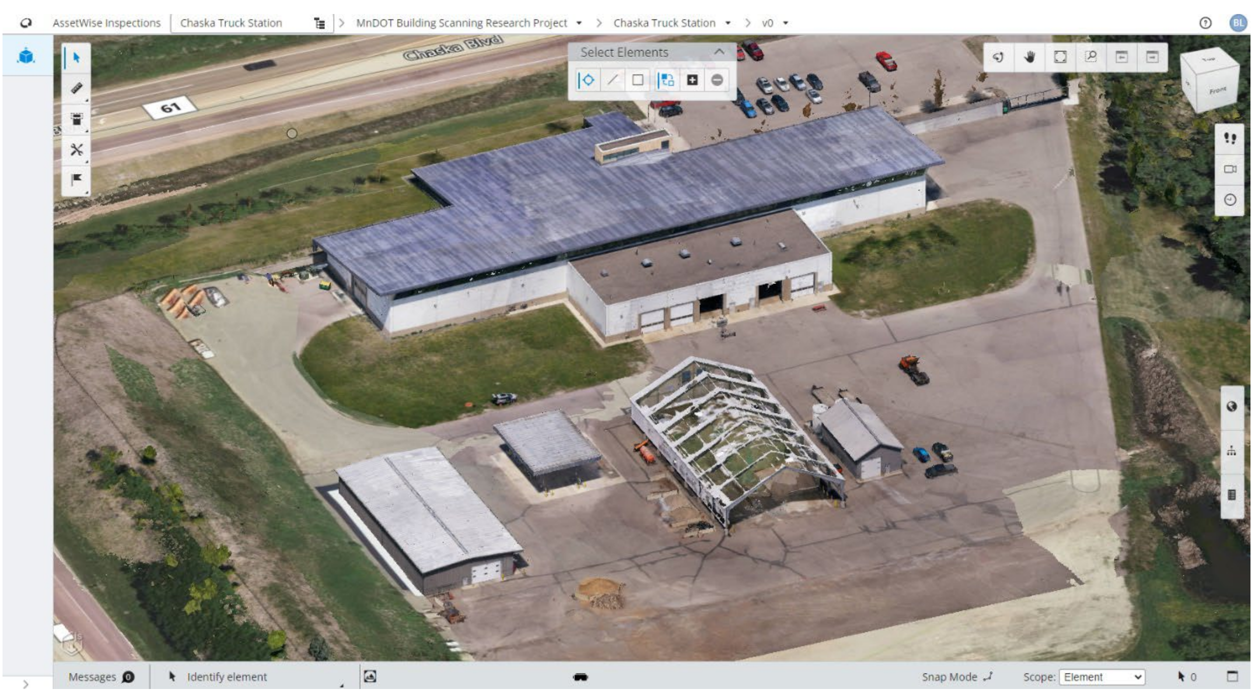

Figure 3.19 Contextcapture Model of Chaska Truck Station Site

Figure 3.20 Close Up of Contextcapture Model Showing Interior of Salt Shad and Stockpiles

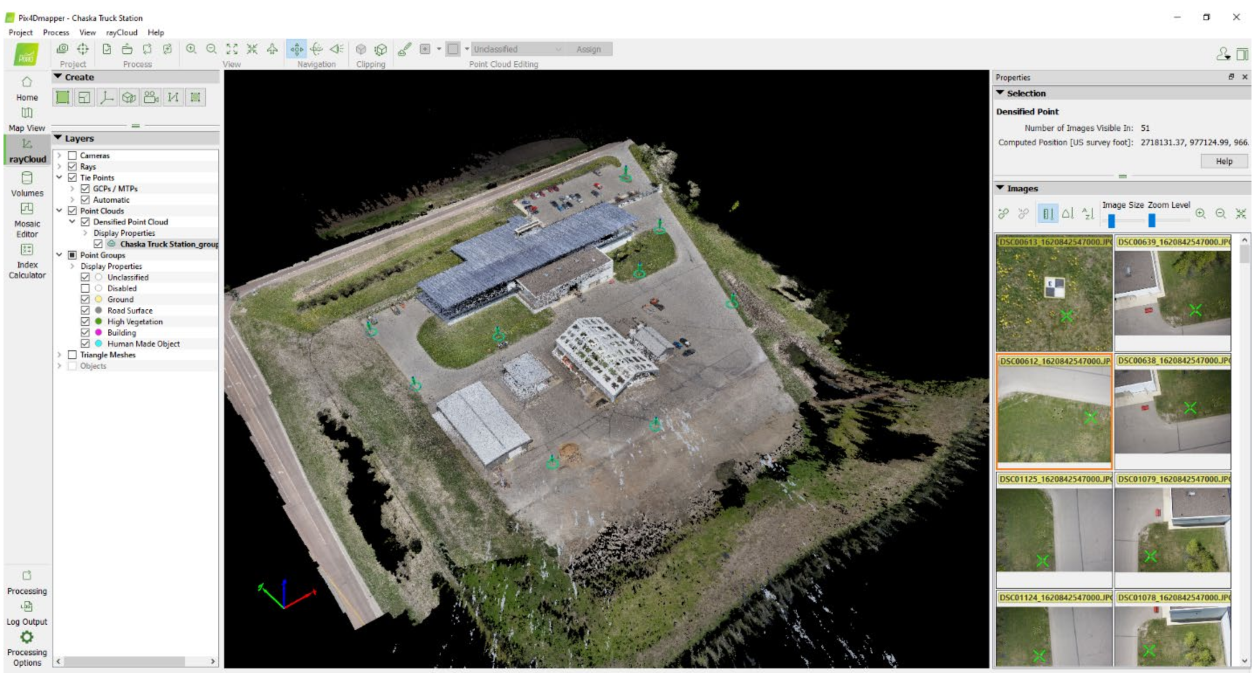

Figure 3.21 Pix4D Point Cloud Post Processing

3.1.2.3 Data Sharing

Models of the Chaska Truck Station Site were shared on the Pix4D Cloud and Contextshare. These models can be viewed by anyone with a web browser and the proper link and credentials. The Contextshare models were also shared in mixed reality via the Microsoft Hololens 2 headset and the Examples are show below and links can be found in the table at the beginning of this section.

Figure 3.22 Pix4D Cloud 3D Model of Walker Truck Station Site\

Figure 3.23 Pix4D Cloud Orthomosaic of Chaska Truck Station Site

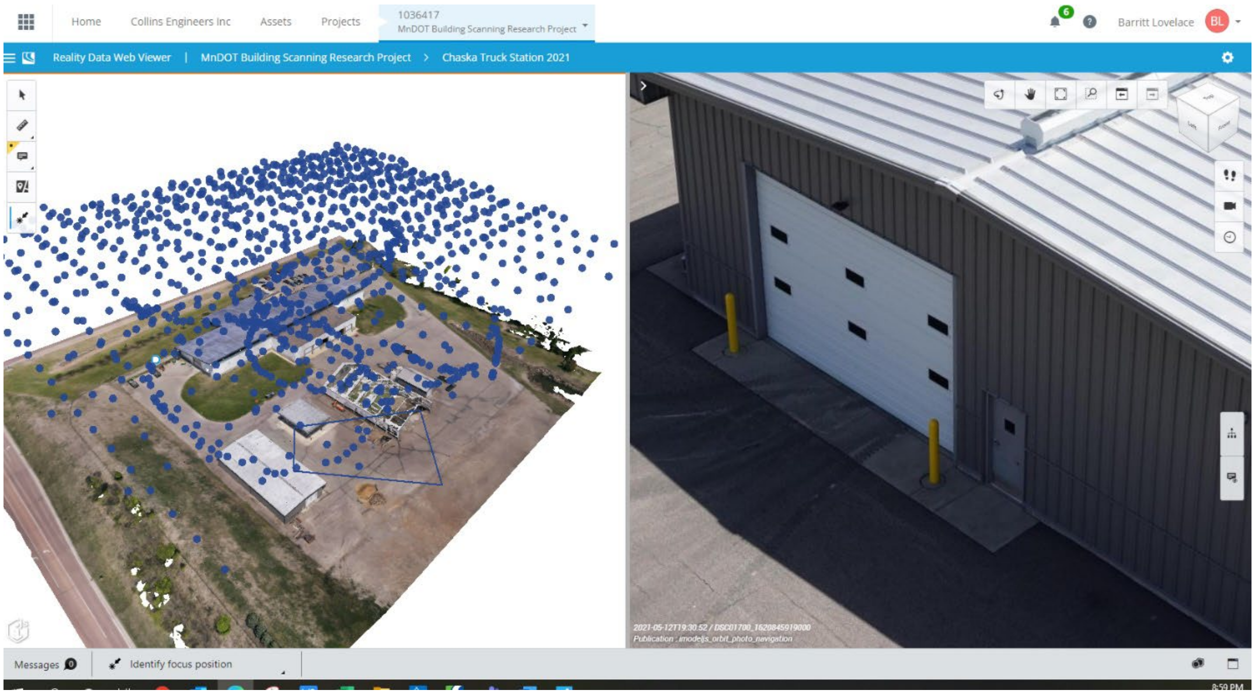

Figure 3.24 Contextshare Model Showing Photo Navigation Tool

Figure 3.25 Microsoft Hololens 2 Screenshot of Chaska Truck Station Site

3.1.3 Eden Prairie Truck Station

The Eden Prairie Truck Station is located in Eden Prairie, Minnesota. The site consists of a main building, salt shed and three accessory buildings. Data of the overall site was collected with the Skydio 2 drone and was post processing in Contextcapture and Pix4D. Aeropoint automatic ground control targets were used for the overall site data collection and modeling. The entire data collection took one person about 3 hours to collect.

