

INTERIOR CLOSE-RANGE DIGITAL PHOTOGRAMMETRY
FOR AN OPERATIONAL BUILDING

A Thesis

by

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ABSTRACT

Laser scanning technology has been well received by the industry practitioners who want to create a 3-dimensional (3D) computer model of existing buildings and structures. However, most 3D laser scanners are expensive and need a special training to be utilized. It also takes a significant amount of time to convert point clouds collected from the laser scanner into a 3D computer model.

Photogrammetry technology may provide an alternative solution to those who want to pick up the 3D model of an existing building. Since it uses snapshot photos of the target object taken at multiple locations, one can create a semi-realistic 3D model of a building cost-effectively without spending their budget for expensive laser scanners.

Basically, it is designed to pick up a 3D model of an object using photos taken from multiple locations outside an object. So, one may speculate if this algorithm would work if someone wants to pick up the 3D model inside the building. If it is possible, then others may be wondering how long it would take to pick up the 3D model of a building's interior, or if the 3D model would be accurate enough for facilities management or other activities sought by construction managers.

This study evaluates the practicality of photogrammetry technology in creating a 3D model of a building's interior. A commercial photogrammetry-based 3D modeling application was used to test if one can create the 3D model of the building interior, how long it takes to pick up a 3D model, and how accurate the 3D model would be. The Francis Hall building located on the Texas A&M University campus in College Station was

chosen for this test. As many as 4,940 photos were taken at multiple locations inside the building. Autodesk Recap 360 was then used to create the 3D model of a unit space inside the building. Unity 3D was used to combine multiple unit 3D models into a 3D model of the entire floor of the Francis Hall.

This test demonstrates that it is possible to create a unit 3D model from building's interior space using photographs. It took 47.95 minutes in average to take photos in one room, and 647.05 minutes to produce its 3D model. In total, it took 14,469 minutes to produce a 3D model of the entire first floor of the Francis Hall. Average tolerance between the real measurements and the dimension of the 3D model from photos is about 0.83 percent.

DEDICATION

This thesis is dedicated to my parents Mahmoud Farzad and Mina Dehghan, to my uncle Mohsen Farzad, to Marta E. Vendrell and other friends and family members for their encouragements and support.

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NOMENCLATURE

3D	3 Dimensional
AEC	Architecture, Engineering and Construction
BIM	Building Information Modeling
FM	Facility Management
SFM	Structure from Motion

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CHAPTER I

INTRODUCTION AND BACKGROUND

1.1. As-built 3D models

Three-dimensional (3D) documentation of a building at different levels of its life cycle from planning to construction and facilities management (FM) can provide valuable information for stakeholders in the project. The as-built condition of the buildings is changing repeatedly which necessitates the current documentations such as building information models (BIM) to be up to date. Otherwise, it will have a negative impact on decision-making during different phases of construction and operation and maintenance (O&M) which causes additional costs for the project. (Akcamete 2009; Fallon and Palmer 2007). Despite the effectiveness of BIM for FM purposes, there is the lack of 3D documentations for many of existing facilities and usually, the electronic copy of the documentations is not transferred to the owner properly (Eastman et al. 2011). Because of the lack of as-built 3D models for existing buildings, facility managers have to develop a Building Information Model using manual processes such as field surveys and tape or laser measurement in order to create the 3D model (Klein et al. 2012). The manual process of creating an as-built building information model is time inefficient and causes many errors (Dickinson et al. 2009).

1.2. Laser scanners

By advancement of technology new tools have been introduced for capturing building's 3D data. 3D laser scanners collect the vast amount of points from surfaces by shooting and receiving laser rays and measuring the time and distance. (Bohler and Marbs 2002). Point clouds collected using 3D laser scanners can be used to produce a 3D model. The ability to collect a vast amount of point clouds in a little amount of time has made laser scanners a favorable option for practitioners in the AEC industry (Huber et al 2010). Facilities management is one of the areas of interest for laser scanning in order to create as-built building information model for the current condition of buildings. Tang et al. (2010) have investigated automation of creating building information models of operating buildings from point clouds extracted from laser scanners. Laser scanners help industry practitioners produce the 3D data faster than when they collect the dimensions of existing structures manually. However, assembling and disassembling them is relatively time-consuming. Also, laser scanner technology is not able to capture the high-quality colored texture of the geometries alone (Alshawabkeh 2006).

1.3. Photogrammetry

Using photographs is an alternative option to create the 3D geometry. Photogrammetry is an approach that converts 2D photographs by analyzing and measuring into the 3D geometry of objects. Close-range photogrammetry has been utilized in different areas such as industry, biomechanics, chemistry, biology, archeology, architecture, automotive and aerospace engineering and accident reconstruction (Jiang et

al. 2008). Photogrammetry is a low-cost technology in relation to laser scanners and the portability makes it more favorable (Sabry et al. 2003). 3D geometry of the building can be captured by a low-cost camera and be processed by a normal computer which does not require any special knowledge (Yilmaz et al. 2008). Photos can be used to reconstruct both interior and exterior of buildings. Using photogrammetry to capture the 3D data of operational buildings can lower the cost and labor time spent on the measurement. This approach results in reconstructed single spaces of the building's interior (Klein et al. 2012).

1.4. Motivation

It has been expected that facilities managers and building owners may be able to make informed decisions if they have an as-built 3D models of buildings. Photogrammetry has been introduced to capture the 3D data of the building's exterior by taking photos towards the object. However, the practicality of capturing the entire building's interior using this approach was still unknown. Also, the accuracy and duration of this process for building's interior had not been assessed yet.

1.5. Research questions

The following questions were raised based on the motivation:

1. Is it practical to create a 3D model of entire interior spaces of an operational building using the photogrammetry approach?
2. How long does it take to create a 3D model of entire interior spaces of an operational building using the photogrammetry approach?
3. What is the accuracy of photogrammetry approach for building's interior spaces?

1.6. Research objectives

This study aims to achieve followings in order to address the existing problems:

1. To prove if it is possible to create a 3D model of the building's interior using photogrammetry technology.
2. To figure out how long it takes to create a 3D model of entire interior spaces of an operational building using the photogrammetry approach.
3. To evaluate the accuracy of the photogrammetry model.

CHAPTER II

REVIEW OF LITERATURE

2.1. Introduction

3D documentation is one of the interesting areas through the history of construction industry and historical preservation. Human has always tried to record and document his environment in various ways. Drawing is one of the first methods of recording 3D data of surrounding environment and buildings. By the advancement of technology and introducing early cameras, documenting steps into a new stage. Furthermore, advancements in digital technologies brought a new generation of cameras. Introducing lasers made them popular tools to document the 3D surfaces and objects. All of these tools from drawings to laser scanners are still used in the construction industry and each has its advantages and disadvantages. In this chapter, these tools are introduced and the studies conducted based on them are reviewed.

2.2. Photogrammetry

2.2.1. History of photogrammetry

The “Photogrammetry” term has been used by Albrecht Meydenbauer for the first time in the late 19 century. However, Aime Laussedat is known as the father of Photogrammetry who established the foundations of photogrammetry (Figure 2.1) (Blachut and Burkhardt 1989). After the Second World War, the need for 3D documentation increased in Europe due to destructions and in North America because of

the increasing demand for mapping and development. Later by the introduction of computers the area of photogrammetry application was expanded (Ghosh 2005).

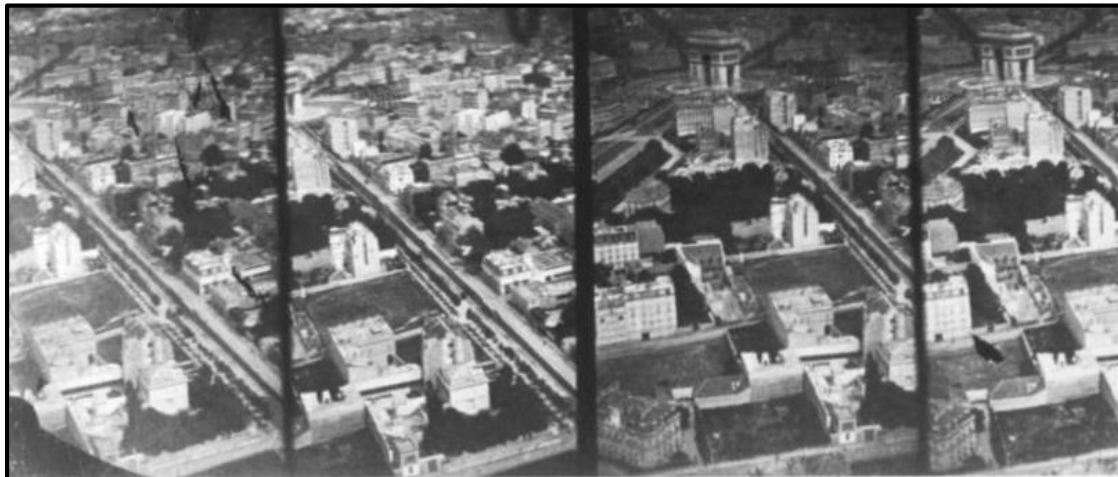


Figure 2.1: Early attempts of Aime Laussedat to create photographic map of Paris (Laussedat 1867)

Although the photogrammetry was introduced in late 19th century and had been developed for mapping purposes, the idea of producing 3D objects from photos was not developed until 1979 by Shimon Ullman as structure from motion (SFM). Ullman (1979) introduced algorithms that can calculate the location of points of an object in three-dimensional environment from several photos (Figure 2.2). This idea expanded the area of usage the photogrammetry into 3D documentation.

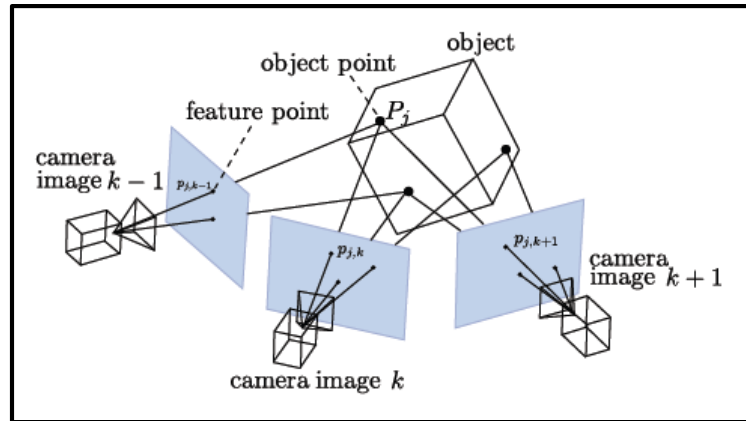


Figure 2.2: Structure from motion
(OpenMVG 2013)

Photogrammetry can be categorized into different areas based on “camera position and object distance”, “number of measurement images”, “method of recording and processing” and by “availability of measurements” (Luhmen et al. 2006). Dai (2010) defined “Digital Photogrammetry” as an approach which images or videos that are taken by digital equipment are processed by a photogrammetric application in order to produce “Spatial Relationship” and the object’s measurements. Close-range photogrammetry refers to a method of capturing images around the object while the camera to object distance is less than 330 ft. (Cooper et al. 1996). Gruen (1996) has categorized close-range photogrammetry into four areas. The latest area is from 1992 until present which has been defined by emerging image sensors which provide cheap high-resolution digital cameras.

2.2.2. Photogrammetry for buildings

Since the early 1800s, photogrammetry has been used to capture 3D documentations in different areas such as industry, biomechanics, chemistry, biology, archeology, architecture, automotive and aerospace engineering and accident reconstruction (Jiang et al. 2008). El Hakim and Sabry (2000) have investigated photogrammetry as an approach to create 3D models of complex environments and buildings. One of the most demanding areas of 3D document capturing is heritage buildings. Yilmaz et al. (2008) have used digital close-range photogrammetry to create documentation of historical caravansaries in the exterior environment. They suggested photogrammetry as a low-cost approach that can be done by affordable cameras and normal computers which do not require any special knowledge to be used. McCarthy (2014) has suggested using photographs for a cultural survey (Figure 2.3).



Figure 2.3: Capturing a 3D model of an ornament (McCarthy 2014)

Using photogrammetry to capture the 3D model of buildings was not limited to specific heritage buildings. Especially by developments of networks and social media, studies have been done to use existing photos on the internet to create 3D models of heritage sites. Snavely et al. (2007) have developed a framework to produce 3D models using SFM from amateur pictures uploaded by people on the internet.

Photogrammetry has been considered in architecture, engineering, construction and operation industry (AECO) industry as well. Photogrammetry among laser scanners has been used to evaluate the progress of construction on the job site (El-Omari and Moselhi 200). Furthermore, the progress of excavation can be recorded and calculated using photographs of the site. Comparing the volume of the 3D models produced from images indicates the excavated volume of the soil (Borrmann et al. 2013).



Figure 2.4: 3D model of excavated jobsite using photos
(Borrmann et al. 2013)

Operational buildings are considered in applications of photogrammetry in the industry. Capturing the 3D documentation of building's interior can assist facility managers and building owners in their daily processes. Liu and Kang (2014) have created

a 3D model of a historical buildings interior based on stitching images manually. Furthermore, photogrammetry has been used to evaluate As-built models of operational buildings. Although it has considered the building interior but it is just limited to a single room in the building (Klien et al. 2012).

Creating 3D model from operational buildings' interior has been a challenge due to the number of connected different rooms that do not have enough sight to each other. Furukawa et al. (2009) have conducted a study on creating building's interior using a new algorithm. The results of their study show that the produced model needs to be modified for a decent quality.

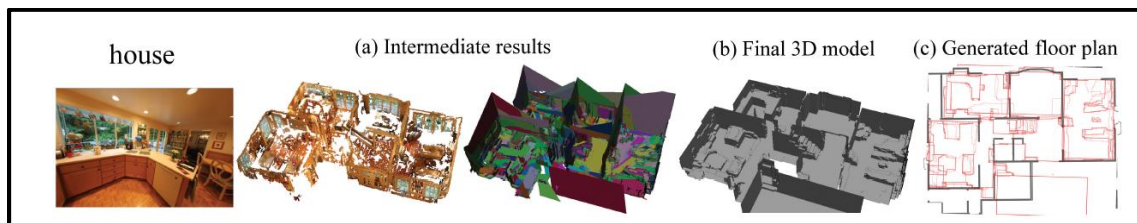


Figure 2.5: A building created using new algorithms in photogrammetry (Furukawa et al. 2009)

2.3. Laser scanners

2.3.1. Applications of laser scanners

Some studies have been conducted on using 3D laser scanners to visualize and to analyze topographic surfaces (Slob and Hack 2004; Abellan et al. 2006; Kasperski et al. 2010). Using laser scanners to create 3D documentation for heritages has been increased recently by the development of this technology. Boehler et al. (2002) have investigated using laser scanners to capture 3D data of various cultural heritage elements. Valera et al. (2012) developed a framework to integrate laser scanners and RFIDs to facilitate the segmentation for capturing the 3D data of a building's interior space. Also, the high-density model of building's interior has been produced to facilitate the creation of BIM for existing facilities. A framework was developed to recognize main building elements to create the 3D model (Figure 2.6) (Xiong et al. 2013).

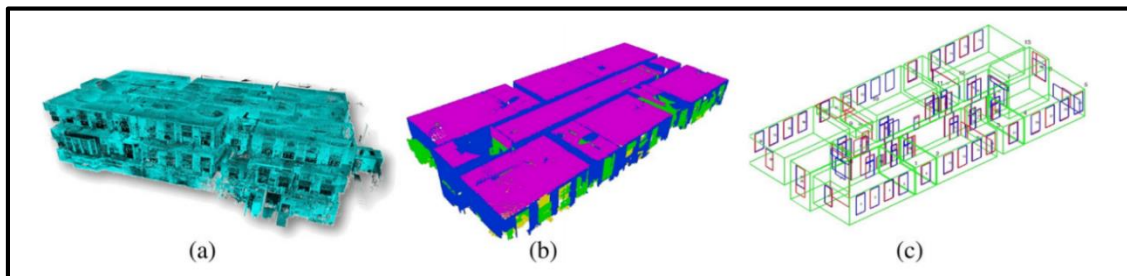


Figure 2.6: Steps of recognizing and creating building from point clouds (Xiong et al. 2013)

2.3.2. Integration of laser scanners and photogrammetry

Although laser scanners have shown promising results, many studies have considered using laser scanners along digital photogrammetry in order to create high-quality texture mapping for 3D model and solve the issue of edges and surface details for laser scanners (Alshwabkeh 2006). Koch and Kaehler (2009) discussed the advantages and disadvantages of photogrammetry and laser scanners. They conducted their study on combining these two technologies to overcome the surface contrast issue of photogrammetry and accuracy of capturing edges and surface details by laser scanners. Kersten et al. (2009) have used mobile terrestrial laser scanners to capture a heritage site in Istanbul while they have utilized digital photogrammetry to capture mapping of facades and roofs (Figure 2.7).