3.1.3.1 Data Collection

Data Collected

- Skydio 2
- Skydio 3D Scan of Building (Partial)

Figure 3.26 Skydio Drone Collecting Data Over the Eden Prairie Truck Station

3.1.3.2 Processed Data

Data was processed in Pix4D, Contextcapture. The Skydio 2 still produced good results, but the 12 MP camera requires flying at a lower altitude and capturing more images. Contextcapture generated significantly better results than Pix4D with the same Skydio images. The figures below compare and contrast the differences in model quality between drones and processing software.

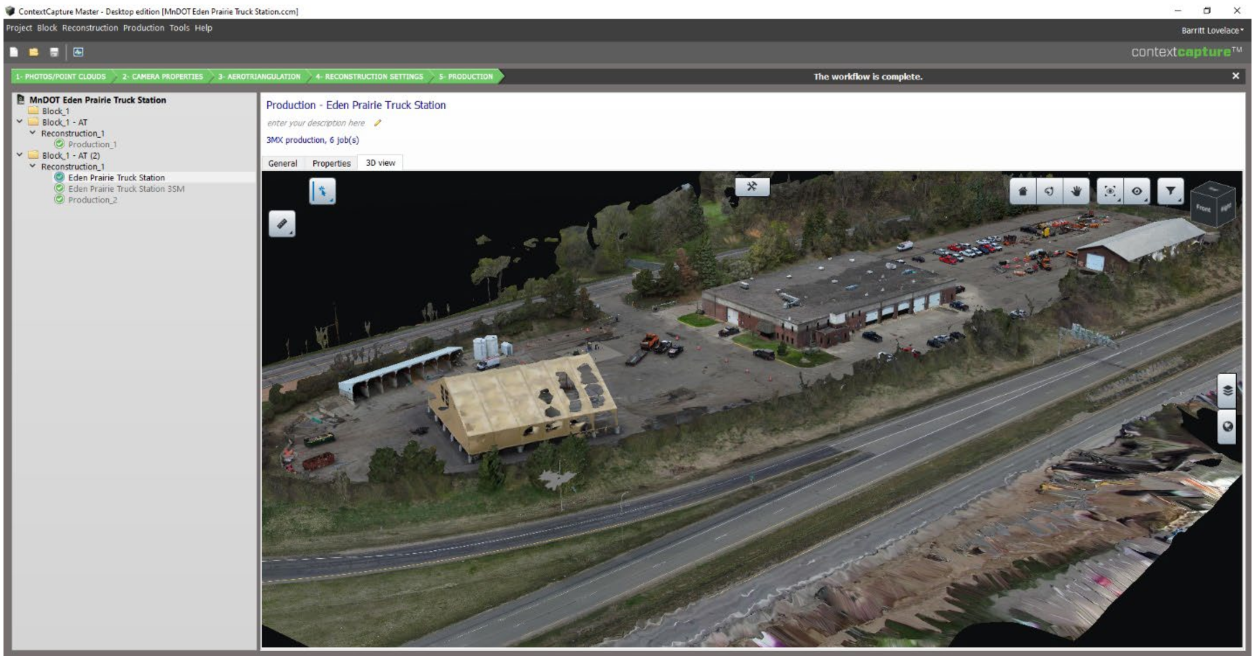

Figure 3.27 Contextcapture Post Processing of Eden Prairie Truck Station

3.1.3.3 Data Sharing

Models of the Eden Prairie Truck Station Site were shared on the Pix4D Cloud and Contextshare. These models can be viewed by anyone with a web browser and the proper link and credentials. The Contextshare models were also shared in mixed reality via the Microsoft Hololens 2 headset and the Examples are show below and links can be found in the table at the beginning of this section.

Figure 3.28 Pix4D Cloud 3D Model of Eden Prairie Truck Station Site

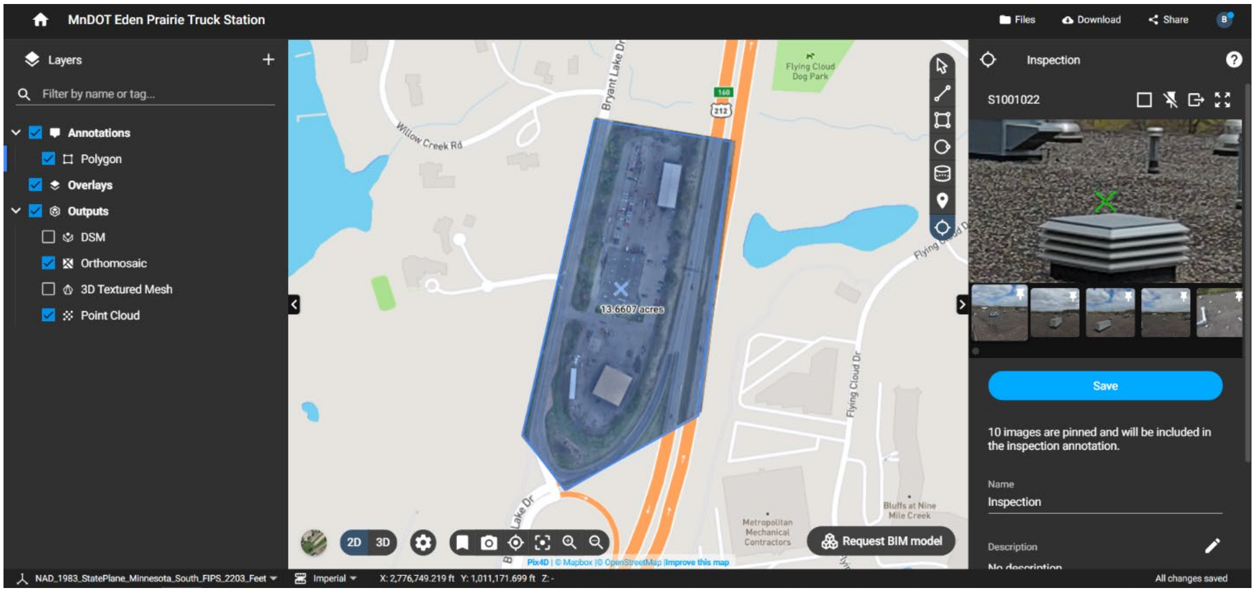

Figure 3.29 Pix4D Cloud Orthomosaic of Eden Prairie Truck Station Site

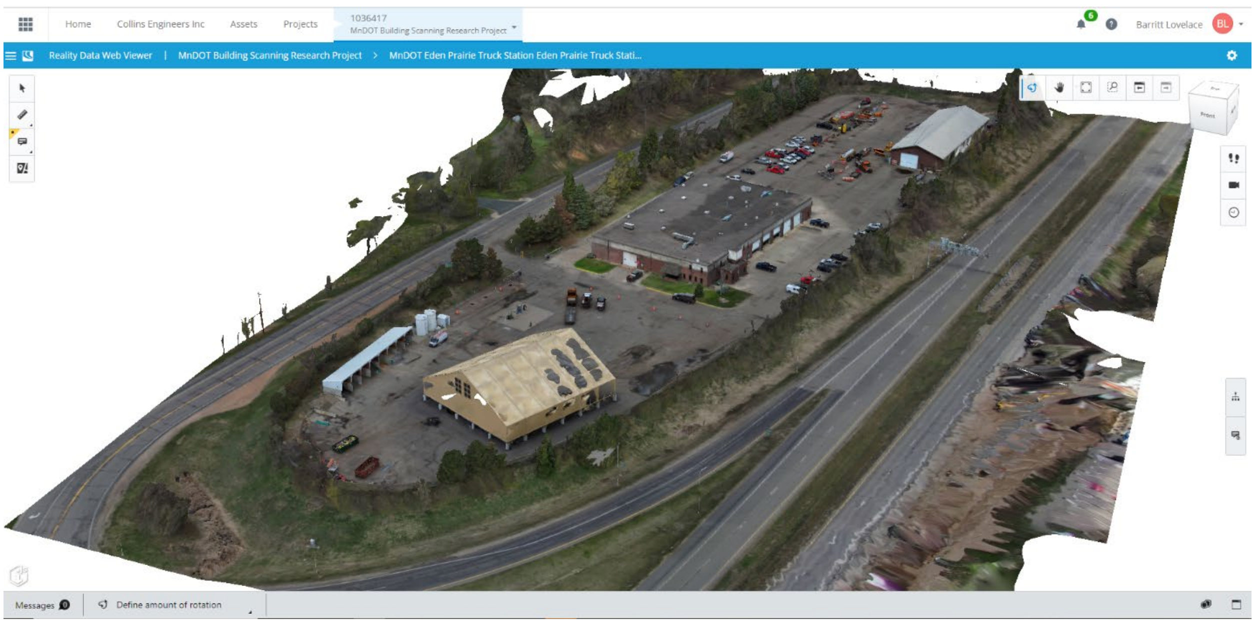

Figure 3.30 Contextshare Model of Eden Prairie Truck Station

3.1.4 MnROAD Research Facility

The MnROAD Research Facility is located in Otsego, Minnesota. The site consists of a main building, accessory building, and a pavement test track. Data of the overall site was collected with both the Intel Falcon 8+ in 2021 and 2022 and was post processing in Contextcapture and Pix4D. Aeropoint automatic ground control targets were used for the overall site data collection and modeling. The interior was captured with a 360 Degree camera with Matterport to capture the building interiors. The main building was captured using the 3D Scan application from Skydio. The entire data collection took one person less than a full day to collect.

3.1.4.1 Data Collection

Data Collected

- Intel Falcon 8+ Drone Overall Site
- Matterport Interiors (main building)
- Skydio 3D Scan of Main Building

Figure 3.31 Intel Falcon 8+ Drone Taking Off at MnROAD Research Facility

3.1.4.2 Processed Data

Data was processed in Pix4D, Contextcapture and the interior 360 degree images were processed in Matterport. The Intel Falcon 8+ images produced a detailed site model as expected with its 36 MP DSLR camera. The Skydio 2 still produced good results of the main building using the 3D scan application. Contextcapture generated significantly better results even with the same Intel Falcon 8+ and Skydio images. The figures below compare and contrast the differences in model quality between drones and processing software.

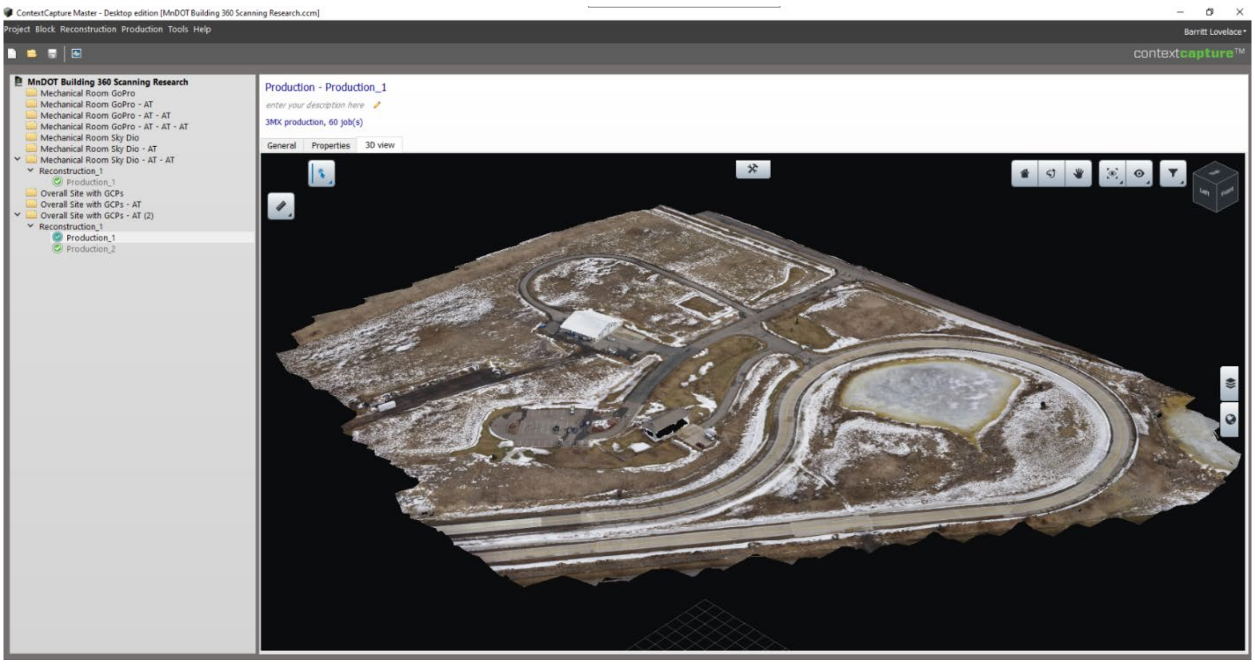

Figure 3.32 Contextcapture Model of MnROAD Research Site in 2022

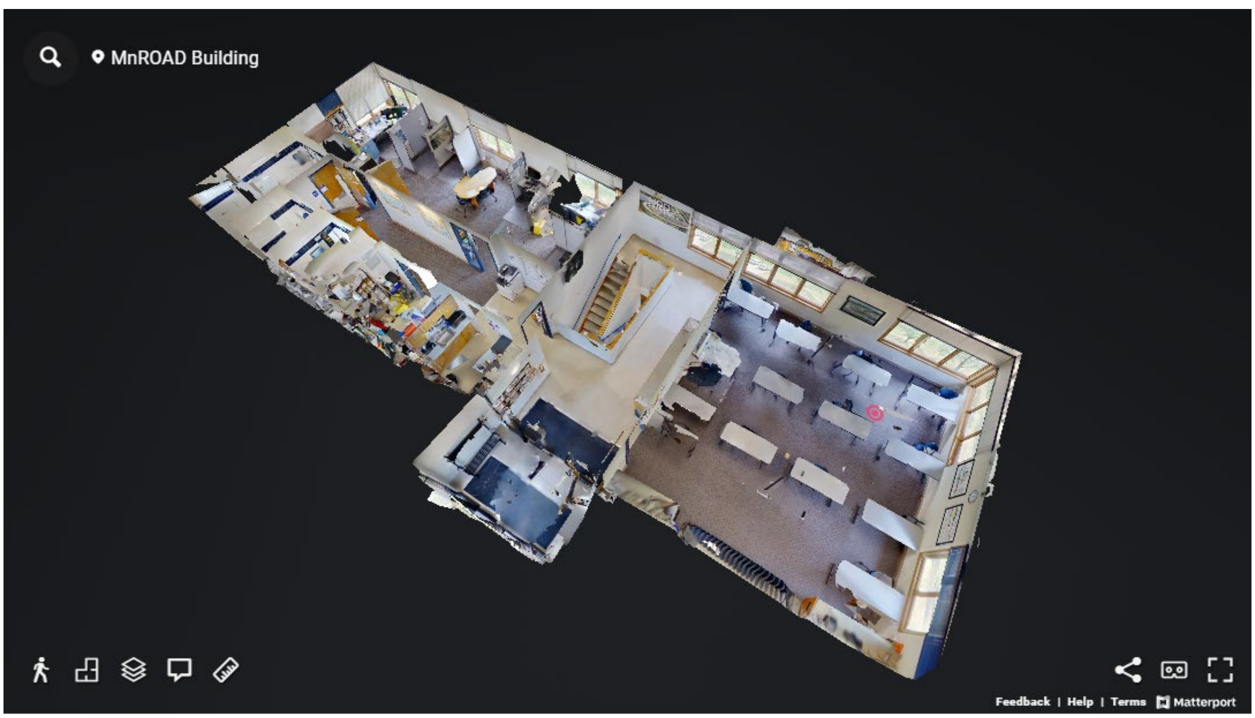

Figure 3.33 Matterport Dollhouse View of MnROAD Building Interior

Figure 3.34 Matterport Plan View of MnROAD Building Interior

Models of the MnROAD Research Site and Building were shared on the Pix4D Cloud, Contextshare and Matterport. These models can be viewed by anyone with a web browser and the proper link and credentials. The Contextshare models were also shared in mixed reality via the Microsoft Hololens 2 headset and the Matterport interior models can be viewed in virtual reality with the Oculus Quest headset. Examples are show below and links can be found in the table at the beginning of this section.