Figure 2.7: Using aerial photogrammetry to produce roofs and terrestrial laser scanners to produce the walls in a neighborhood in Istanbul, Turkey (Kesten et al. 2009)

2.3.3. Comparison of laser scanners and photogrammetry

Using 3D laser scanning over photogrammetry has been increased as a method for capturing 3D data in many areas. Many advantages have been identified for laser scanners and the technology is still improving. However, many studies have been conducted comparing photogrammetry and 3D laser scanning since the early years of introducing laser scanners. Baltsavias (1999) has compared airborne laser scanning with photogrammetry in different areas such as accuracy, production time, and cost. He found the laser scanners more potent for future development regarding their better accuracy, automation process and less production time. He mentioned that there were still uncertainties about the cost of using each method to capture the 3D data. However, later Boehler and Marbs (2004) have found the Photogrammetry as a cheaper technology for capturing heritage 3D model. They mentioned photogrammetry as a better option to capture well-textured surfaces while laser scanners perform better on complex and irregular shapes. Also, the deficiency of laser scanners to capture colors is one of the issues in heritage 3D documentation. This issue can be solved by integrating photographs with the 3D model extracted from laser scanners (Kadobayashi et al. 2004). Remondino et al. (2005) have mentioned the lower cost of photogrammetry in comparison of two technologies to create 3D models of heritage buildings and objects. Photogrammetry has been identified as a better option to capture terrestrial data due to its lower cost, capturing colors and better portability (Kolecka 2009). Ruther et al. (2012) have compared Terrestrial Laser scanning with close-range photogrammetry results which were conducted in 1995 and 2011. They found all of the results reliable and accurate. In their

point of view, photogrammetry is still a reliable option despite the recent tendency towards laser scanners. Most of the studies in comparing these two technologies are focusing on heritage buildings and few studies have been done on operational buildings concerning laser scanners and photogrammetry.

2.4. Conclusion

3D laser scanner technology has evolved since it was introduced in early 1990's. Because of their accuracy and faster capturing process, they have replaced traditional photogrammetric approaches. But there are still some disadvantages for laser scanner technology that can be solved by integration with digital photogrammetry. Also, many studies have been done comparing 3D laser scanning and Photogrammetry which most of them agree on the effectiveness of digital photogrammetry. Photogrammetry can be a low-cost solution to capture the 3D data of interior spaces. Although studies have been done considering using photogrammetry for interior uses, none of them evaluated the practicality of creating the 3D model of a whole building's interior using SFM.

CHAPTER III

RESEARCH METHODOLOGY

3.1. Research design

3.1.1. Overview

The objective of this research was to investigate the practicality of using photogrammetry to capture the 3D data of operational buildings' interior. In order to achieve this objective, the research was conducted on a case study and the data were collected from one building and they were processed through an existing commercial application. The practicality of photogrammetry for building's interior spaces was assessed in the process of connecting the 3D meshes created from images. The challenges and limitations were identified through this process. The study followed the following steps:

Step 1: Taking photos from the case study's building interior spaces

Step 2: Process the taken photos using an existing application

Step 3: Create a 3D model from the whole spaces of the building

Step 4: Record the duration of each step of the process

Step 5: Compare dimensions of the 3D model with the built environment

3.1.2. Shooting photos

The Francis Hall building was chosen as the case of the study. The building's interior space was divided into 22 sections. In each section, 12 locations on the parameter of each space were specified based on 30 degrees intervals to place the camera and to take photos toward the center of the space. On each location, 20 photos were taken based on 20 different horizontal and vertical rotations to assure the coverage of all surfaces.

3.1.3. Processing photos

Autodesk Recap commercial application was chosen to process the photos. The photos were uploaded for each section separately on the cloud server and were processed using photogrammetry algorithm. The application created 3D mesh models from the photos for each section. 3D models were downloaded to be prepared for stitching.

3.1.4. Creating the 3D model

Completed mesh models were cropped, scaled and fixed using Autodesk Memento commercial application to be prepared for stitching process. The fixed sections were imported to Unity 3D commercial application to be stitched. Sections were repositioned to have the same rotation. 3D mesh models of the sections were stitched using similar elements such as columns and doors.

3.1.5. Recording the duration

The duration was recorded for each step of the test. The time was recorded using a stopwatch for each section separately.

3.1.6. Evaluating the Tolerance

For each section, 6 dimensions were measured from different elements. Each dimension was compared to the corresponding dimension of the same element in the 3D model to evaluate the tolerance of the approach.

3.2. Case of the study

The Francis Hall building at Texas A&M University was chosen for this study (Figure 3.1). The building is a 3 story educational facility that was renovated to host the department of construction science. This building was chosen as a typical educational building because of the variety of spaces such as public spaces, stairways, classrooms, faculty rooms, restrooms, an auditorium and a room designated for Building Information Modeling Computer Aided Virtual Environment (BIM CAVE) facilities.

This study was limited to the first floor of the building since it encompasses all of the important spaces existed in the building (Figure 3.2).



Figure 3.1: Francis Hall building
(Archone, 2013)

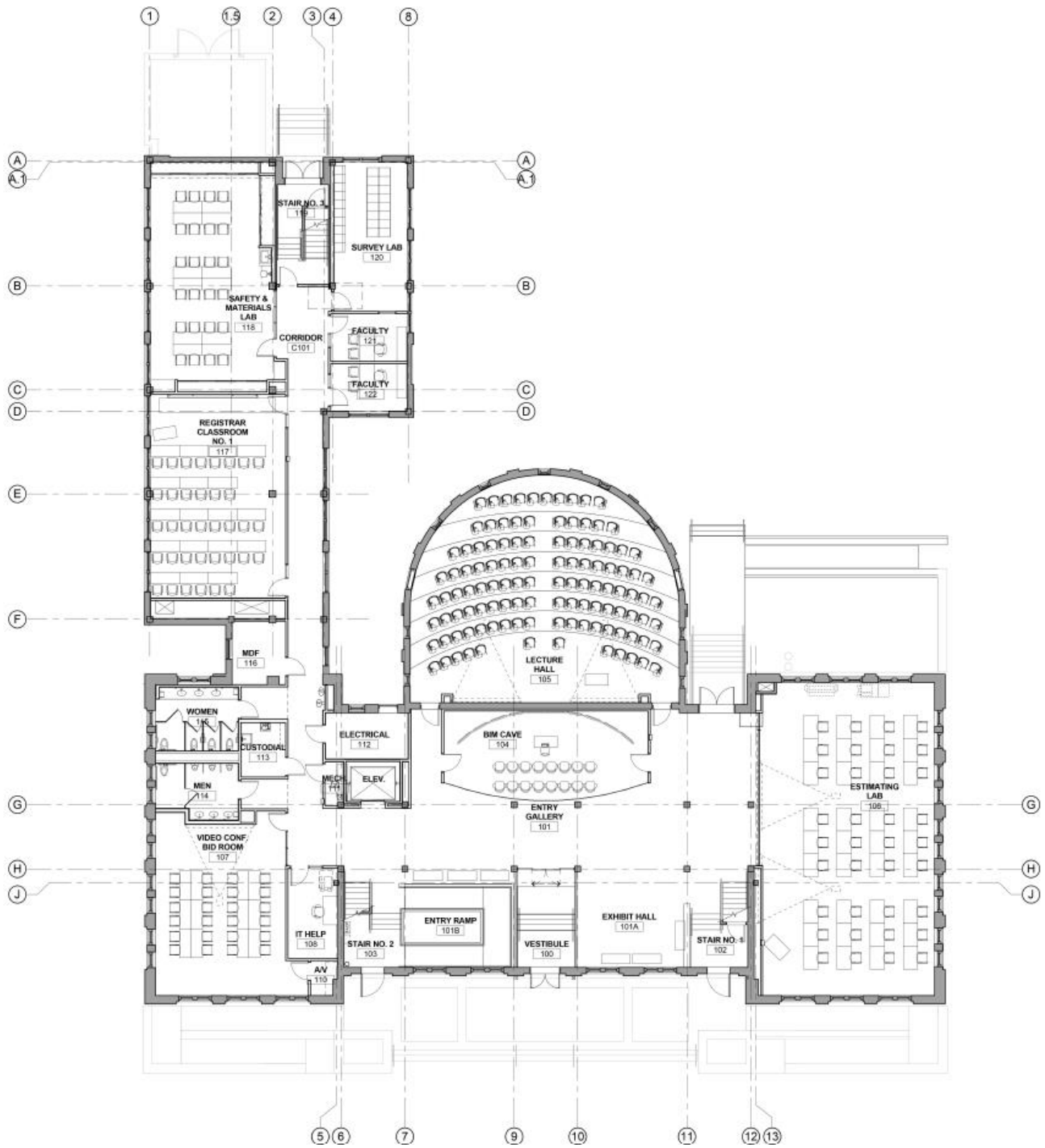


Figure 3.2: Interior spaces of Francis Hall's first floor (B. R. W. Architects 2013)

3.3. Shooting photos

Photogrammetry is based on matching the same points from different views to define the 3D geometry of an element (Ullman 1979). The photos should have overlaps to cover an element multiple times. Moreover, due to the interconnection of rooms taking the whole floor's interior spaces at once is challenging (Furukawa et. al. 2009). Hence, the building should be divided into sections with a defined center.

3.3.1. Sections

The Francis Hall building's interior accessible spaces were divided into 22 sections which cover important spaces of the building (Figure 3.3).

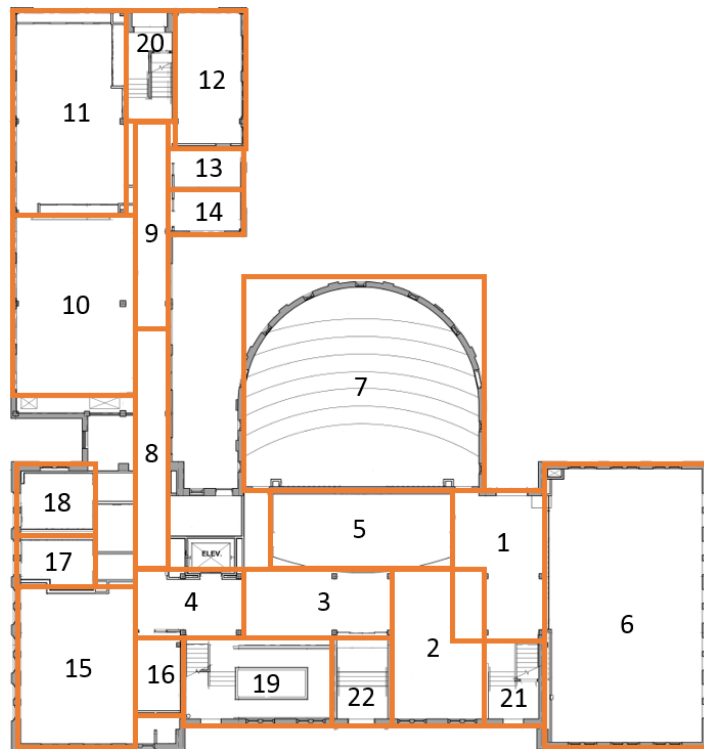


Figure 3.3: Sections of the interior space (B. R. W. Architects 2013)

Sections 1, 2, 3, 4: Entry gallery

The Entry gallery of the building is a common space which connects the entrance of the building to other spaces. Due to the irregular shape of the room, it was divided into 4 sections to acquire the best result (Figure 3.4).



Figure 3.4: Entry gallery from section 3

Section 5: BIM CAVE

The BIM CAVE is located in the heart of the building. The room has a curve glass wall which is facing the building's entrance. There are 32 monitors to illustrate BIM visualizations.

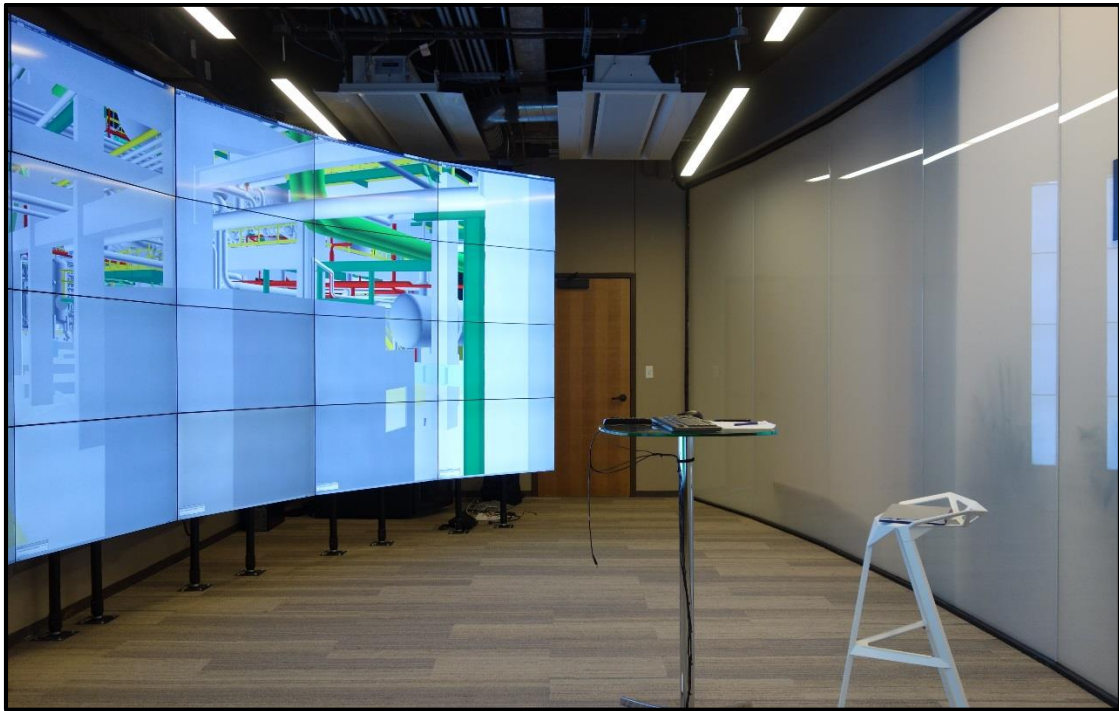


Figure 3.5: BIM CAVE

Sections 6, 10, 11, 12, 13, 14, 15, 16, 17, 18: Rooms

These sections include single accessible rooms which have the functions of classrooms, labs, faculty rooms and restrooms. These sections have different sizes with different furniture sets (Figures 3.6 – 3.9).

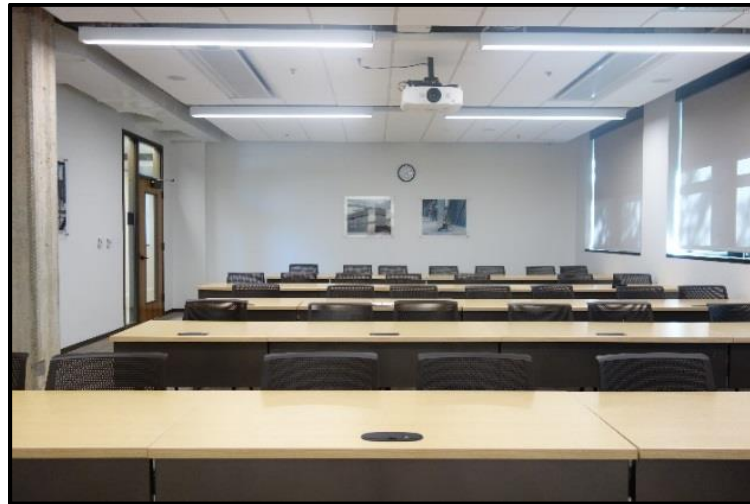


Figure 3.6: Section 10 (classroom)



Figure 3.7: Section 16 (IT helpdesk)



Figure 3.8: Section 17 (men's restrooms)



Figure 3.9: Section 15 (classroom)

Section 7: Auditorium

The auditorium is an oval shaped double height room which is the biggest section among the 22. This space has arrays of similar chairs on a stepped floor. The stepped floor makes the elevation of the floor variable in different locations (Figure 3.10).

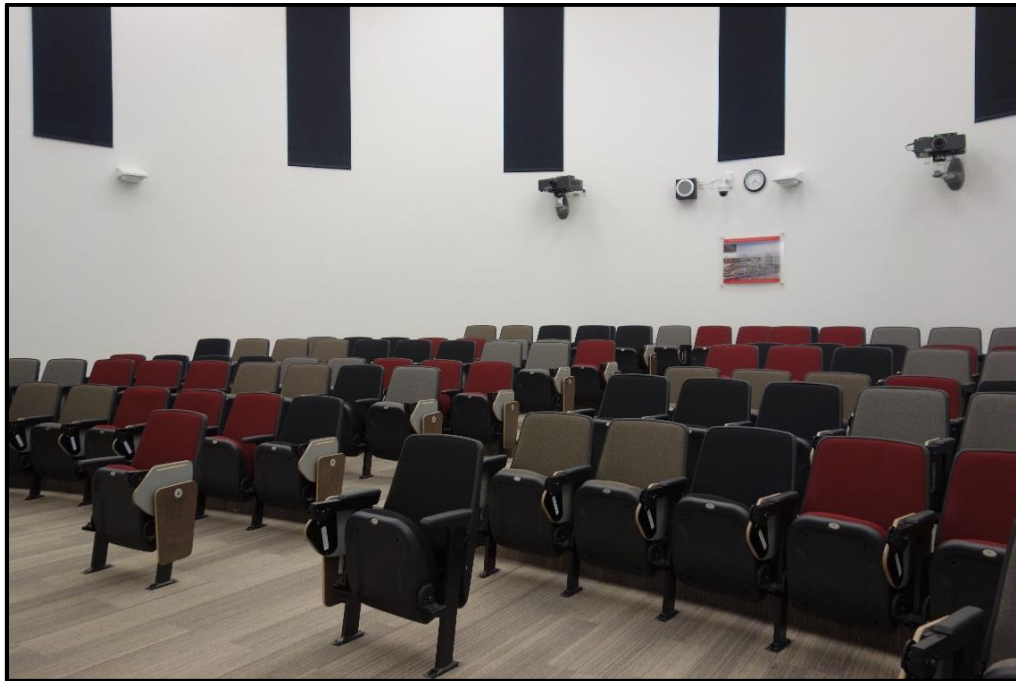


Figure 3.10: Section 7 (auditorium)

Sections 8, 9: Hallway

The first floor has a hallway that provides the access to the restrooms, classrooms and faculty rooms. In order to achieve a better result, the hallway was divided in half to create reasonable rectangular sections (Figure 3.11).