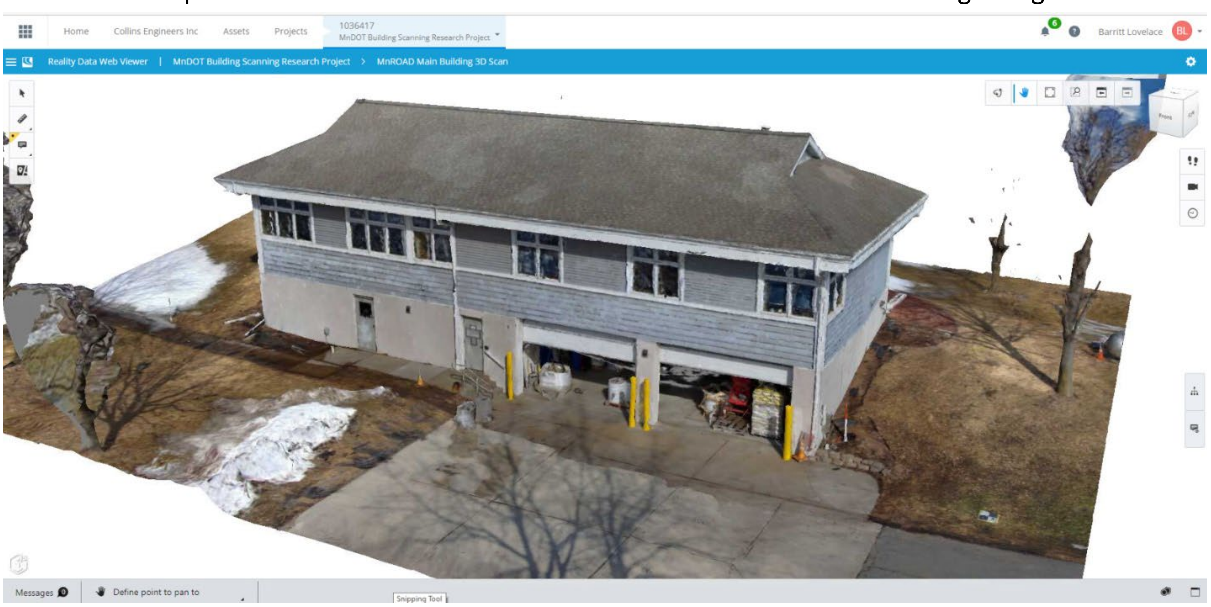

Figure 3.35 Contextshare Cloud Model of MnROAD 3D Scan of Main Building

Figure 3.36 Pix4D Cloud Orthomosaic Model of MnROAD Research Facility

Figure 3.37 Matterport Screenshot of MnROAD Main Building

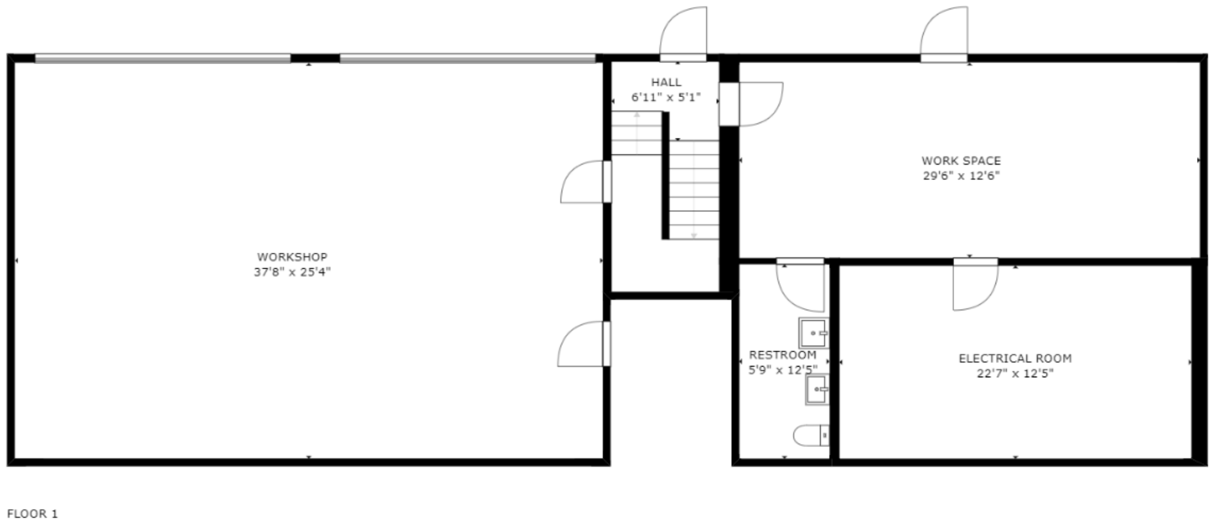

Figure 3.38 Matterport Generated Floorplan of MnROAD Main Building Floor 1

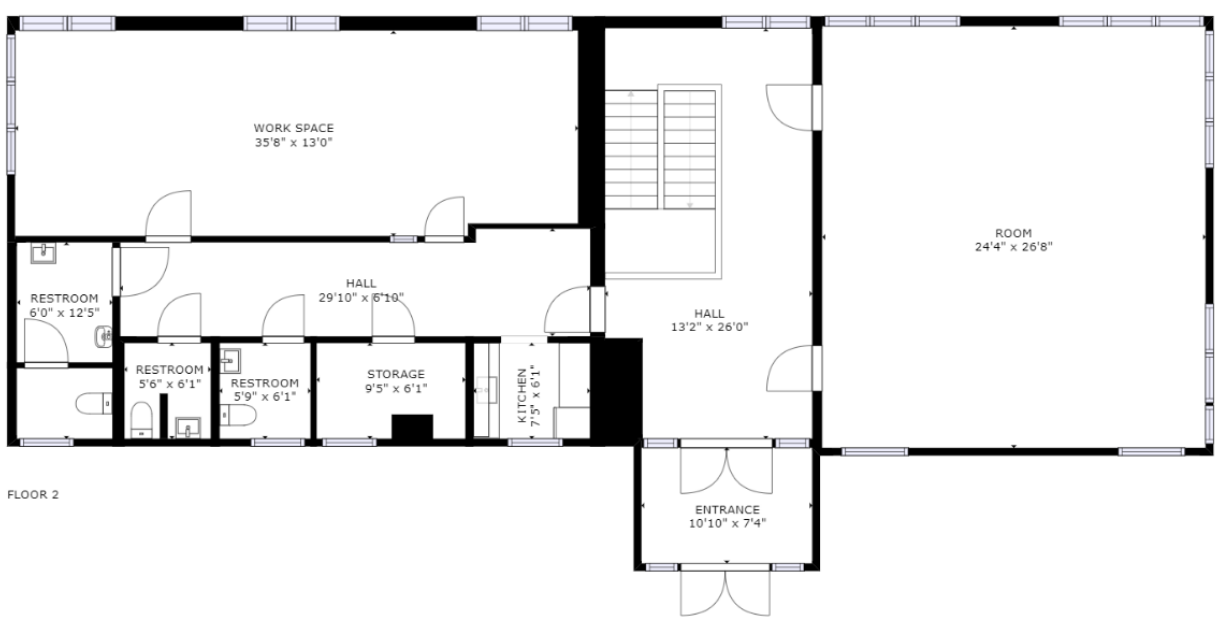

Figure 3.39 Matterport Generated Floorplan of MnROAD Main Building Floor 2

3.1.5 Maplewood Material Lab

The Maplewood Material Lab is located in Maplewood, Minnesota. The site consists of a main building and one accessory building. Data of the overall site was collected with the Intel Falcon 8+ drone and was post processing in Contextcapture and Pix4D. Aeropoint automatic ground control targets were used for the overall site data collection and modeling. The entire data collection took one person 3 hours to collect.

3.1.5.1 Data Collection

Data Collected

- Intel Falcon 8+ Drone Overall Site

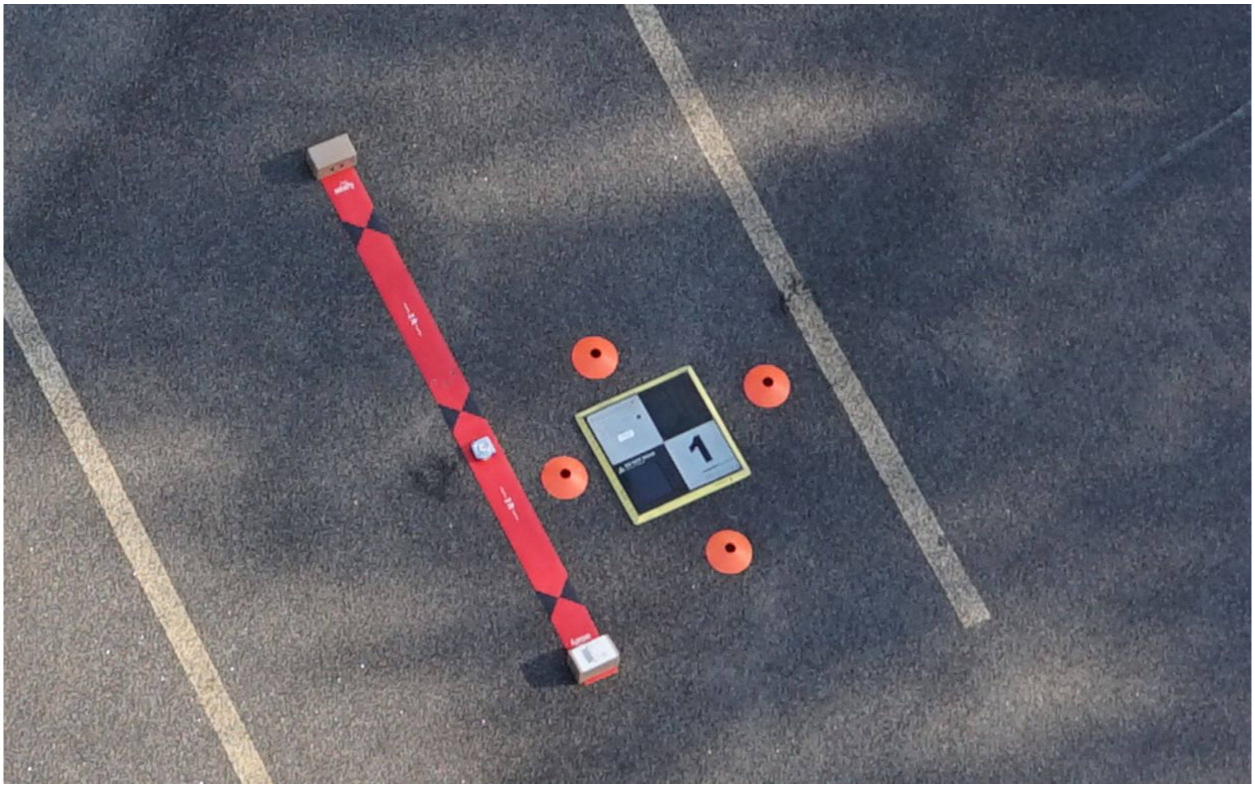

Figure 3.40 Ground Control Target and Scale

3.1.5.2 Processed Data

Data was processed in Pix4D, Contextcapture. The Intel Falcon 8+ images produced detailed models as expected with its 36 MP DSLR camera. Contextcapture generated significantly better results than Pix4D even with the same Intel Falcon 8+ images. The figures below demonstrate the different deliverables produced for this building site.