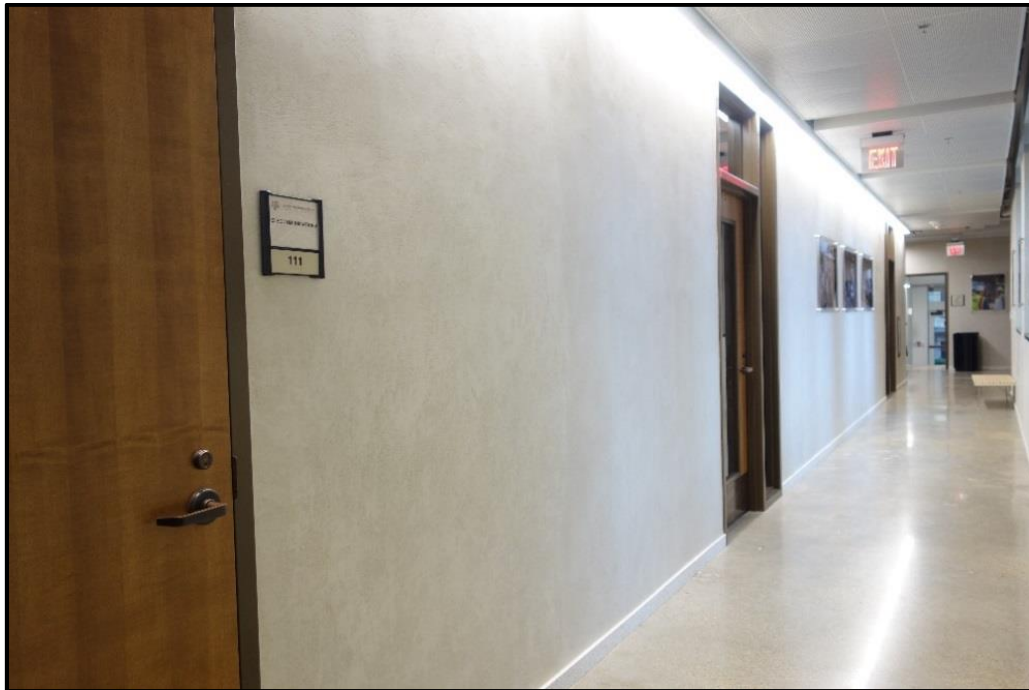


Figure 3.11: First floor hallway from section 8

Sections 19, 20, 21, 22: ramp and stairways

These sections include the entrance vestibule of the building, stairways, and an accessible ramp way. These sections have different elevations. (Figures 3.12 and 3.13)



Figure 3.12: Section 21 (stairways)

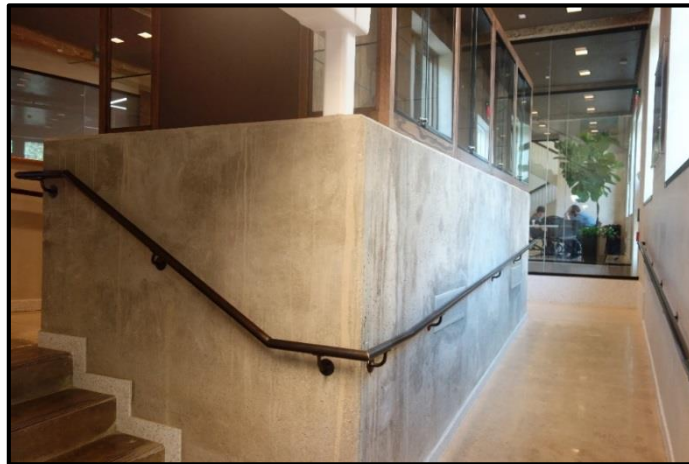


Figure 3.13: Section 19 (accessible ramp)

3.3.2. Camera placement

Photos should cover all of the surfaces with proper overlap while following the principles of SFM. The camera was placed on the perimeter of each section facing the center. The orientation of the camera was changed in 30 degrees intervals around the center. The orientation of the camera was changed in 30 degrees intervals around the center to create 12 different placements to cover the surfaces (Figure 3.14).

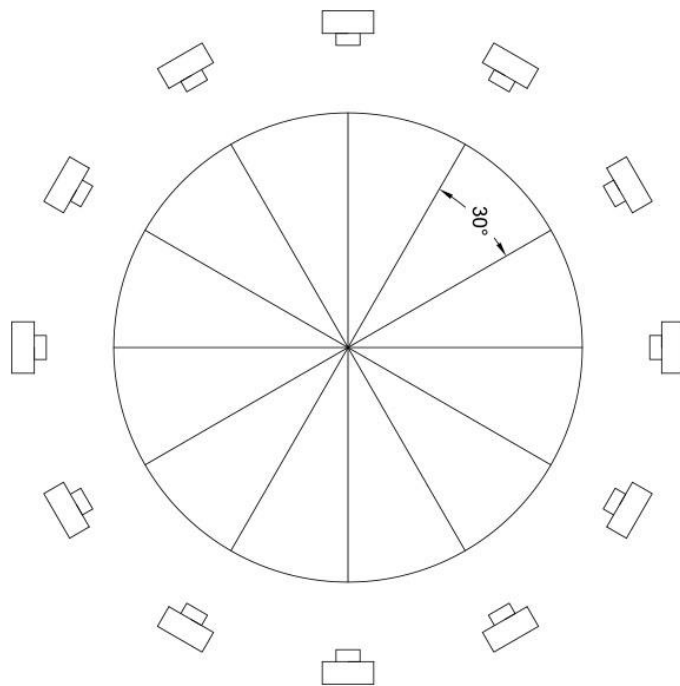


Figure 3.14: Camera placement in each section

In order to indicate the center and assist the photographer to locate the camera in 30 degrees intervals, a paper was placed on the center of each section (Figure 3.15).

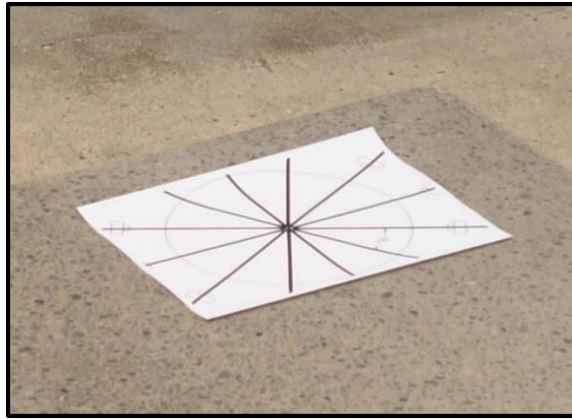


Figure 3.15: A paper placed in the center to facilitate the camera placement with alignment of the camera grids with the lines

For each placement, 20 photos were taken in total based different camera rotations which were created by five 30 degrees horizontal rotations and four 30 degrees vertical rotations. The result was 240 photos per sections (Figure 3.16).

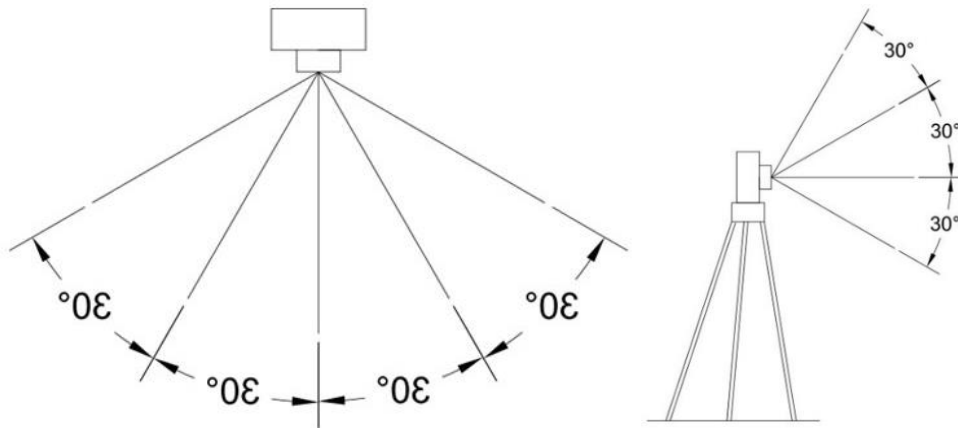


Figure 3.16: Horizontal and vertical rotations of camera in each placement

Using the camera grids, 30-degree rotations were fulfilled to achieve 20 different orientations per each location (Figure 3.17).



Figure 3.17: Camera grids

In order to take the photos, a tripod was used to make the elevation and rotation of the camera consistent. Sony Cyber-shot DSC-RX100 digital camera was used as an amateur regular camera to shoot the photos (Figure 3.18).



Figure 3.18: A normal digital camera is used with a tripod to take the photos

The photographer took photos from all 22 sections using the manual process of locating and rotating the camera (Figure 3.19).

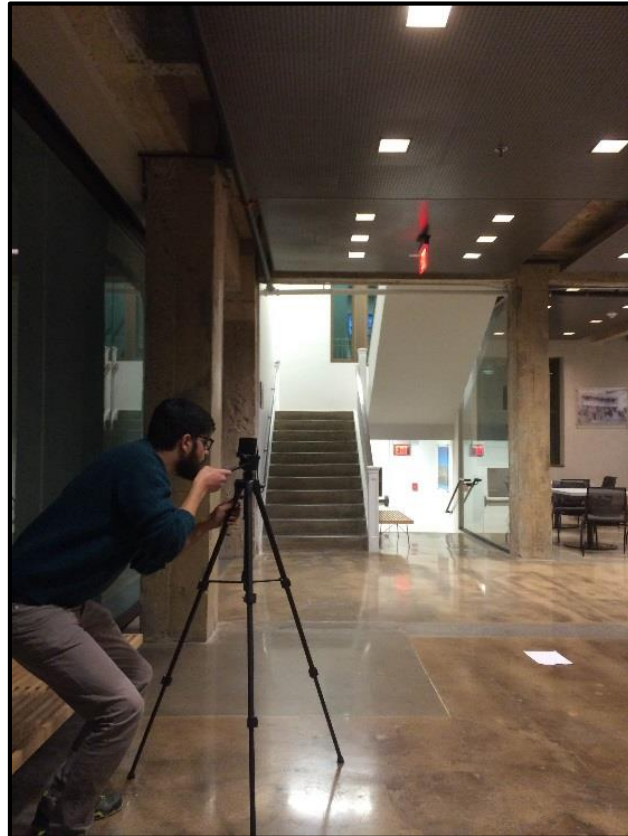


Figure 3.19: Process of taking pictures in section 1 of entry gallery

Although the study was designed to capture 240 photos per section by locating the camera in 12 different location in each section, due to the limited space, furniture arrangement or shape of the sections, number of camera locations were less than 12 for some sections. The total number of photos taken from the building's interior spaces was 4940 photos. Following table 3.1 shows the number of photos for each section:

Section	Locations	Number of Photos	Section	Locations	Number of Photos
1	12	240	12	11	220
2	12	240	13	8	160
3	12	240	14	9	180
4	12	240	15	12	240
5	12	240	16	12	240
6	12	240	17	12	240
7	12	240	18	8	160
8	12	240	19	12	240
9	12	240	20	9	180
10	12	240	21	10	200
11	12	240	22	12	240

Table 3.1: Number of photos per section

The table 3.1 shows that 16 out of 22 sections were photographed by placing the camera in 12 designated locations. The following diagrams show the camera placement in each section. Sections 1, 2 and 14 are demonstrated here (Figures 3.20, 3.21 and 3.22). Other sections can be found in appendix A (Figures A.1 – A.18).

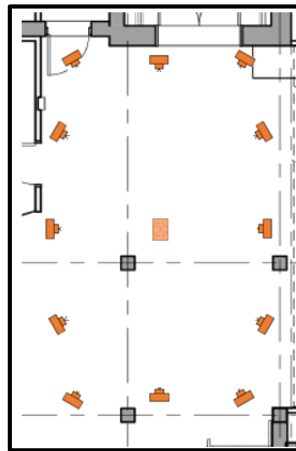


Figure 3.20: Section 1 camera placement diagram (B. R. W. Architects 2013)

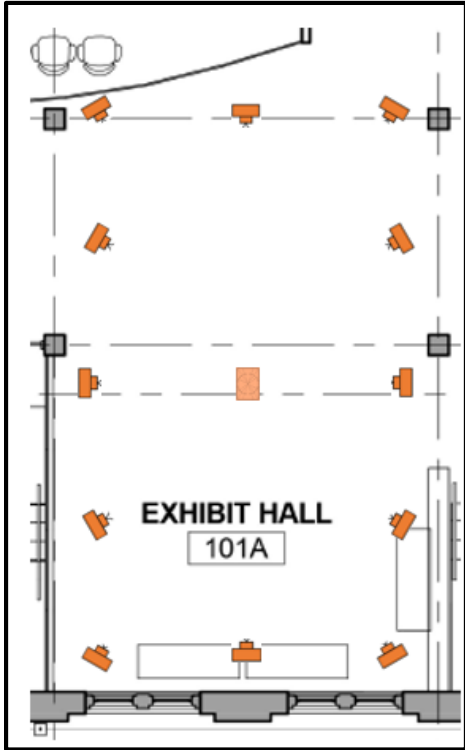


Figure 3.21: Section 2 camera placement diagram (B. R. W. Architects 2013)

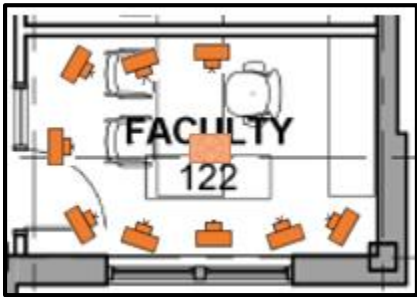


Figure 3.22: Section 14 camera placement diagram (B. R. W. Architects 2013)

3.4. Processing

In order to process the photos and create the 3D model, a commercial photogrammetry application had to be chosen. Although there is no comprehensive comparison showing advantages and disadvantages of each commercial application, all of them follow the same principles for acquiring 3D coordinates of objects in the photos. One of the objectives of this study was to investigate the practicality of using photogrammetry to create the building's interior spaces, and any commercial application that follows the principles of photogrammetry was acceptable for this study. Autodesk Recap 360 was chosen as a commercial application which processes the photos on a cloud server, so the result of the study would not be limited to a single computer.

The photos were processed through a photogrammetry application to create point clouds and 3D meshes automatically. Autodesk recap 360 (Figure 3.23) is a cloud-based image processing application which provides the feature of capturing interior spaces of buildings. The application creates a 3D model based on the photos that were uploaded to the server. The applications provides the 3D model in the following formats:

- *.obj - common 3D format compatible with most of the 3D modeling applications
- * .fbx - Autodesk 3D file format compatible with most of the Autodesk applications
- * .rcm - Autodesk Memento file format
- * .rcs - Point cloud file format to be opened in Autodesk recap desktop application

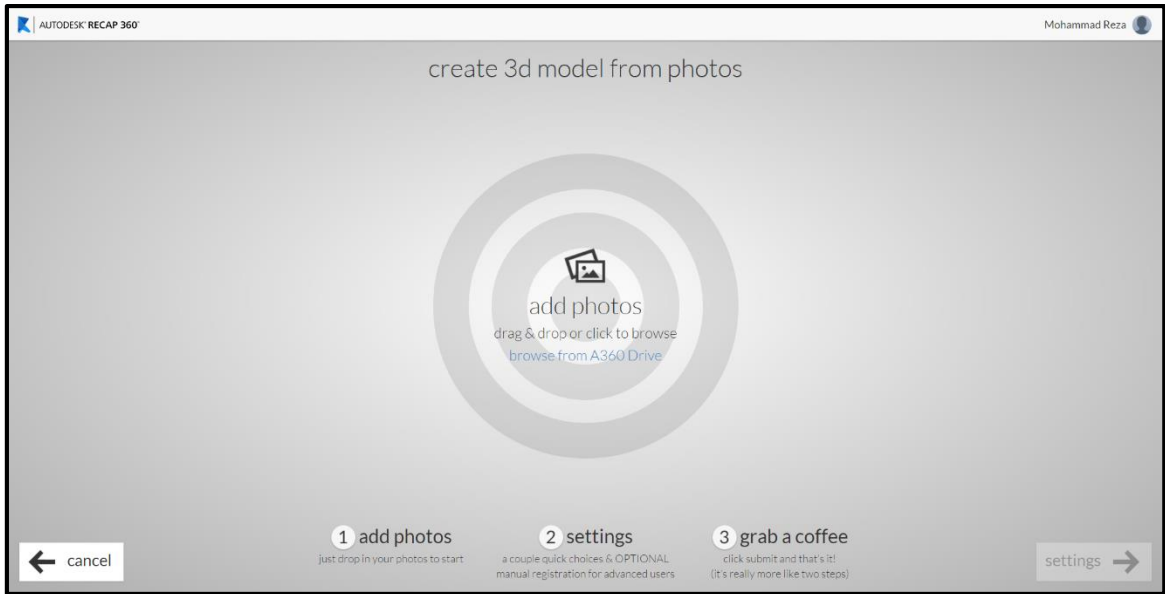


Figure 3.23: Autodesk Recap 360 interface

After the photos were taken, they were uploaded on the Autodesk Recap server to be processed automatically. Ultra was selected as the quality of the processing (Figure 4.24). RCM format was selected as the final result to be used in Autodesk Memento application.

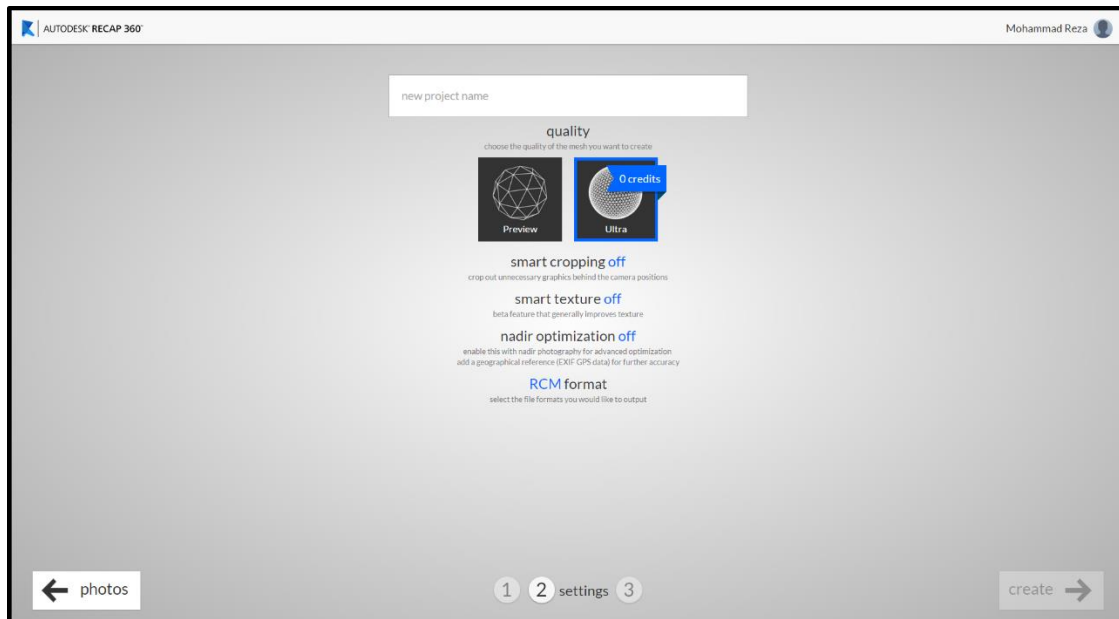


Figure 3.24: Autodesk Recap cloud image processing settings

The sections created using this process, were downloaded as the RCM format to be viewed and edited in Autodesk Memento application. The results showed that the application not only has created a 3D model from designated sections, but also it has created a 3D model from the background which was visible in the photos. Following are screenshots of the produced 3D model for section 1 and 2 (Figures 3.25 and 3.26). Other sections are provided in the appendix B (Figures B.1 – B.19).



Figure 3.25: Section 1 mesh model extracted from Autodesk Recap



Figure 3.26: Section 2 mesh model extracted from Autodesk Recap

3.5. Preparing the 3D model

One of the goals of the research was investigating the practicality of creating the entire building's interior spaces. 3D models of sections processed by Autodesk Recap had to be stitched to create the entire floor's model. The sections had to be edited to be prepared for stitching. Editing included: Scaling, fixing, and cropping. The figure 3.27 shows the raw mesh model downloaded from Autodesk Recap's online server.

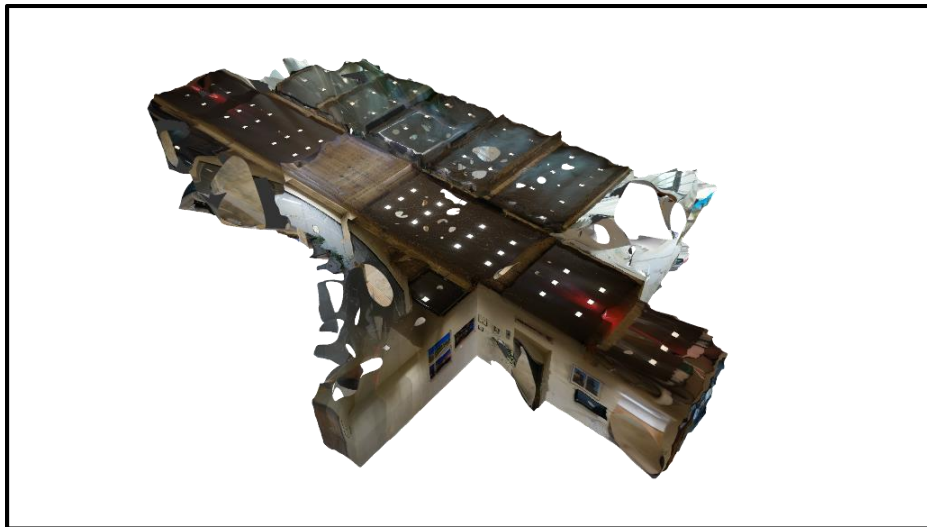


Figure 3.27: Section 3 mesh model downloaded from Autodesk Recap's online server

3.5.1. Cropping

The processed models were downloaded from the Autodesk's cloud server with RCM format to be opened by Autodesk Memento. As mentioned before, the produced model was not limited to the designated section and the background was produced as well. Hence, the sections had to be cropped so the best quality models could be stitched together.

The cropping step was done manually based on the boundaries of designated sections on the plan. The undesired parts were selected by Memento's selecting tools (Figure 3.28).

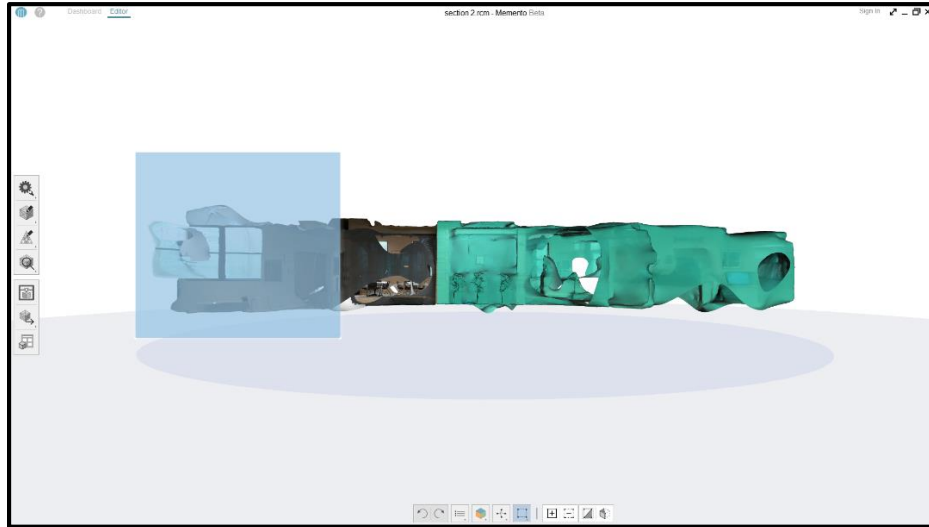


Figure 3.28: Cropping process in Autodesk Memento

The selected unwanted parts were deleted and the remaining of the model was investigated to remove other unnecessary parts in more details. The unnecessary parts included particles and unconnected meshes in the space (Figure 3.29).



Figure 3.29: Unnecessary parts to be cropped



Figure 3.30: Section 3 cropped mesh model

When the cropping was completed the section was ready to be stitched to other sections (Figure 3.30). But there were some deficiencies in the model that could be fixed by mesh fixing tools of the application.

3.5.2. Fixing

Deficiencies could be found in the model such as holes and particles which could be fixed by the application automatically. The application is designed to detect issues in the meshes and remove them automatically.

In order to fix the model, the issues had to be detected first. The application has a tool to detect and fix the issues (Figure 3.31).



Figure 3.31: Detecting issue process in Autodesk Memento

The application highlighted the issues such as holes, particles, and intersections. The user was able to fix the issues collectively or all at the same time. Holes could be fixed both by a flat surface or smoothing (Figure 3.32). Particles are the meshes that are not connected to other meshes and can be deleted using this tool (Figure 3.33).

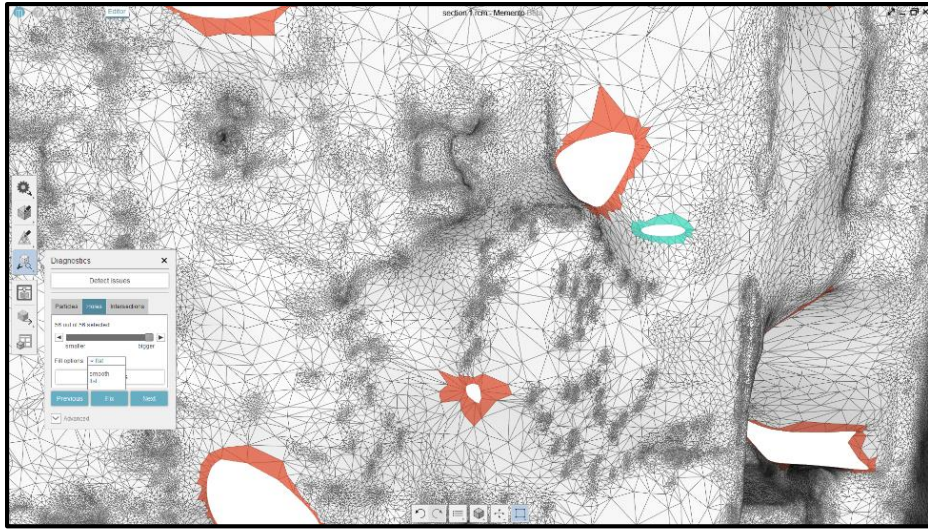


Figure 3.32: Fixing holes using Autodesk Memento issue detecting tool

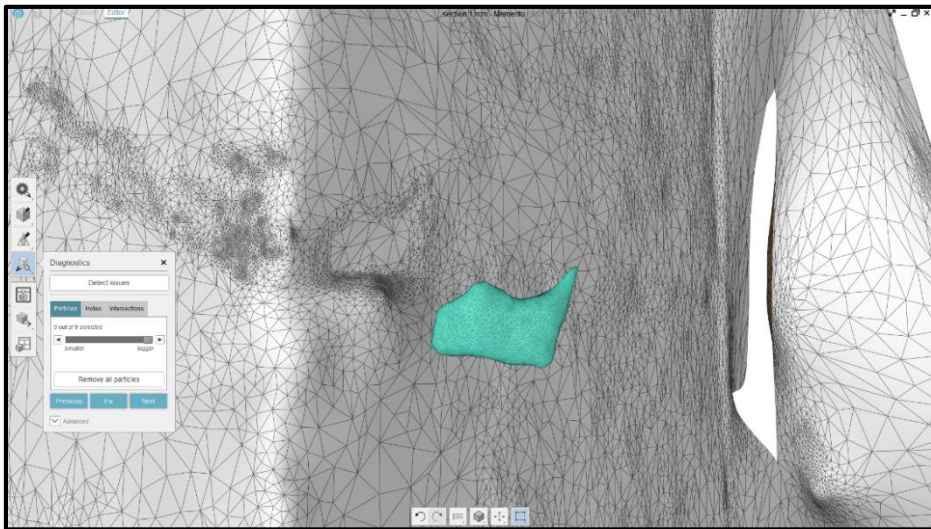


Figure 3.33: Removing particles using Autodesk Memento detecting tool

All sections were cropped and fixed using the application's tools. The computer detected the existing issues and filled the holes using the same mesh pattern around them. The computer automatically applied the texture color of the surrounding areas. Moreover, the computer detected existing particles in the space and removed them automatically. Following is an example from section 3 of the building (Figure 3.34):



Figure 3.34: Fixing the holes in the mesh model by the same texture

3.5.3. Scaling

The last step before exporting the 3D model was scaling the model to its real size. The image processing application does not produce the 3D model in its realistic scale.

One dimension was selected from each section and was matched to the same location in the model. Using the scaling tool of the Memento's application the section was scaled up to its original scale (Figure 3.35).

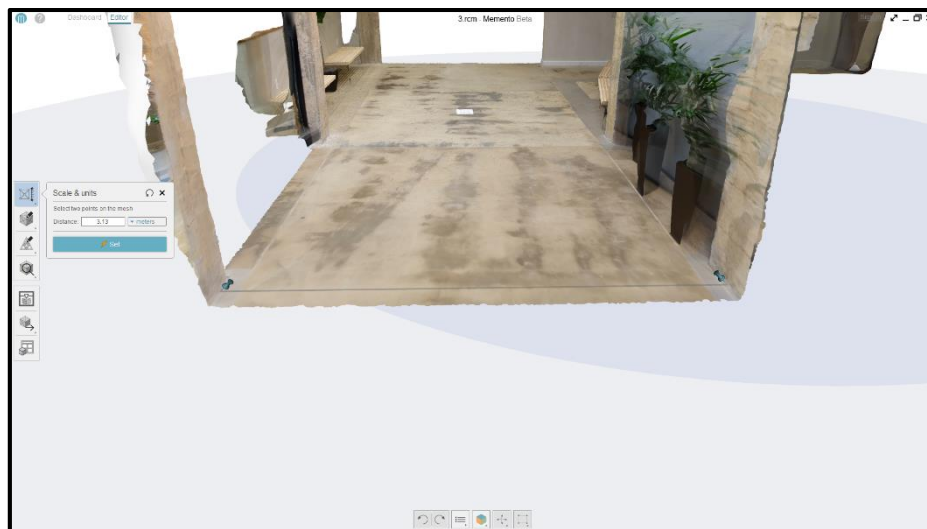


Figure 3.35: Scaling the mesh model to the original size using one dimension

3.5.4. Exporting

The 3D models were fixed and scaled to be exported to another application to be stitched manually. In order to achieve the best result, the best possible quality was chosen for the meshes to be exported. FBX format was selected as the exporting format to preserve the texture while exporting. All of the sections were exported using Memento's exporting tool (Figure 3.36).



Figure 3.36: Exporting settings

3.6. Stitching sections

The sections that were produced and fixed had to be stitched to create the 3D model of the whole first floor. Unity 3D application was chosen as a 3D modeling application to move, rotate and stitch multiple meshes (Figure 3.37). The models were imported into the application using FBX format which is a common format among 3D modeling applications and has the ability to preserve the texture while exporting and importing.

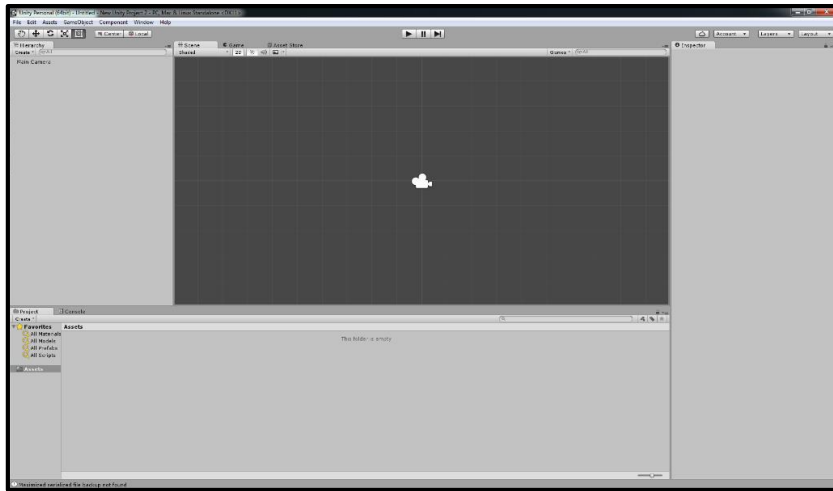


Figure 3.37: Unity application interface

Exported sections were imported to Unity application to be stitched to create a 3D model of the first floor of the Francis Hall building. The models were rotated 270 degrees around X axis so the ground surface of the model could be aligned with the horizontal plain of the application (Figure 3.38).



Figure 3.38: Imported model needed to be rotated in Unity

All sections were imported into the Unity 3D application to be stitched like pieces of puzzles (Figure 3.39). Sections were not aligned so they had to be rotated to be stitched using the move feature. Sections were rotated around the Y axis to align together. The rotations in many cases were 90, 180 or 270 degrees.