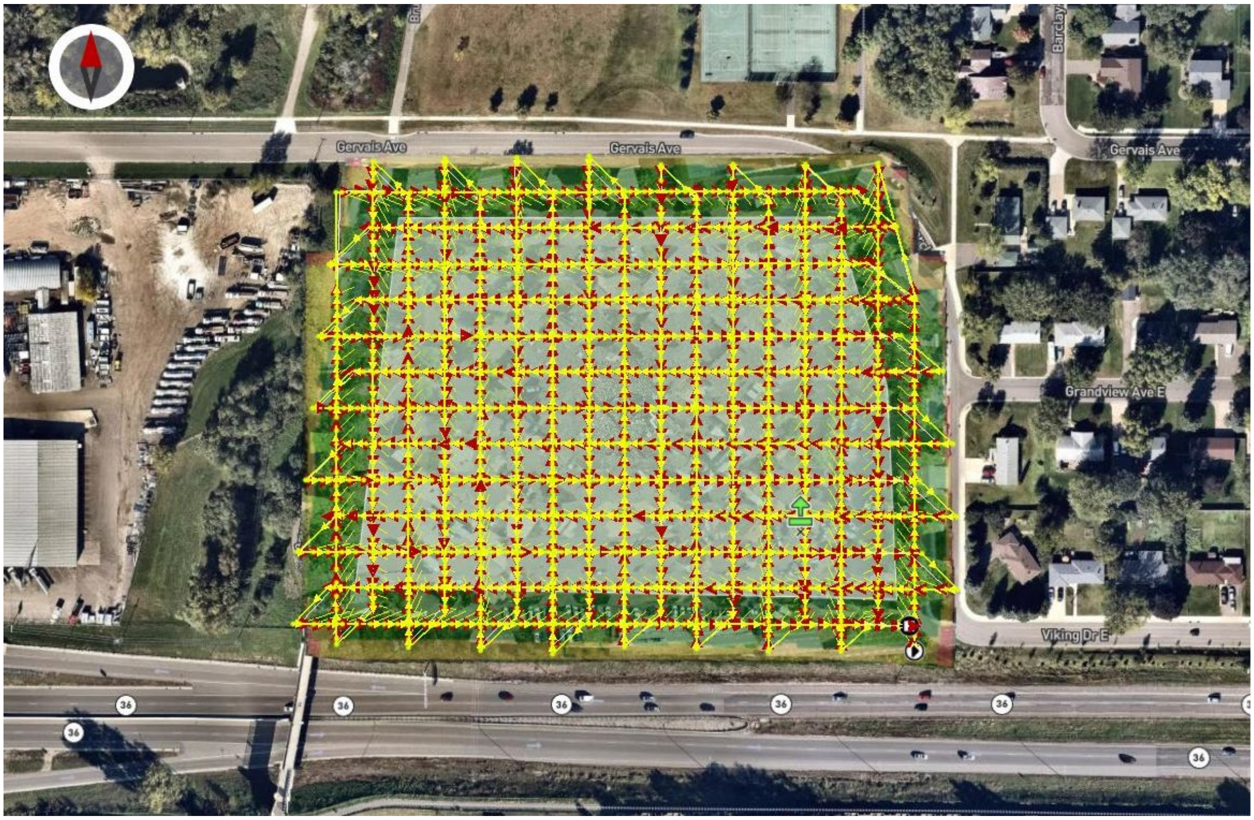

Figure 3.41 Intel Falcon 8+ Flight Plan Results

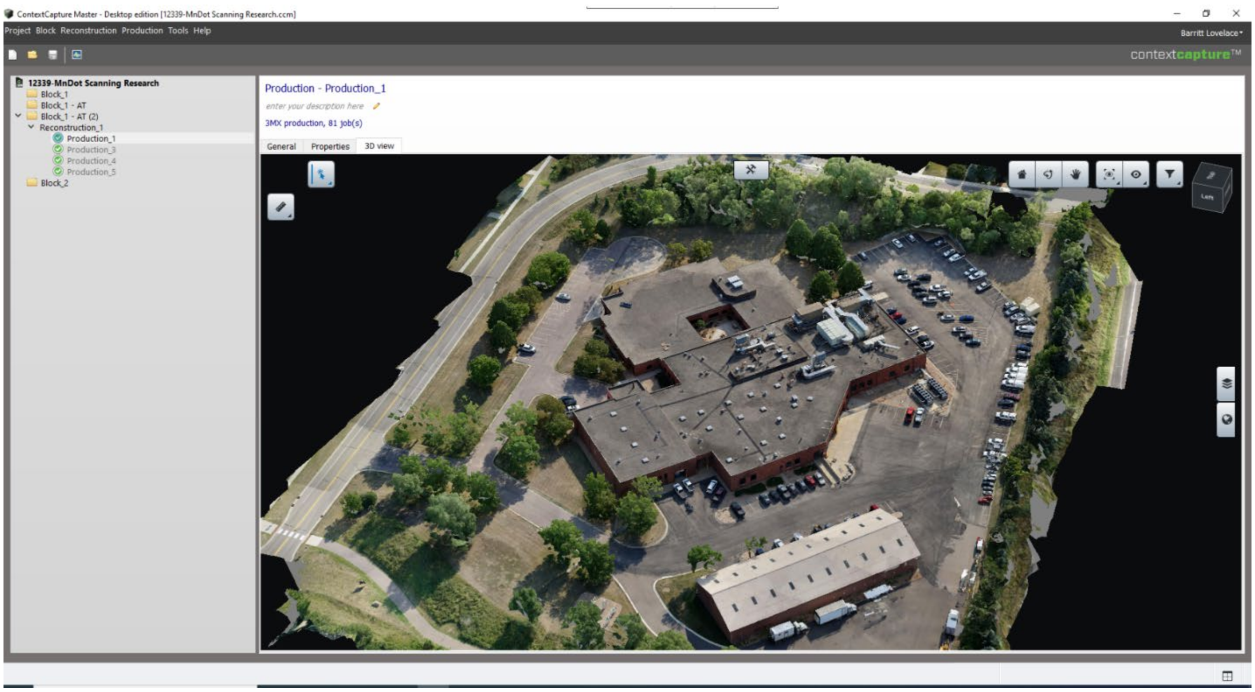

Figure 3.42 Contextcapture Model of Maplewood Materials Lab

3.1.5.3 Data Sharing

Models of the Chaska Truck Station Site were shared on the Pix4D Cloud and Contextshare. These models can be viewed by anyone with a web browser and the proper link and credentials. The Contextshare models were also shared in mixed reality via the Microsoft Hololens 2 headset and the Examples are show below and links can be found in the table at the beginning of this section.