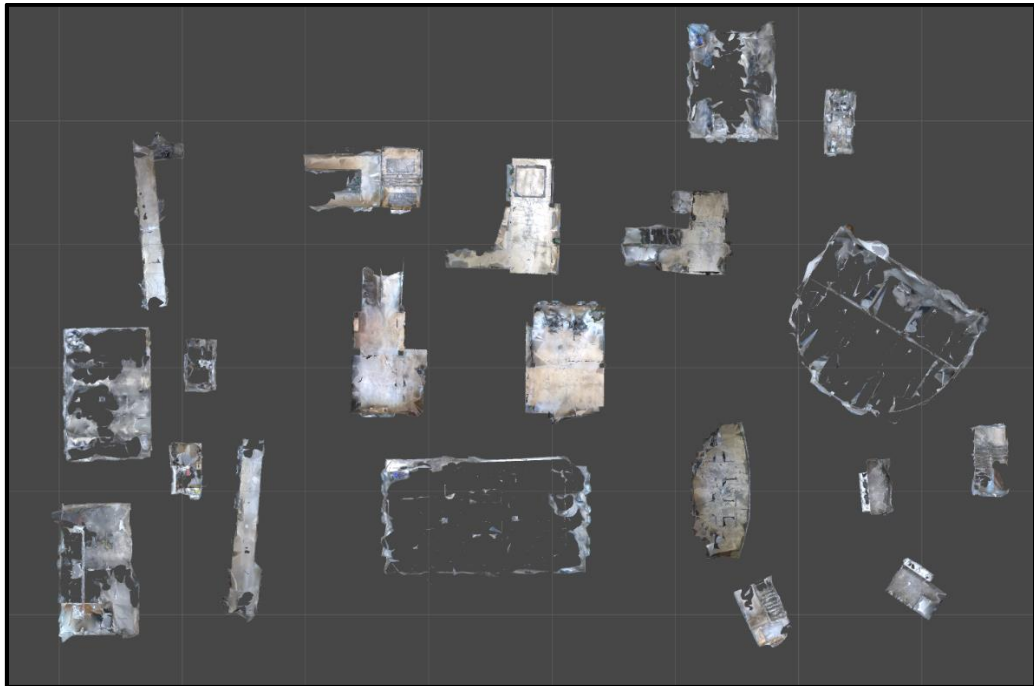


Figure 3.39: Section after uploading in the Unity with various rotations

The sections of the building that were connected visually, stitched by matching columns, walls or other mutual elements (Figure 4.58).

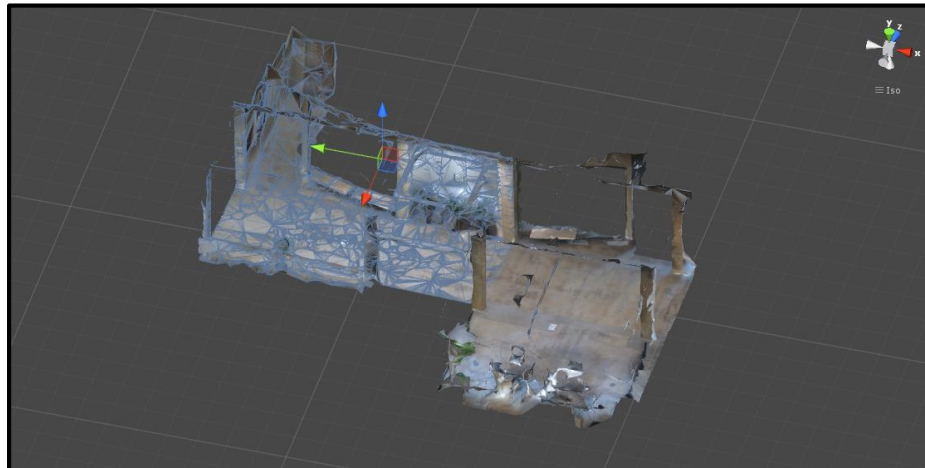


Figure 3.40: Stitching models using similar elements

Rooms were stitched to the main model using doors as the mutual elements of the models (Figure 4.59).

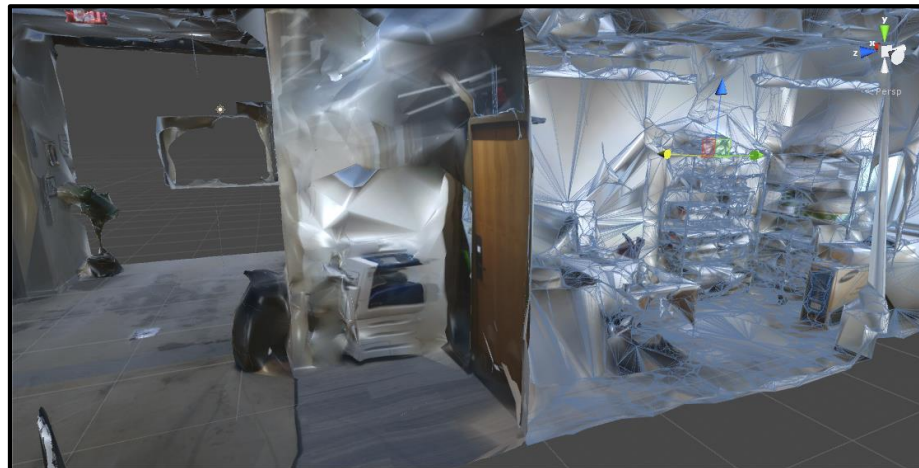


Figure 3.41: Stitching rooms to other spaces using doors as similar elements

All sections were stitched using the explained manual approach in Unity application except sections 12 and 19. Section 12 was not produced completely by the image processing application and the 3D model of section 19 was not sufficient to add anything to the main model.

3.7. Recording time

One of the major issues of manual approaches to create 3D models of existing buildings is time. In order to evaluate the efficiency of the photogrammetry approach to create the 3D model, the duration of the process had to be recorded. The duration of each step in this process from taking the photos to processing and creating the 3D model was recorded for each section individually. A stopwatch was used to record the duration and the results were rounded up in minutes. The total duration for each section and each process was calculated at the end.

3.8. Evaluating the level of tolerance

Although the studies have shown the accuracy of this approach is acceptable for buildings' elements (Dai and Lu 2010), the accuracy of this approach for buildings' interior elements was still unknown. Hence, another goal of this study was to assess the level of the accuracy of the produced model. The level of tolerance was calculated by comparing measurements from the real environment to the processed 3D model. The comparison was done after processing the photos. For each section, one dimension was

measured to scale the produced 3D model from photos. In the next step, 6 items from each section were measured using a laser measuring tool (Figure 3.42).



Figure 3.42: Laser measurement tool

The results were compared with the same dimensions from 3D models which were calculated using Autodesk Memento measuring tool. The tolerances of the measurements were calculated to evaluate the approach accuracy. All measurements were rounded to centimeters.

18 sections in total were measured due to the limitation of accessing sections 18 and 14. However, sections 17 and 13 has the same characteristics respectively.

Various elements were chosen in each section to evaluate the accuracy for different objects with different lengths. As can be seen in Figures 3.43 and 3.44, dimensions such as long and short distances, heights, doors, and windows were measured. The diagrams showing other section dimension are provided in the appendix C (Figures C.1 – C.16).

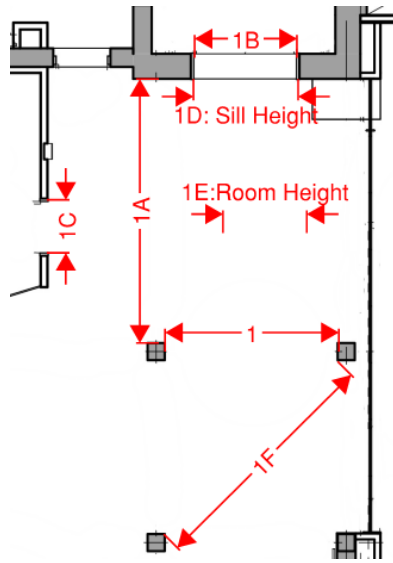


Figure 3.43: Dimensions of section 1 (B. R. W. Architects 2013)

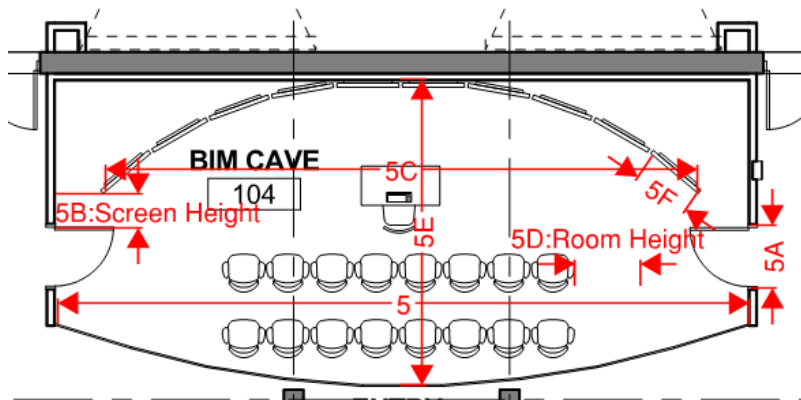


Figure 3.44: Dimensions of section 5 (B. R. W. Architects 2013)

CHAPTER IV

RESULTS

4.1. Introduction

As mentioned in the previous section, photos were taken from the Francis Hall building's interior spaces. The photos were uploaded on Autodesk Recap's online servers to be processed. The results were 3D meshes of different sections of the building. These meshes were edited and prepared in Autodesk Memento application. The edited sections were imported in Unity 3D to be stitched.

In this chapter, the results of the study are reported. For the purpose of this study, the final result of the study is demonstrated. Also, the time that was recorded during the process is reported for each section separately. Moreover, as explained in the previous chapter, the tolerance of the 3D models is provided for each section.

4.2. 3D model

As described previously, sections were imported to Unity 3D application and stitched together using similar elements. However, 2 sections were removed from the study due to incomplete meshes. Section 12 was not defined as a room and did not have any similar elements with other sections (Figure B.9). Section 19 was replaced with the background meshes of section 22 due to the poor quality.

Other sections were stitched using similar elements such as doors and columns. Figure 4.1 shows all sections were connected and shaped the building's mass.

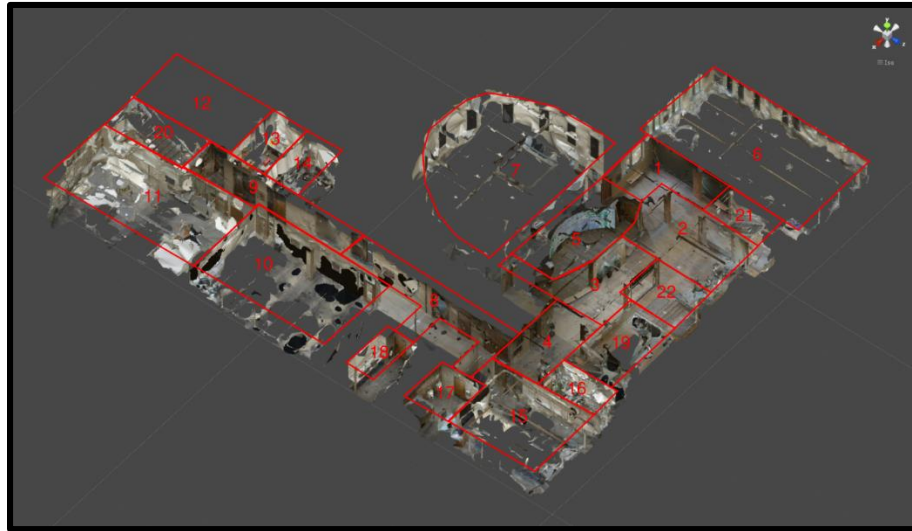


Figure 4.1: All sections connected using similar elements

The connections of sections can be seen in the ceiling plan view of the model as well (Figure 4.2).



Figure 4.2: Stitched sections ceiling shows the connection

In the following interior spaces of stitched sections can be seen (Figure 4.3 and Figure 4.4):



Figure 4.3: interior view of stitched sections (Entry gallery and BIM CAVE)



Figure 4.4: Interior view of stitched sections (Hallways)

4.3. Time recording

The duration of the steps for each section was recorded separately. In this section, tables are provided and the total time of each step in addition to the average duration of the step is calculated. At the end, the total time for each section, total duration of the process and the average time for each section is provided. Also, the duration of sections 12 and 19 is not considered because they were removed from the study.

4.3.1. Shooting photos

The process of taking photos in each section was recorded using a stopwatch. During the process, the watch was stopped for issues such as changing the battery of the camera or any other interruptions. Following is the table 4.1 showing the net time for taking photos:

Section	Duration	Section	Duration
1	63	13	34
2	80	14	32
3	70	15	55
4	40	16	58
5	42	17	32
6	48	18	40
7	53	20	35
8	40	21	43
9	41	22	51
10	55		
11	47		
Total	959		
Average	47.95		

Table 4.1: Duration of taking photos (in minutes)

4.3.2. Processing

The photos were uploaded onto the Autodesk cloud server to be processed to produce 3D meshes of the section. In order to record the duration, starting time was recorded and the finish time was obtained from the notification email sent by Autodesk after finishing each section. Following is the table 4.2 showing the duration of processing for each section:

Section	Duration	Section	Duration
1	710	13	420
2	863	14	648
3	639	15	577
4	793	16	693
5	588	17	793
6	590	18	611
7	522	20	391
8	793	21	435
9	792	22	931
10	591		
11	561		
Total	12941		
Average	647.05		

Table 4.2: Duration of image processing (in minutes)

4.3.3. Fixing, cropping and scaling

The models were downloaded and opened by Memento application to be fixed, cropped and scaled to be ready for the stitching process. The time for each step was recorded using a stopwatch. The cropping process is manual but the issue detecting step is done by the application. The durations were rounded up to minutes. Sections 12 and 19 were removed from the study and the fixing and cropping process were not applied to them, hence, the time is not recorded. Following is the table 4.3 showing the duration for each step per each section:

Section	Scaling and Cropping	Fixing	Section	Scaling and Cropping	Fixing
1	7	5	13	2	5
2	6	4	14	2	4
3	7	5	15	2	4
4	4	4	16	2	6
5	5	4	17	2	5
6	3	5	18	2	4
7	4	2	20	3	4
8	3	5	21	2	1
9	5	5	22	5	7
10	3	3			
11	2	4			
Total	71	86			
Average	3.55	4.3			

Table 4.3: Duration of scaling, fixing and cropping (in minutes)

4.3.4. Exporting and importing

Exporting the model from Autodesk memento to FBX format and importing the FBX file into the unity is time-consuming. The time required for this process was recorded using a stopwatch. Seconds were rounded up to a minute. Furthermore, section 12 and section 19 are not included in this table due to the incompleteness. Following is the table 4.4 showing exporting and importing process duration:

Section	Exporting	Importing	Section	Exporting	Importing
1	5	15	13	4	14
2	6	15	14	4	12
3	7	16	15	4	11
4	7	17	16	11	20
5	13	23	17	7	16
6	3	10	18	3	8
7	3	10	20	3	8
8	2	12	21	1	5
9	6	15	22	9	20
10	3	10			
11	4	11			
Total	105	268			
Average	5.25	13.4			

Table 4.4: Duration of exporting and importing process (in minutes)

4.3.5. Stitching

Stitching was the last step through the creation of building's 3D model. After importing all of the models into the application, they were dragged into the working space one by one and rotated and moved to be placed in the right location. The process was started from section 1 and was continued by the sequence of the section numbers. The duration of the process was recorded for each section separately and can be seen in the following table 4.5:

Section	Stitching	Section	Stitching
1	1	13	2
2	1	14	3
3	1	15	2
4	1	16	3
5	2	17	2
6	2	18	2
7	2	20	2
8	2	21	2
9	2	22	2
10	2		
11	3		
Total	39		
Average	1.95		

Table 4.5: Duration of stitching (in minutes)

4.3.6. Total for each section

The process encompasses multiple steps to achieve the final result. As described previously, duration of each step has been calculated separately. The objective is to achieve the total time of the process to create the 3D model of the whole first floor of the building. Here the total time of the process for each step is calculated and the total time of the process and the average time for each step is calculated as well (Table 4.6). Sections 12 and 19 were removed from the study due to failure.

Section	Total	Section	Total
1	806	13	481
2	975	14	705
3	745	15	655
4	866	16	793
5	677	17	857
6	661	18	670
7	596	20	446
8	857	21	489
9	866	22	1025
10	667		
11	632		
Total	14469		
Average	723.45		

Table 4.6: Total duration of the process per section (in minutes)

4.4. Tolerance

As described previously, Sections 12 and 19 were removed from the study due to failure in producing a complete 3D model. Furthermore, deficiencies in some sections prevented measuring some major elements such as heights and walls. Hence, elements were chosen that were measurable in the 3D models. Measurements were done from 18 section out of 20 completed sections. Following tables 4.7 – 4.24 show the result of the measurements and the calculated tolerances:

	1	1A	1B	1C	1D	1E	1F
Actual	3.08	4.69	2.64	0.88	1.16	3.02	4.36
3D Model	NA	4.68	2.63	0.89	1.14	3.02	4.39
Tolerance	NA	0.01	0.01	-0.01	0.02	0	-0.03

Table 4.7: Level of accuracy for section 1 according to figure 3.43 (in meters)

	2	2A	2B	2C	2D	2E	2F
Actual	5.26	1.62	1.01	3.13	6.15	3.38	0.39
3D Model	NA	1.61	1.02	3.13	6.15	3.36	0.38
Tolerance	NA	0.01	-0.01	0	0	0.02	0.01

Table 4.8: Level of accuracy for section 2 according to figure C.1 (in meters)

	3	3A	3B	3C	3D	3E	3F
Actual	3.13	2.95	1.475	1.47	3.38	4.32	0.39
3D Model	NA	2.94	1.47	1.46	3.39	4.32	0.38
Tolerance	NA	0.01	0.005	0.01	-0.01	0	0.01

Table 4.9: Level of accuracy for section 3 according to figure C.2 (in meters)

	4	4A	4B	4C	4D	4E	4F
Actual	3.03	1.3	1.58	1.6	1.33	0.18	3.38
3D Model	NA	1.28	1.58	1.59	1.32	0.17	3.39
Tolerance	NA	0.02	0	0.01	0.01	0.01	-0.01

Table 4.10: Level of accuracy for section 4 according to figure C.3 (in meters)

	5	5A	5B	5C	5D	5E	5F
Actual	10.64	0.91	0.44	7.52	3.31	4.64	1.01
3D Model	NA	0.9	0.44	7.54	3.29	4.64	1.02
Tolerance	NA	0.01	0	-0.02	0.02	0	-0.01

Table 4.11: Level of accuracy for section 5 according to figure 3.44 (in meters)

	6	6A	6B	6C	6D	6E	6F
Actual	9.04	8.08	1.61	0.9	0.76	6.71	1.9
3D Model	NA	8.12	1.62	0.92	0.77	6.72	1.92
Tolerance	NA	-0.04	-0.01	-0.02	-0.01	-0.01	-0.02

Table 4.12: Level of accuracy for section 6 according to figure C.4 (in meters)

	7	7A	7B	7C	7D	7E	7F
Actual	13.92	0.88	0.53	0.61	11.73	2.19	3.81
3D Model	NA	0.89	0.53	0.61	11.74	2.18	3.8
Tolerance	NA	-0.01	0	0	-0.01	0.01	0.01

Table 4.13: Level of accuracy for section 7 according to figure C.5 (in meters)

	8	8A	8B	8C	8D	8E	8F
Actual	1.6	1.7	1.01	2.18	2.65	1.52	1.93
3D Model	NA	1.7	1.01	2.17	2.64	1.51	1.92
Tolerance	NA	0	0	0.01	0.01	0.01	0.01

Table 4.14: Level of accuracy for section 8 according to figure C.6 (in meters)

	9	9A	9B	9C	9D	9E	9F
Actual	1.6	0.9	2.07	2.77	1.08	2.13	2.81
3D Model	NA	0.89	2.05	2.72	1.07	2.11	2.8
Tolerance	NA	0.01	0.02	0.05	0.01	0.02	0.01

Table 4.15: Level of accuracy for section 9 according to figure C.7 (in meters)

	10	10A	10B	10C	10D	10E	10F
Actual	6.92	0.9	2.06	1.1	0.53	2.89	10.78
3D Model	NA	0.91	2.06	1.09	0.54	2.9	10.78
Tolerance	NA	-0.01	0	0.01	-0.01	-0.01	0

Table 4.16: Level of accuracy for section 10 according to figure C.8 (in meters)

	11	11A	11B	11C	11D	11E	11F
Actual	5.75	0.9	2.07	1.1	2.92	4.43	10.65
3D Model	NA	0.91	2.02	1.08	2.88	4.42	10.63
Tolerance	NA	-0.01	0.05	0.02	0.04	0.01	0.02

Table 4.17: Level of accuracy for section 11 according to figure C.9 (in meters)

	13	13A	13B	13C	13D	13E	13F
Actual	4.14	0.91	0.97	0.62	2.84	2.43	2.13
3D Model	NA	0.91	0.97	0.63	2.83	2.43	2.11
Tolerance	NA	0	0	-0.01	0.01	0	0.02

Table 4.18: Level of accuracy for section 13 according to figure C.10 (in meters)

	15	15A	15B	15C	15D	15E	15F
Actual	6.84	0.9	1.63	0.99	8.67	3.33	0.75
3D Model	NA	0.92	1.65	0.98	8.66	3.39	0.76
Tolerance	NA	-0.02	-0.02	0.01	0.01	-0.06	-0.01

Table 4.19: Level of accuracy for section 15 according to figure C.11 (in meters)

	16	16A	16B	16C	16D	16E	16F
Actual	5.1	2.27	0.76	2.07	0.31	3.63	0.91
3D Model	NA	2.28	0.75	2.07	0.31	3.64	0.91
Tolerance	NA	-0.01	0.01	0	0	-0.01	0

Table 4.20: Level of accuracy for section 16 according to figure C.12 (in meters)

	17	17A	17B	17C	17D	17E	17F
Actual	3.27	1.15	4.32	1.8	1	2.64	0.88
3D Model	NA	1.17	4.33	1.8	1.02	2.66	0.88
Tolerance	NA	-0.02	-0.01	0	-0.02	-0.02	0

Table 4.21: Level of accuracy for section 17 according to figure C.13 (in meters)

	20	20A	20B	20C	20D	20E	20F
Actual	2.64	1.5	0.32	0.17	1.3	2.82	1.33
3D Model	NA	1.49	0.32	0.16	1.29	2.81	1.32
Tolerance	NA	0.01	0	0.01	0.01	0.01	0.01

Table 4.22: Level of accuracy for section 20 according to figure C.14 (in meters)

	21	21A	21B	21C	21D	21E	21F
Actual	2.97	1.2	0.3	0.16	1.85	2.43	1.34
3D Model	NA	1.2	0.28	0.16	1.86	2.42	1.33
Tolerance	NA	0	0.02	0	-0.01	0.01	0.01

Table 4.23: Level of accuracy for section 21 according to figure C.15 (in meters)

	22	22A	22B	22C	22D	22E	22F
Actual	3.2	1.6	0.29	0.16	4.68	4	2.12
3D Model	NA	1.6	0.3	0.16	4.68	4.01	2.12
Tolerance	NA	0	-0.01	0	0	-0.01	0

Table 4.24: Level of accuracy for section 22 according to figure C.16 (in meters)

CHAPTER V

DISCUSSION

5.1. Introduction

In this chapter, the results of the study are discussed. Based on the objectives of this research a 3D model was produced and the time of the process was recorded. Also, the tolerances of the produced models were calculated. In this section findings of the study is discussed in terms of practicality of producing 3D model, duration of the process and tolerances of 3D models and the existing building.

5.2. Photo shooting

The process of taking photos as described previously was a manual process in terms of placement of the camera, rotations and shooting the photos. During the process of taking photos, the photographer can face many challenges. These challenges, as well as limitations, is discussed in this chapter. Also, the results of this process are evaluated.

5.2.1. Challenges

Taking photos in a public operational building had many challenges. Although the process of taking photos was planned and camera placement was anticipated before starting the process, there were many limitations which made the process slightly different from the original plan. Followings are the challenges and the limitations:

1. Access: Although the building is a public educational building, access to some spaces were limited at certain times. Sections 7, 10, 11 and 15 are classrooms which usually are occupied by students. Also, some of these sections are locked after classes and should be unlocked by the responsible person. This problem is not limited only to the classrooms, but also spaces such as section 5 (BIM CAVE), sections 13 and 14 (faculty rooms), section 16 (IT helpdesk) and section 12 (survey lab) are locked or occupied most of the times. Considering this issue, the photographer had to coordinate a specific time with the responsible person to take photos of these spaces which could only be on business days. Furthermore, there are other spaces such as electrical and mechanical rooms on the first floor which only could be opened by certain staffs that are not available at normal hours. Those spaces were removed from the study.

To summarize, this study shows that one of the significance limitation of taking photos from operational buildings is the limited access to spaces which are occupied or locked due to various reasons. This can result in removing some sections or delaying the whole process.

2. People: Another challenge of taking photos in an operational building was people using the facility. The presence of people can affect the final result of the study by covering some surfaces. During the day, most of the public spaces were occupied and people were usually moving in those spaces which caused delays in taking photos process (Figure 5.1). In the entry gallery's sections including sections 1, 2, 3, 4, 19, 21 and 22 and also hallways and stairways including section 8, 9 and 20 presence of people caused delays in taking photos. In some sections, the tripod could close the walkways which was unfavorable.

Due to these issues, the public sections were photographed after the class hours and in some cases in the midnight hours. Furthermore, spaces such as sections 17 and 18 which are the restrooms could only be photographed after midnight when the building was empty to prevent uncomfoting the people using those facilities.

To conclude, operational buildings are defined by people using the facilities. This can cause many delays and problems for capturing the 3D data of the building.

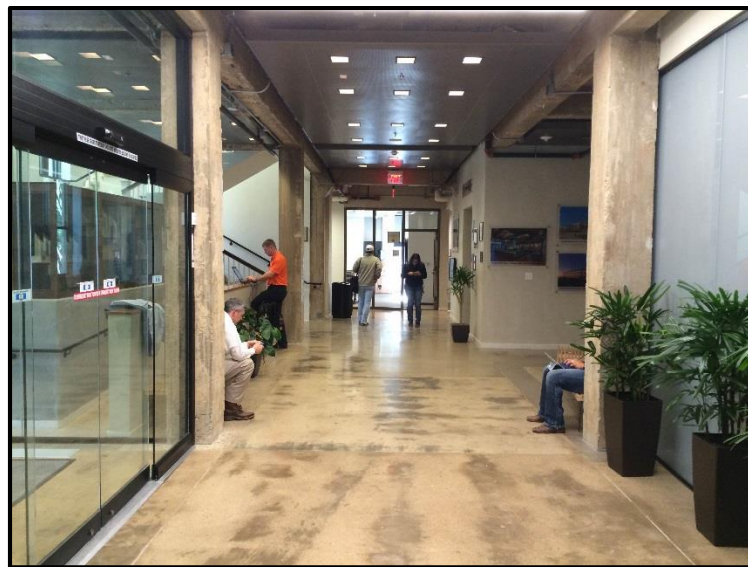


Figure 5.1: People presence in the Francis Hall building

3. Equipment: Taking photos of the existing facility required a digital camera and a tripod to set the height and position of the camera. Digital equipment such as cameras have a limitation which is the battery life. The camera needs to be recharged from time to time. In this study in some cases, the camera was going out of the battery in the middle of the process which had to be removed from the tripod to be recharged. In these cases, the tripod

was preserved in the same location and rotation to continue the process. This issue could cause delays in the process and considering the limited time for taking photos in many spaces this problem was a challenge for the photographer. Therefore, the camera had to be recharged before each section to assure the continuous process. Moreover, the battery life is not the only limitation of cameras. Digital cameras use SD memory cards which have a limited space for photos. In the case of this study, a 32 GB memory card was used which was enough for the number of photos in this study. But for bigger projects this limitation should be considered. Although the space was enough for the number of photos in this study, precaution should be taken due to the vulnerability of digital memory cards in losing information. After taking photos from each section, photos were copied on a hard disk to make a backup from the photographs.

To summarize, limitation of digital equipment should be considered and planned before starting the process to assure the efficiency of the whole process of taking photos both in quality and time.

4. Manual process: As described before, the process of taking photos was planned based on parameters to achieve the best result possible and cover all of the surfaces of spaces. However, the whole process of taking photos is a manual process that is done by a human which can cause many errors during the process. Tripod is a lightweight equipment which can easily be dispositioned. In some cases, the camera location was changed which led the process to be repeated at that location to assure the photos were taken from a fixed position of the camera. Moreover, as described before the camera had to be located in 12 different positions and 20 different rotations were planned in each

location for taking the photos. In some cases, one or multiple rotations were missed or repeated unnecessarily. These problems usually were found after finishing the process and counting the photos by the photographer. In this cases, the photographer had to redo a location with all 20 rotations to assure the fixed location of the camera for those rotations.

To conclude, a manual process done by a human can lead to errors which can affect the final result of the study and add to the duration of the process.

5. Furniture and space conditions: The photos were taken in different spaces with different sets of furniture. The presence of these furniture sets not only covered the surfaces behind and under them but also caused some limitation for camera positioning. A tripod occupies wider area than a camera to be fixed. In many cases placing the tripod was impossible in designated locations. In sections 12, 13 and 14 the planned positioning of the camera was changed due to the furniture sets such as tables and shelves in the rooms (Figure 5.2). This resulted in decreasing the number of camera location in these rooms. Moreover, the shape and size of the spaces caused some limitation in locating the camera in desired locations. In section 18 considering the size of the room, the tripod locations would be overlapped which led to decreasing the number of locations in this section. In sections 20 and 21, the stairs leading to the higher were not favorable locations for camera placement due to covering higher level surfaces. In these two sections, the unfavorable locations had been removed from the process. Furthermore, the furniture and other described conditions can make difficulties for the photographer to stand behind the camera and view the camera's screen before taking the picture. This issue made the photographer

place the camera slightly far from the walls and other furniture to be able to view the screen and set the rotations (Figure 5.3).

To summarize, furniture and the conditions of the space can cause many difficulties and also can cover surfaces and prevent the photographer to set the desired location to shoot photos.

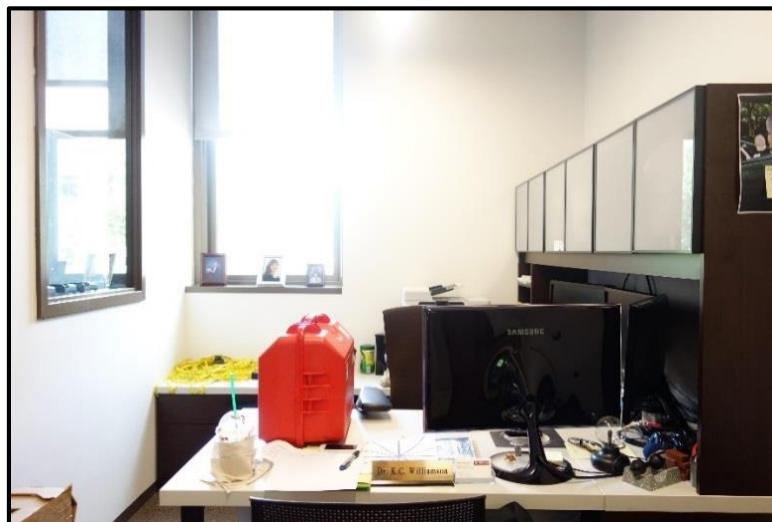


Figure 5.2: Shelves and tables hindered the photographer to place the camera

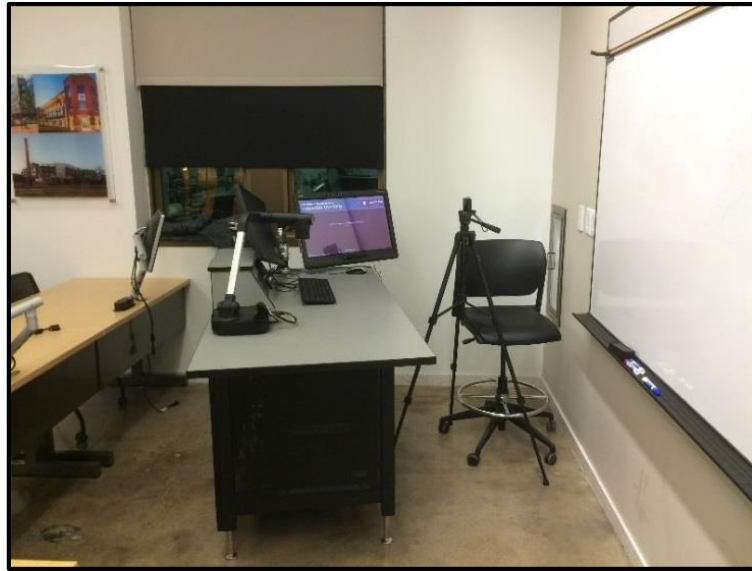


Figure 5.3: Camera placement in a corner in section 6 in presence of furniture

5.2.2. Results

As shown in table 3.1 the total number of photos taken from the Francis Hall building's first floor was 4940 taken from 22 different sections of the building. Depending on the camera, the quality of photos can be different as well as the size of them. In this section, various factors of final results is evaluated:

1. Size: For this study, a normal digital camera was used which led to the total size of 24.3 GB of data. This means each photo has the average size of 5 MB. This amount of data takes the time to be transferred to hard disks as well as online. Since the image processing step was done using cloud servers, the size of the photos which is directly related to the quality can impact the total time of uploading and image processing. The objective of this study was limited to practicality and the duration of the process, and not considering the impact of the image qualities of the final result and the duration. In future

studies, different factors can be tested to evaluate their impacts on the duration and final 3D model.

2. Image quality: A quick overview of images shows a decent quality that is expected from a normal digital camera. A closer look at photos shows some issues such as blurriness that cannot be recognized from the camera's small screen. The camera could be shaken slightly while the photo had been taken. However, these issues were not considerable to result in retaking the photos and were just only limited to a few number of photos.