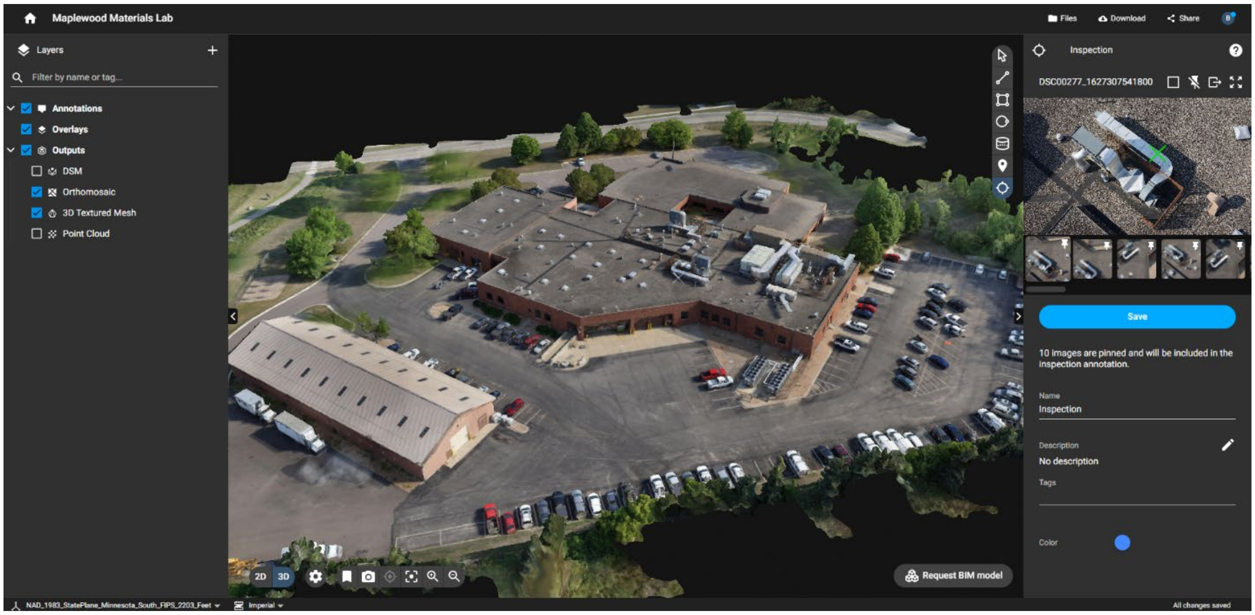

Figure 3.43 Pix4D Cloud 3D Model of Maplewood Materials Lab

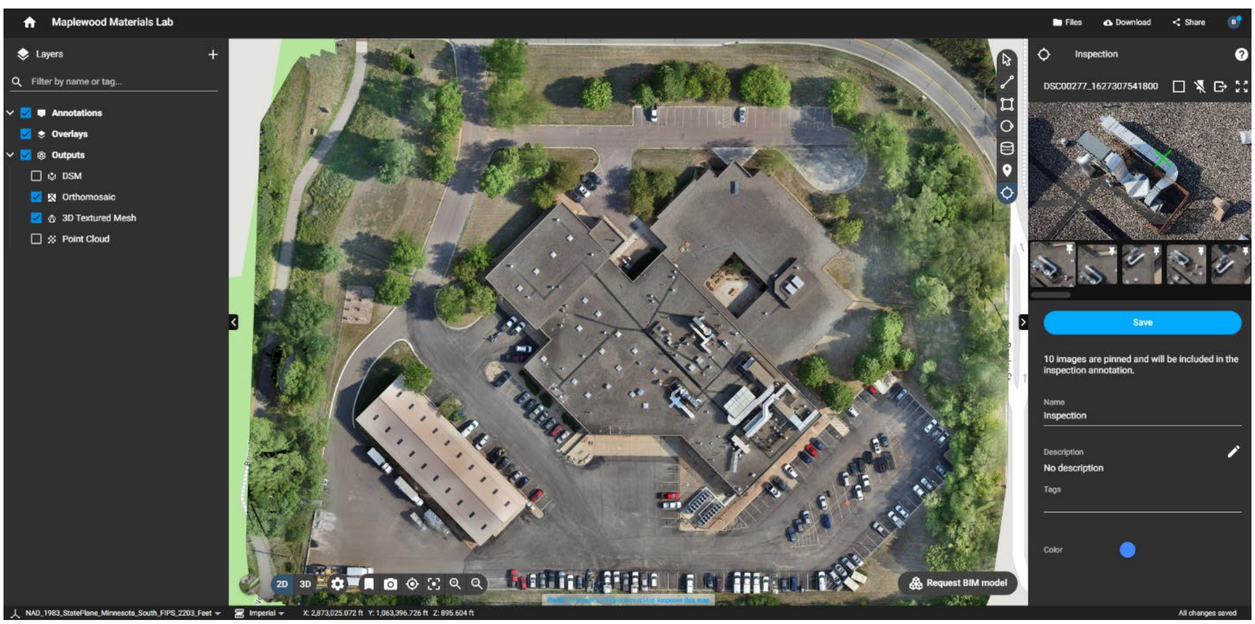

Figure 3.44 Pix4D Cloud Orthomosaic of Maplewood Material Lab

Figure 3.45 Microsoft Hololens 2 Screenshot of Maplewood Materials Lab

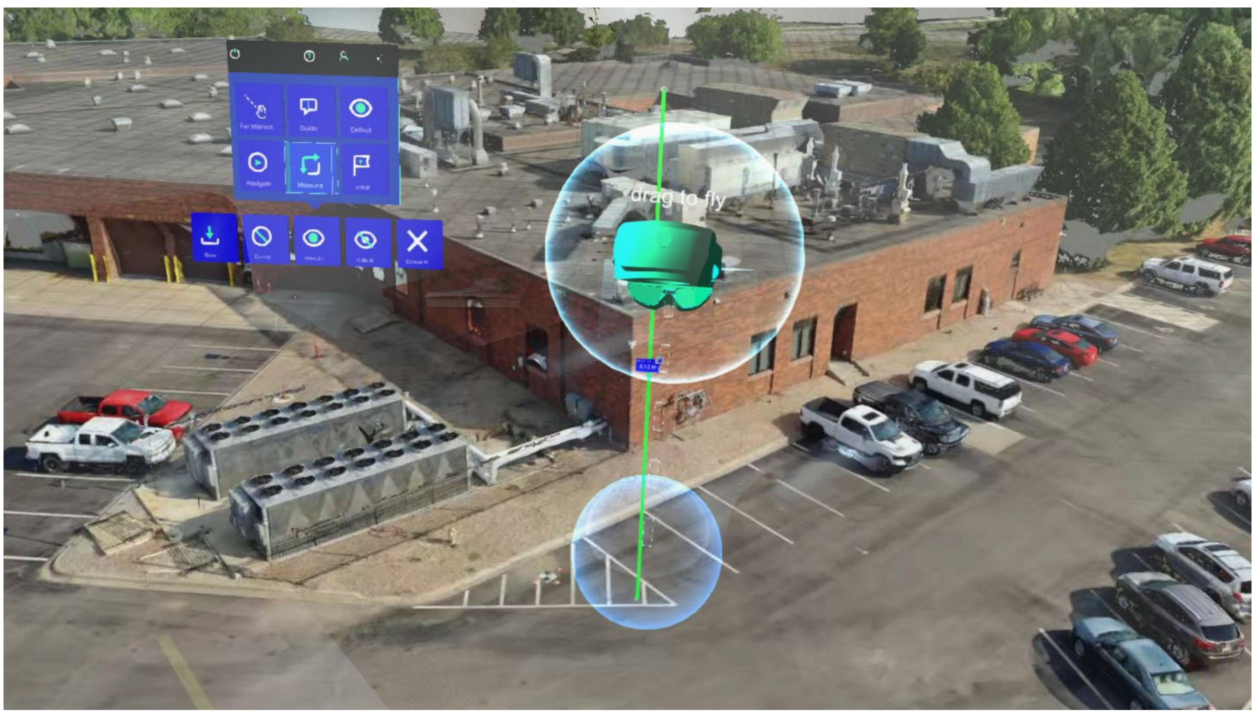

Figure 3.46 Hololens 2 Screenshot of Maplewood Materials Lab

3.1.6 Mendota Heights Truck Station

The Mendota Heights Truck Station is located in Mendota Heights, Minnesota. The site consists of a main building and two accessory buildings. Data of the overall site was collected with the Skydio 2 drone and was post processing in Contextcapture and Pix4D. Aeropoint automatic ground control targets were used for the overall site data collection and modeling. The entire data collection took one person about 3 hours to collect. The site is close to MSP airport and a special FAA waiver was obtained to fly in this location in order to comply with the FAA Part 107 Rules.

3.1.6.1 Data Collection

Data Collected

- Skydio 2

Figure 3.47 Skydio Drone View of Data Collection Over the Mendota Truck Station

3.1.6.2 Processed Data

Data was processed in Pix4D, Contextcapture. The Skydio 2 still produced good results, but the 12 MP camera requires flying at a lower altitude and capturing more images. Contextcapture generated significantly better results than Pix4D with the same Skydio images. The figures below compare and contrast the differences in model quality between drones and processing software.

3.1.6.3 Data Sharing

Models of the Mendota Truck Station Site were shared on the Pix4D Cloud and Contextshare. These models can be viewed by anyone with a web browser and the proper link and credentials. The Contextshare models were also shared in mixed reality via the Microsoft Hololens 2 headset and the Examples are show below and links can be found in the table at the beginning of this section.

Figure 3.48 Pix4D Cloud 3D Model of Mendota Truck Station

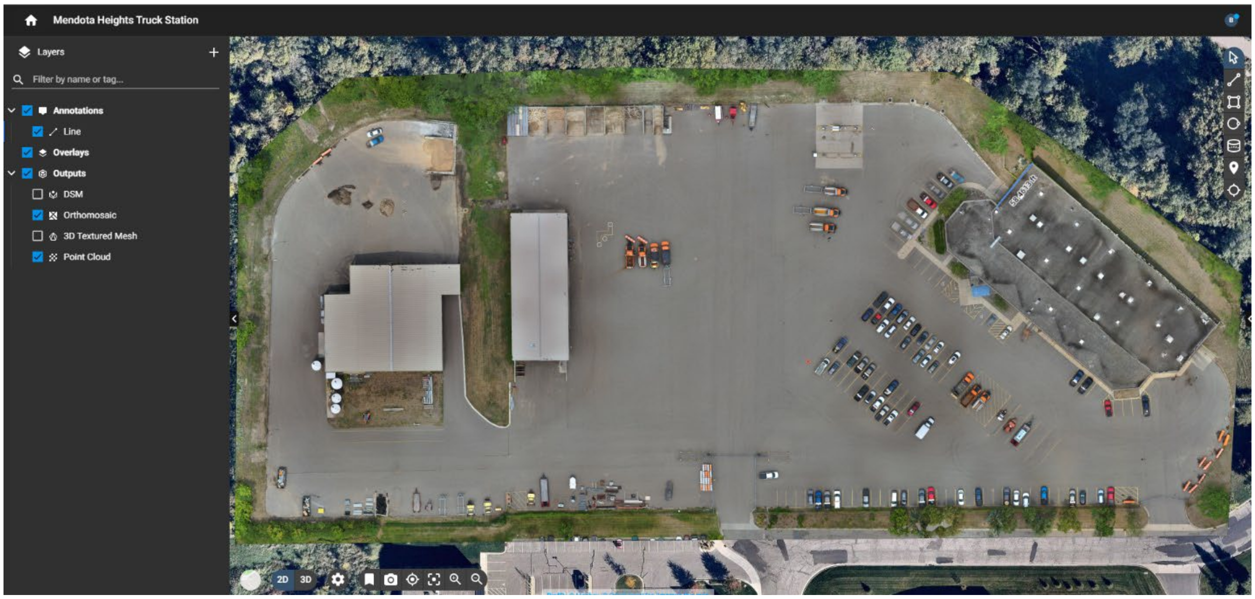

Figure 3.49 Pix4D Cloud Orthomosaic of Mendota Truck Station

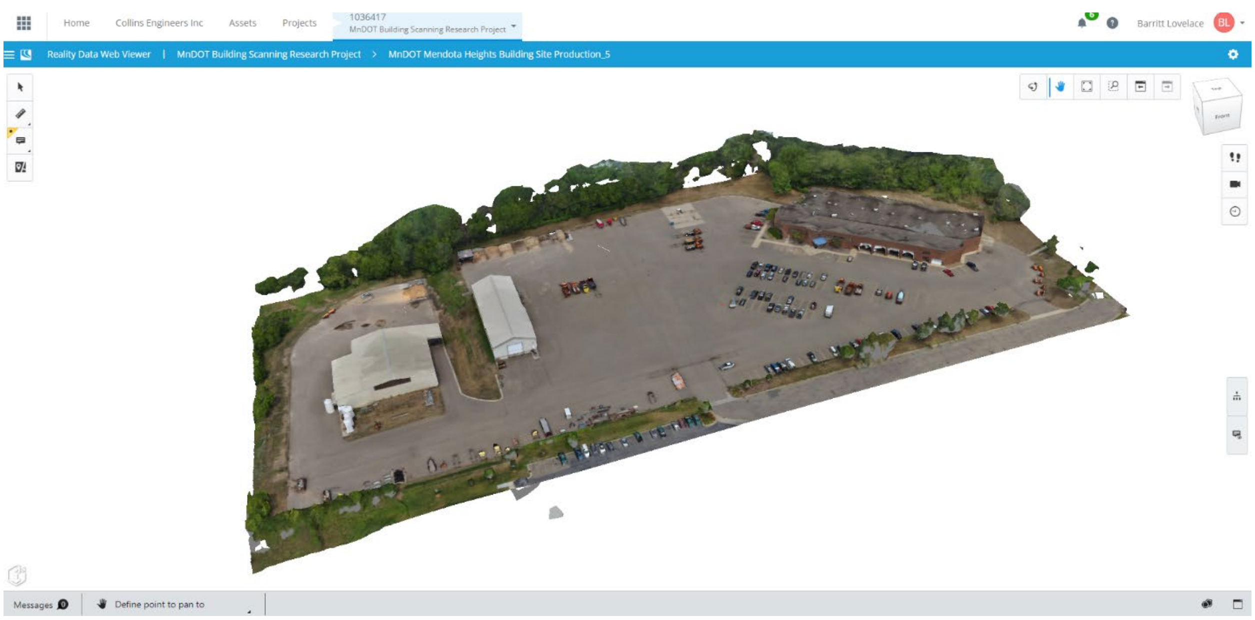

Figure 3.50 Contextshare Model of Mendota Truck Station

3.1.7 Cedar Avenue Truck Station

The Mendota Heights Truck Station is located in Rickfield, Minnesota and is directly adjacent to MSP airport. Data of the overall site was collected with the GeoSLAM mobile lidar unit and post processed in the GeoSLAM software. The interior of the building was scanned and a portion of the roof where mechanical units are located. The entire data collection took one person about 2 hours to collect.

3.1.7.1 Data Collection

Data Collected

- GeoSLA|M Mobile Lidar

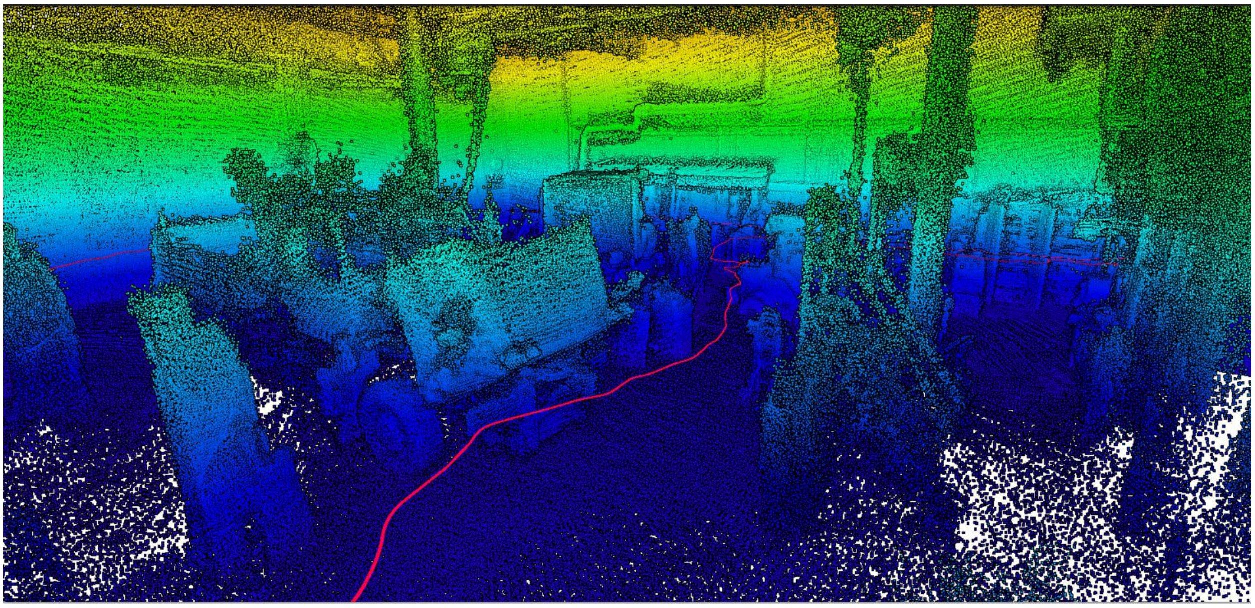

Figure 3.51 GeoSLAM LiDAR generated pointcloud of Cedar Avenue Truck Station

3.1.7.2 Processed Data

Data was processed in GeoSLAB Hub software. The results are in the form of a point cloud. Measurements from the point cloud are very useful but the point cloud itself does not provide context. A gopro was also included as part of the data collection so video still can be reference to show context.

3.1.7.3 Data Sharing

The point cloud files are easily shared as a .las file which can be opened and viewed in a variety of CAD software packages.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

Digital Twins and UAS and 360degree cameras are changing the way we collect data, consume and share asset data. The Minnesota Department of Transportation owns and maintains over 900 individual buildings at over 250 sites. With this many buildings and sites even small efficiencies in collecting and sharing data can yield significant savings. This research project examined existing technologies that can scan and process both exterior and interior of building and sites. This project also examined different cloud sharing methods so that the data can be easily shared in context to designers and decision makers.

4.1 CONCLUSIONS

Our work identified several benefits of these digital twin workflows including cost efficiencies, improved quality and quantity of data, improved ability to utilize and share data and safety improvements.

By utilizing digital twins, we give team members a photographic memory in the form of access to thousands of images of a site or building through photo navigation. Digital twins also give team members the ability to time travel and access data from different time periods in order to evaluate change over time of a facility. The third benefit is the ability to access portions of a building or site that may not be accessible without special access equipment. For instance, team members could inspect a roof virtually without having to climb on top of the building.

4.1.1 Cost

There are two ways of comparing costs when evaluating new methods vs. traditional methods. The first compares the time and expenses to collect data. We found that these costs are similar but there are some upfront equipment costs using UAS and Digital Twins. The commercial setup with the Intel Falcon8+, Aeropoints, software and a 360 degree camera are approximately $35,000. Using the Skydio 2 setup reduces the upfront costs to approximately $18,000. The main differentiator however is the increase in the amount of data and the quality of the data is greatly improved. In addition, the data is readily shared across teams.

The greater cost savings comes from reduced site trips by project staff to gather data for a project. It is not uncommon for MnDOT to send several staff to a site when a project is proposed for a building site. In this case an architect, mechanical engineer, structural engineer, and other staff may all travel to the site to collect data for their portion of the project. Using digital twins could significantly reduce the need for these trips if not completely eliminate them which is a significant cost savings.

An even larger costs savings was identified that relates to making quality decisions with good data. Traditionally on any infrastructure project team members have limited data in order to make decisions and so those decisions are either very conservative or incorrect which can add significant project cost. By reducing these risks MnDOT can significantly reduce project costs. While the cost savings associated with reduced risks are more difficult to quantify, they are likely the largest area of cost savings to be realized by using this technology.

An estimate is provided below for data collection and processing for a single site and building with minimal travel time. The cost is based on Collins performing the work and all equipment is included as overhead.

Task Number	Task Description	Labor Costs Lead Engineer UAS Pilot	Engineer UAS Pilot		Task Total
1	Planning	2	4		$1,023.38
2	Field Work	4	4		$1,519.87
3	Data Processing	4	8		$2,046.76
	Subtotal Hours	10	16		
	Hourly Rate	$79.23	$42.04		
	Overhead (184.84%)	$146	$78		
	Profit (10%)	$22.57	$11.97		
	Subtotal Labor	$2,482	$2,108		**$4,590**
Expense Description		Direct Costs Quantity	Unit	Unit Price	Cost
Mileage		50	Miles	$0.58	$29
Expendable Field Equipment					
UAS Battery		1	Each	$250.00	$250
Shipping			Each	$500.00	$0
Lodging		0	Day	$120.00	$0
Meals		0	Day	$46.00	$0
Total					**$279**
				Total Fee	**$4,869**

4.1.2 Improved Data

We estimate the quantity of data available to team members is on the order of 100,000 times increase. Even with this large increase in the amount of data the ability to utilize and share the data is also improved. Utilizing cloud sharing services allows team members to access all of the data through a webpage from any location. The data is all in context and is easily navigated. A traditional site inspection and survey may collect many individual measurements and data points a reality model generates an infinite number of measurements and almost anything on the site can be measured remotely.

Since this data is collected at a finite time, we can start to build a historical record of the buildings or site. This historical record can be valuable when evaluating change over time or trying to determine changes that have been made to a site.

4.1.3 Safety

MnDOT Building sites can be busy areas with truck traffic, loading and unloading of material and equipment and can pose hazards to staff collecting data. Traditional inspections or site surveys may require staff to walk an entire site to collect data. This could involve traversing slopes, working around truck traffic and trip and slip hazards. MnDOT Building sites can be busy areas with truck traffic, loading and unloading of materials and equipment and can pose hazards to staff collecting data.

Special inspections may also require staff to utilize special access equipment including man lifts, scaffolding or ladders to access portions of building or structures out of reach. For instance, a roof inspection would require individual climb on top of a building using ladders. All of these access methods can increase risks to staff members.

Utilizing digital twins can reduce the need to for staff to work around traffic or from heights even if it cannot be eliminated. These safety improvements are invaluable.

4.2 RECOMMENDATIONS

Implementation of these workflows would benefit MnDOT by reducing costs, improving data and safety. Overall, these benefits reduce overall risks for MnDOT without many obstacles for adoption. Some equipment and software purchases may be required within the building group if the work is to be done by that group specifically. Some training may also be required for both data acquisition and post processing, but those needs are not significant. Other areas of MnDOT own and operate many drones and have the ability to post process data including photogrammetry and the bridge inspection group.

Our recommendations would be for MnDOT to start implementing this technology to take advantage of the benefits. Interior scanning is probably the area that has the lowest barrier to entry. By utilizing a relatively low cost 360 camera along with the Matterport software can show significant benefits almost immediately. The idea of scanning all of the buildings and sites may be a large effort but scanning individual sites as resources allow will start to spread the value of these workflows as users are able to utilize the data. New building site scans would be very beneficial to obtain as new buildings or sites come online to capture the as-built condition.

REFERENCES

Federal Aviation Administration (2020). Internet. Uncrewed Aircraft Systems, Retrieved from https://www.faa.gov/uas/.