3. Undesired images: The rotation of camera in some location especially in more confined spaces caused photos which are only covering walls or objects which don't provide a proper perspective of the space to be used in 3D modeling process (Figure 5.4). These photos are usually seen as unstitched photos at the end of the image processing. This issue decreases the number of useful photos in each section and can be prevented by moving the further from the perimeter surfaces and corners which result in less coverage of the whole space.

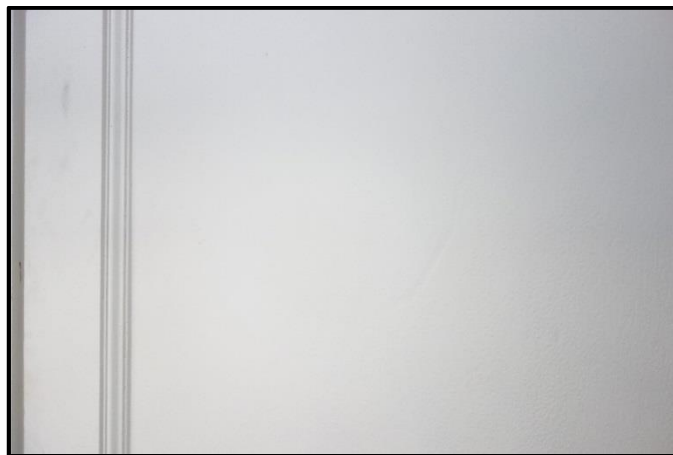


Figure 5.4: Undesired photos with no perspective of the space, from section 21

5.3. 3D models

Images were processed using a commercial application (Autodesk Recap). The final result of the process were 3D meshes from 22 sections of the building. These sections were fixed and cropped to be stitched and create the whole building's floor. In this section, the challenges during creating the 3D model is explained as well as deficiencies in 3D meshes. Finally, the final result of the study is evaluated.

5.3.1. Challenges

The process of creating the final 3D model of the first floor included 3 steps using 3 different commercial applications, each step had its own limitation and challenges which are described in the following:

1. Unstitched images: At the end of the image processing, some photos were not stitched and processed due to various issues that made it impossible for the application to match them with other photos. Unstitched photos were mainly the undesired images that did not provide any perspective of the space.

2. Computer limitation: the meshes created from photos were more than 100 MB which required a decent computer system to be opened by various applications. Opening the models slowed down the computer and made the process difficult for the operator to modify the 3D meshes. In the stage of stitching, as more sections were imported to the application the system got slower and the process of navigating in the model got tougher. This problem increased the duration of manual modification such as cropping the meshes

or stitching them to create the final model. Also, the size of the meshes had a significance impact on exporting and importing duration of the models.

To conclude, the limited processing power of the computer affects the efficiency of the process and easiness of navigating into the model.

3. Manual processes: The process of modifying and stitching the models was mainly done manually. The manual process which is done by a human can cause many errors in the final results. In the stage of cropping the sections, the boundary of sections was assumed by the operator based on the plans of the building. The operator left a margin for each section as an overlapping element to make the stitching process easier. The process had to be tested by the operator to find the perfect approach. This manual process of cropping could cause errors such as removing parts of the model which were necessary. Furthermore, these errors could happen in the scaling process where a dimension of the real environment was chosen to be applied to the same element in the 3D model. The selection of the dimension of this element was necessary since errors could lead to slightly larger or smaller models. Moreover, the main step of this study was done manually. Stitching the sections was done based on the similar elements between them and by fixing them with eyes which could cause many inaccuracies in the final model of the project. Errors such as repetitive surfaces could happen in the model which was the result of manual cropping. Also, the manual process of stitching models was time-consuming due to moving the sections, rotating them and checking the surfaces of two stitched models.

5.3.2. Deficiencies

The result of the processing shows that sections are different in the final quality. Holes can be noticed on the surfaces such as walls and ceilings. Some surfaces were distorted and their textures were changed. Some were not captured completely and in most of the cases furniture were distorted or not captured at all. In this section, the major issues of the 3D meshes are discussed.

1. Holes: 3D model that was created using Autodesk Recap included deficiencies such as holes on the surfaces. Evaluating different sections shows that these kinds of deficiencies could be caused by certain reasons.

Reviewing the 3D models shows that the sections with the white and bright surfaces have holes on them. Sections 7 is one of the examples of this problem in the 3D model (Figure 5.5).



Figure 5.5: Holes appear on bright texture-less walls in section 7

Also, holes appeared on the glass surfaces. Glass material has reflection and transparency which can be the cause of this problem. This problem can be seen majorly on interior glass surfaces. This problem majorly occurred on glass surfaces in the entry gallery (Figure 5.6).



Figure 5.6: Holes appear on reflective glass surfaces in section 1

Furthermore, holes can be seen on ceiling surfaces. Results show that not only white and bright ceilings appeared to have holes on them but also dark and textured ones have this problem. Ceilings in the classrooms are white and texture-less which can be the cause of this problem. Also, Sections such as the BIM CAVE which is exposed and includes mechanical and piping facilities has the same problem which occurred in darker and spots with a low visibility (Figure 5.7).



Figure 5.7: Holes appear on dark spots on ceiling in section 5

This problem occurred in the textured ceiling such as the ones in the entry gallery which are dark colored and the ones in the hallway which are in a bright colored. This problem could be caused by the repetitive pattern on the ceiling (Figure 5.8).



Figure 5.8: Holes appear on repetitive texture pattern ceilings on entry gallery

2. Incomplete surfaces: Deficiencies are not just limited to the holes. In some sections some surfaces were incomplete and no 3D model was created for them. This issue can be found in smaller sections such as sections 13, 14 and 16 (Figure 5.9). Fixing these sections required more time to create and define a boundary for these incomplete parts so they could be fixed by the issue detection feature.



Figure 5.9: Incomplete surfaces in section 14

This can be caused by less coverage of camera in this room. Fewer photos could be used to create the surfaces which could cause in the incomplete production of this surface. Furthermore, incomplete surfaces can be seen in sections with furniture sets. These sections including sections, 6, 7, 10, 11 and 15 did not have a complete ground surface (Figure 5.10). This problem created a challenge to anticipate the space's ground level for placement of the section in the final model. These models were not eligible for measuring the heights to be compared with the real environment. Since no part of the

ground surface was existed, these sections could not be fixed using the issue detection feature of the Memento application.



Figure 5.10: Ground section is incomplete due to furniture presence in section 6

3. Furniture: Various furniture sets can be found in the sections. As described previously, rooms with more furniture had more deficiencies. Section 7, the auditorium has a repetitive set of seats with the same size and the same color. The result of this section had no ground floor and no seats as well. Traces of the seats' textures can be seen on other surfaces. This issue shows that the image processing application was not able to recognize them as a 3D object, and instead, it recognized them as pictures and textures on the walls (Figure 5.11).



Figure 5.11: Furniture traces on other surfaces in section 7

In sections with fewer furniture sets and the ones that furniture does not cover the majority of the surfaces, the result was different. The application was able to produce the object but it was incomplete and deformed. The chair and the table in the middle of section 5, BIM CAVE can be a good example. The two objects were created but some parts of them were missing. Also same as section 7, some traces of the objects can be seen on other surfaces (Figure 5.12).

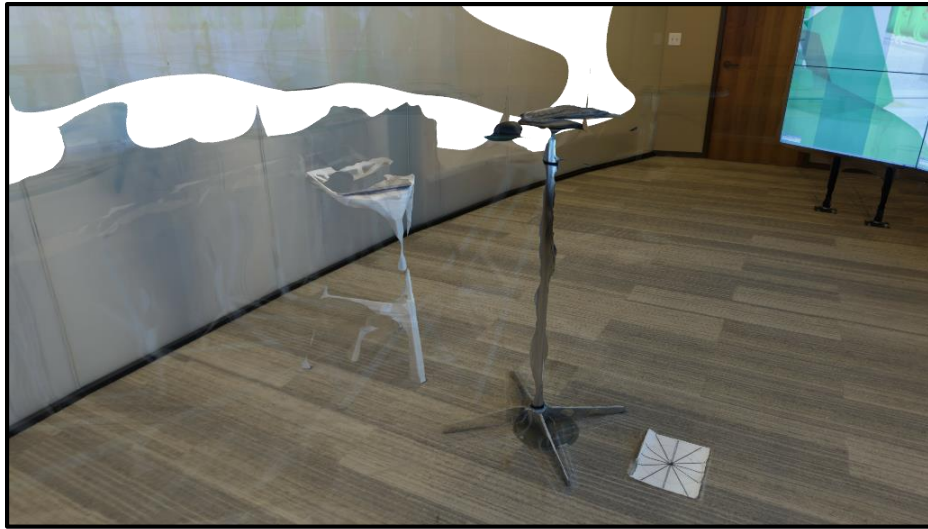


Figure 5.12: Creation of objects in the middle in section 5

As described previously, furniture sets that cover the surfaces can have a negative impact on the model quality. In some cases, they created false 3D meshes instead of the surface behind them. Furniture set at one end of section 2 in the entry gallery is a good example (Figure 5.13). The photos were taken from one side of the objects and the image processing application connected the top of the object to the wall behind.



Figure 5.13: Deformation of meshes in section 2 due to presence of furniture

4. Incomplete Sections: 22 sections based on the ability to access them in the building were planned for this study. After processing the images two sections were incomplete and the researcher decided to remove these sections from the study. Section 12 included a few meshes of cabinets in the room which were not indicating the boundary of the room. This could happen due to the limited spaces between cabinets which made the camera positioning too close to the objects. Also the same shape and material of the cabinets could cause the problems in photo matching process (Figure 5.14).

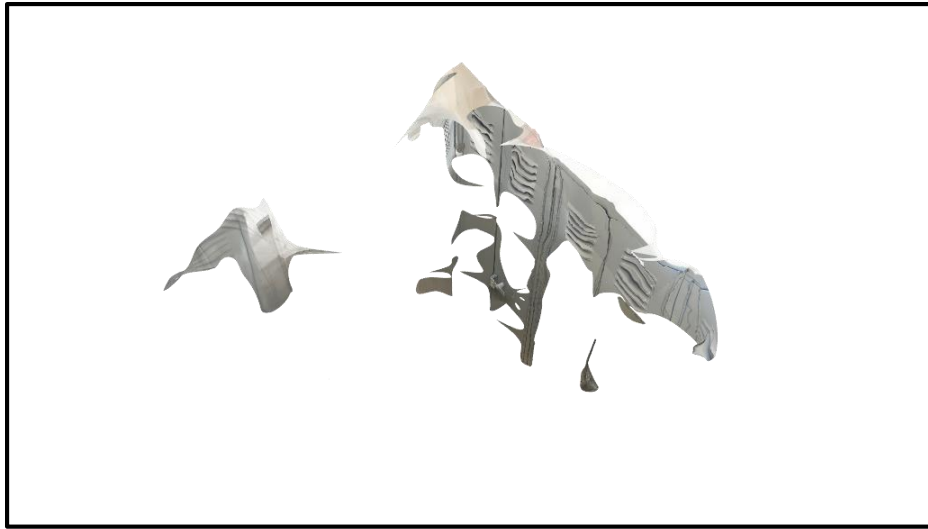


Figure 5.14: Section 12 was incomplete due to confined spaces and cabinets

Furthermore, Section 19 was designated for the accessible ramp of the building. Because of the sloped ground surface of the ramp, the camera height was different in most of the locations. Also the middle section of the ramp which had wooden shelves on top made locating the center of the section difficult for the photographer. Also, the tight space of the ramp made the camera too close to the walls of the section. The result of the section was incomplete but still some boundaries could be defined. But the result of section 22, the entrance gallery showed a better quality with more details of the ramp section in the background. The researcher decided to remove section 19 from the study and replace it with the background of section 22 from the entrance accessible ramp. In the following the difference of the sections from the same point of view can be seen (Figures 5.15 and 5.16).



Figure 5.15: Section 19 was removed from the study

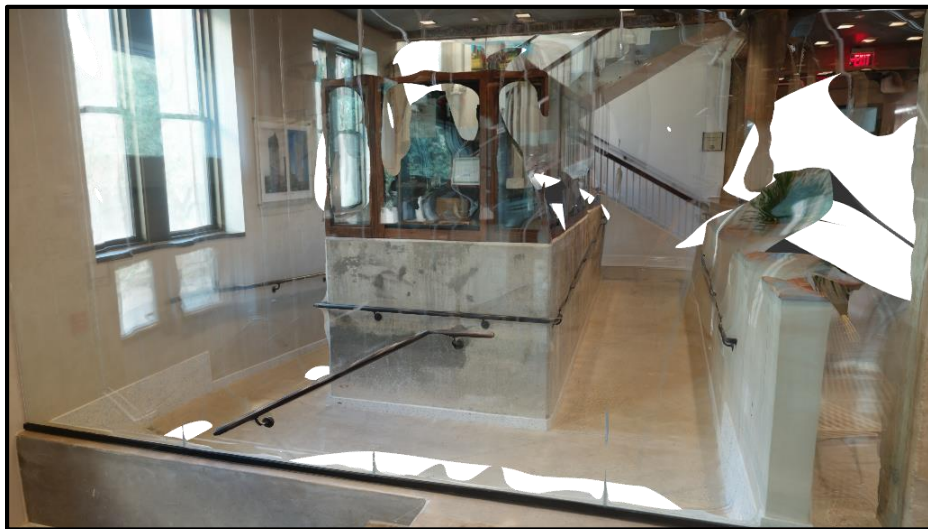


Figure 5.16: Section 22's background was replaced section 19

5.3.3. Stitching

The final step of the study to evaluate the practicality of creating a 3D model of an operational building's first floor from photos was stitching the sections. This step was done manually using Unity 3D application. Stitching process was challenging and needed precision to create a decent model of the first floor. The steps of creating this model were designed in a way that the final step would be only stitching sections like pieces of a puzzle to create the first floor of the building.

However, as it can be seen in the figure 3.39, sections were not aligned at the same rotation after importing into Unity application. This problem delayed the process of stitching. Furthermore, this problem can cause some errors since the operator had to rotate sections such as 7, 8, 9, 17 and 18 manually.

Furthermore, as discussed previously, two sections were removed from the study. However, drawing a boundary around the stitched model shows other gaps in the model as well (Figure 5.17).

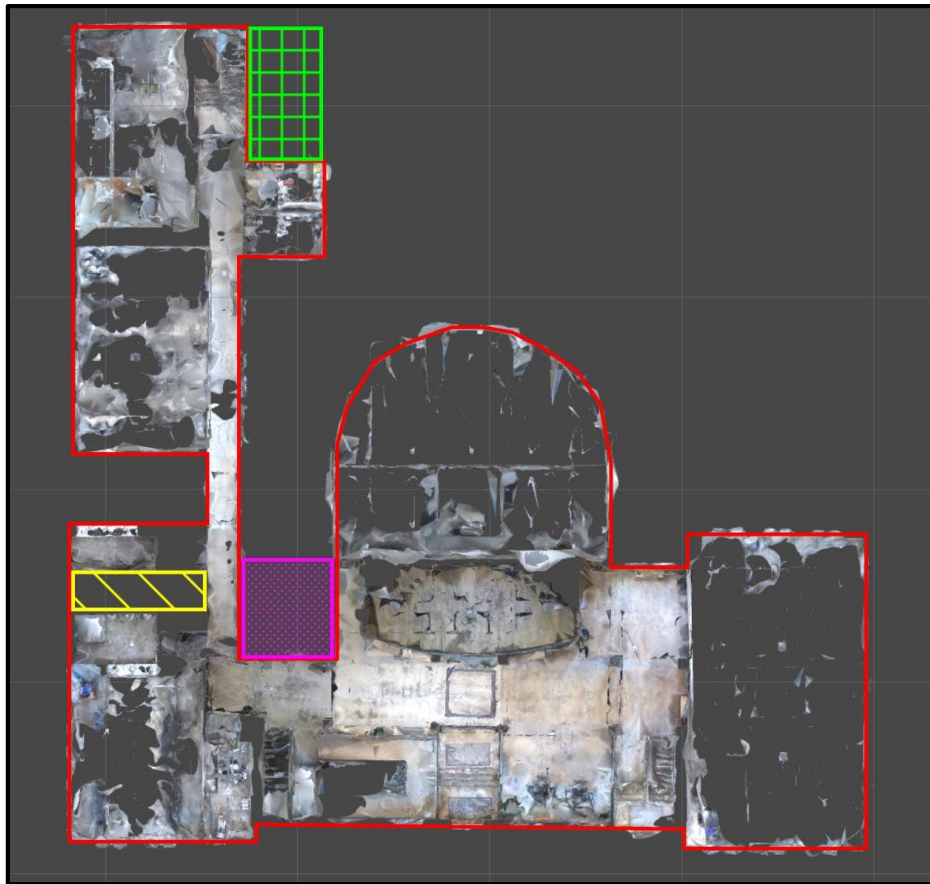


Figure 5.17: Building's boundary is demonstrated from stitched sections

In the top figure, the green square pattern shows the section 12 which was removed from the study due to incomplete 3D model. The yellow cross pattern shows the space between restrooms including the toilets and the custodial room which the photographer could not access them. The pink dotted pattern shows the electrical room and the elevator which were out of access to take photos as well.

The goal of this study was to create a 3D model of the first floor of the Francis Hall Building. The boundaries of this model should match the boundaries of the real building which can be found on the shop drawings that were used to renovate the building. Following is the overlay of the model's boundary in red on the shop drawings of the building (Figure 5.18).

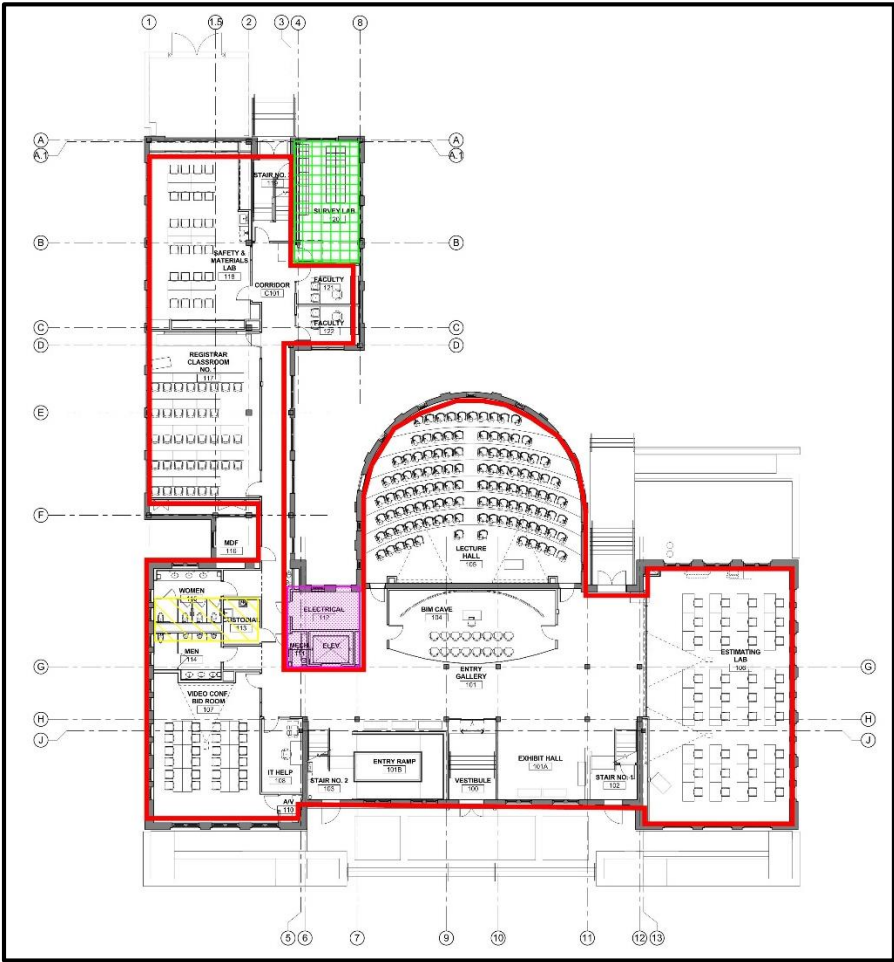


Figure 5.18: boundary of the stitched model overlaid on the shop drawing (B. R. W. Architects 2013)

This drawing shows that the created model perfectly fits on the east side of the building while it is slightly different on the west side of the drawing. However, it should be considered that the model was created from interior spaces and cannot provide an accurate boundary of the building's exterior due to the existence of closets in sections 10 and 11 and also the thickness of the walls. Furthermore, BIM of the building is overlaid on the photogrammetry model to indicate the differences in the application interface (Figure 5.19).



Figure 5.19: BIM model overlaid on the stitched model

5.4. Time

As indicated in the previous chapter, time of the process was recorded throughout all steps of the study. Based on table 4.6, the whole process took 14469 minutes for this building to be completed. This number can be compared to the duration of other approaches in future studies.

A closer look at the recorded data shows that major time of the process was related to the image processing step which was done by a cloud server. The following table 5.1 shows the time categorized by steps of the study.

Step	Duration	Percentage
Taking photos	959	6.63%
Image processing	12941	89.44%
Scaling and Cropping	71	0.49%
Fixing	86	0.59%
Exporting	105	0.73%
Importing	268	1.85%
Stitching	39	0.27%
Total	14469	

Table 5.1: Total duration of each step of the process (in minutes)

As can be seen in this table, the majority of time was spent on processing the images. Also, the percentage of each step can be seen in the table.

The image processing step was 89 percent of the whole process which means decreasing the duration in this process can significantly reduce the total duration of creating the 3D model. However, in this study, sections were uploaded and processed one by one. Uploading the sections after finishing the photography section can significantly

reduce the total duration of the process. By overlapping the steps a huge amount of time can be saved in the process.

The durations can be divided into passive and active durations. While in the active, the operator is directly involved with the process but in the passive the computer is handling the process. Image processing, fixing, importing and exporting can fall into passive duration while taking photos, scaling, cropping and stitching fall into active durations. The following show the proportions of each (Figure 5.20).

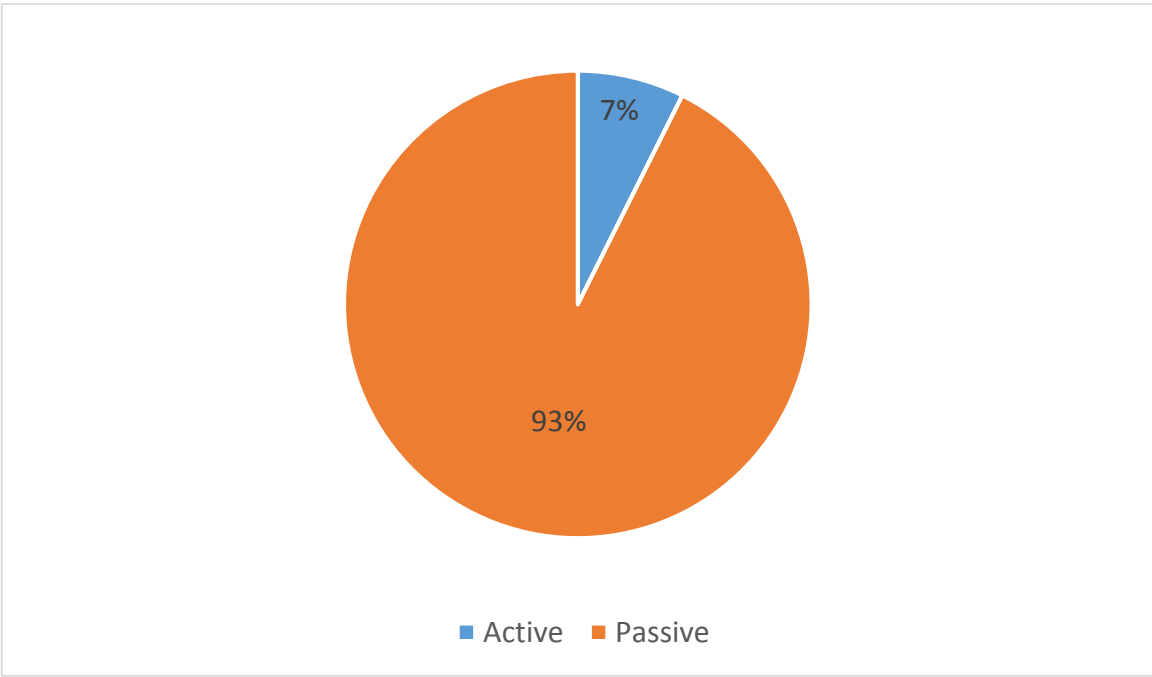


Figure 5.20: Active duration versus passive duration

This graph shows that 93 percent of the process was handled by the computer and was not related to the productivity of the operator. In the next sections, the passive and active process is discussed in more details.

5.4.1. Active duration

The active processes were the ones done by the operator and included taking photos, scaling, and cropping and stitching the 3D sections. As described before the active duration was only 7 percent of the total time of the process in this study. Improving the productivity might decrease the total time of the process but will not have a significant effect on the final duration of the project.

Furthermore, the duration of the active process can be decreased while the operator gains more experience in the process. Table 4.1 which shows the duration of taking photos indicates that the operator spent less time for sections in the later stages of the process than the ones in the earlier stages.

Moreover, errors are the factors that usually lead to redoing a process and adding to the active duration. By gaining more experience the operator can eliminate the errors and reduce the active duration.

5.4.2. Passive duration

Unlike the active processes, the passive ones were handled by the computers. Passive processes included image processing, fixing, exporting and importing. In this study, 93 percent of the time spent on the project was the passive duration and the operation did not have any direct influence on the duration.

As discussed previously, most of the duration were related to the image processing which was done by Autodesk online servers. One of the advantages of using cloud processing in this study was the ability to upload and process several sections at the same time.

Although the cloud processing cannot be improved by the operator, using more powerful computers can decrease the passive processes on the user's computer, such as fixing, exporting and importing which were proportionally more than the active time in total.

Furthermore, applications that have the ability to fix and stitch various section in the same interface can eliminate the time that is needed to export and import the model. Transferring models into different formats is not only time consuming but also can impact the quality of the model.

5.5. Accuracy

Another goal of this study was to evaluate the accuracy of the sections created by images in comparison to the original building. As described previously, elements were selected in each section and measured both in the real environment and the 3D model. The results were provided in tables in the previous chapter. Due to limited access two sections, section 18 (ladies restroom) and section 14 (faculty room) were removed from this part. In this section, the tolerances of 108 measured elements are provided and the average of the tolerances is calculated (Table 5.2).

No.	Tolerance	No.	Tolerance	No.	Tolerance	No.	Tolerance	No.	Tolerance	No.	Tolerance
1A	0.01	1B	0.01	1C	0.01	1D	0.02	1E	0	1F	0.03
2A	0.01	2B	0.01	2C	0	2D	0	2E	0.02	2F	0.01
3A	0.01	3B	0.005	3C	0.01	3D	0.01	3E	0	3F	0.01
4A	0.02	4B	0	4C	0.01	4D	0.01	4E	0.01	4F	0.01
5A	0.01	5B	0	5C	0.02	5D	0.02	5E	0	5F	0.01
6A	0.04	6B	0.01	6C	0.02	6D	0.01	6E	0.01	6F	0.02
7A	0.01	7B	0	7C	0	7D	0.01	7E	0.01	7F	0.01
8A	0	8B	0	8C	0.01	8D	0.01	8E	0.01	8F	0.01
9A	0.01	9B	0.02	9C	0.05	9D	0.01	9E	0.02	9F	0.01
10A	0.01	10B	0	10C	0.01	10D	0.01	10E	0.01	10F	0
11A	0.01	11B	0.05	11C	0.02	11D	0.04	11E	0.01	11F	0.02
13A	0	13B	0	13C	0.01	13D	0.01	13E	0	13F	0.02
15A	0.02	15B	0.02	15C	0.01	15D	0.01	15E	0.06	15F	0.01
16A	0.01	16B	0.01	16C	0	16D	0	16E	0.01	16F	0
17A	0.02	17B	0.01	17C	0	17D	0.02	17E	0.02	17F	0
20A	0.01	20B	0	20C	0.01	20D	0.01	20E	0.01	20F	0.01
21A	0	21B	0.02	21C	0	21D	0.01	21E	0.01	21F	0.01
22A	0	22B	0.01	22C	0	22D	0	22E	0.01	22F	0
Average	0.010972										

Table 5.2: Level of tolerances for each dimension (in meters)

The result shows that the average tolerance of the measurements is 1 centimeters. These tolerances can be caused by the error of manual measurement using the laser measurement tool and also the manual process of scaling and measuring the elements in 3D models. However, having a quick overview of results shows that the models with the more deficiencies such as section 11 have more tolerances. Following is a chart showing the distribution of tolerances based on the sequence in the previous table 5.2 (Figure 5.21).

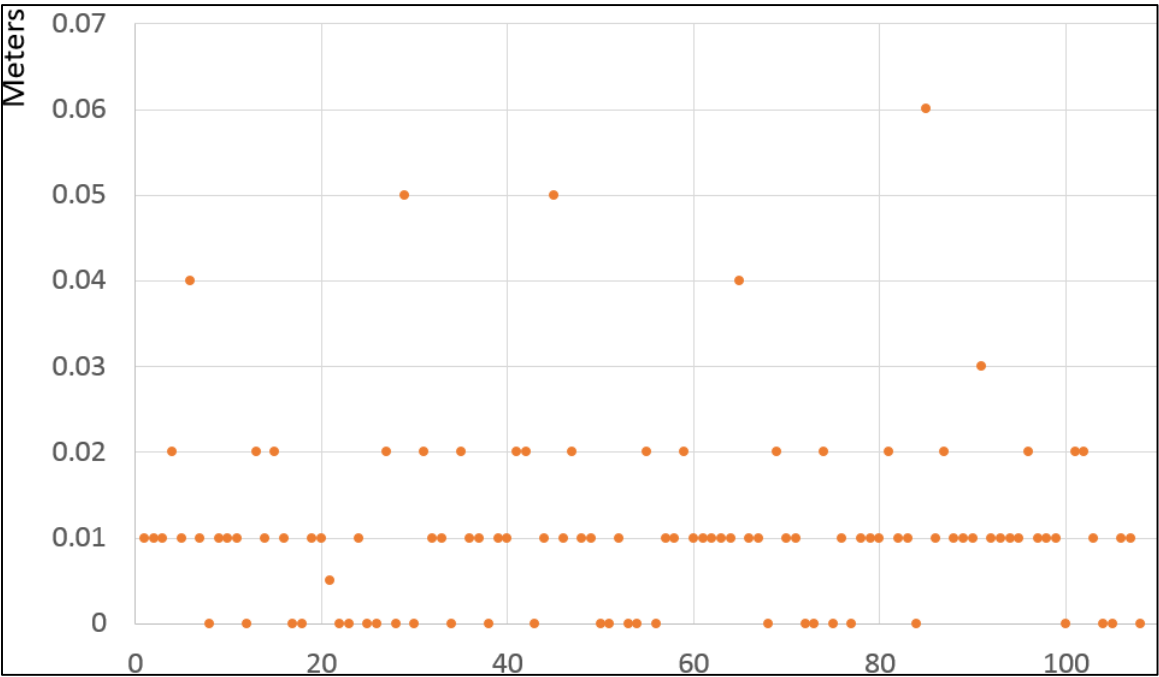


Figure 5.21: Tolerances distribution

Also considering length of the dimensions in calculating tolerances shows the average tolerance for all 108 dimensions is 0.83 percent. Table 5.3 shows the percentage of tolerances for each dimension:

No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage	No.	Percentage
1A	0.21%	1B	0.38%	1C	1.14%	1D	1.72%	1E	0.00%	1F	0.69%
2A	0.62%	2B	0.99%	2C	0.00%	2D	0.00%	2E	0.59%	2F	2.56%
3A	0.34%	3B	0.34%	3C	0.68%	3D	0.30%	3E	0.00%	3F	2.56%
4A	1.54%	4B	0.00%	4C	0.63%	4D	0.75%	4E	5.56%	4F	0.30%
5A	1.10%	5B	0.00%	5C	0.27%	5D	0.60%	5E	0.00%	5F	0.99%
6A	0.50%	6B	0.62%	6C	2.22%	6D	1.32%	6E	0.15%	6F	1.05%
7A	1.14%	7B	0.00%	7C	0.00%	7D	0.09%	7E	0.46%	7F	0.26%
8A	0.00%	8B	0.00%	8C	0.46%	8D	0.38%	8E	0.66%	8F	0.52%
9A	1.11%	9B	0.97%	9C	1.81%	9D	0.93%	9E	0.94%	9F	0.36%
10A	1.11%	10B	0.00%	10C	0.91%	10D	1.89%	10E	0.35%	10F	0.00%
11A	1.11%	11B	2.42%	11C	1.82%	11D	1.37%	11E	0.23%	11F	0.19%
13A	0.00%	13B	0.00%	13C	1.61%	13D	0.35%	13E	0.00%	13F	0.94%
15A	2.22%	15B	1.23%	15C	1.01%	15D	0.12%	15E	1.80%	15F	1.33%
16A	0.44%	16B	1.32%	16C	0.00%	16D	0.00%	16E	0.28%	16F	0.00%
17A	1.74%	17B	0.23%	17C	0.00%	17D	2.00%	17E	0.76%	17F	0.00%
20A	0.67%	20B	0.00%	20C	5.88%	20D	0.77%	20E	0.35%	20F	0.75%
21A	0.00%	21B	6.67%	21C	0.00%	21D	0.54%	21E	0.41%	21F	0.75%
22A	0.00%	22B	3.45%	22C	0.00%	22D	0.00%	22E	0.25%	22F	0.00%
Average	0.83%										

Table 5.3: Percentage of tolerances for each dimension (in meters)

CHAPTER VI

CONCLUSION

6.1. Conclusion

As-built documents are essential for building operation and maintenance. They can help the owners and facilities managers to make informed decisions for their daily tasks. Building Information Modeling (BIM), which is a new trend in the construction industry, may provide a better view of the building to the end users as essential information is integrated with the 3D model. However, the previous studies show that as-built documents are not as current as they should be and the Building Information Models used in the stage of construction are not useful for facility managers. In order to provide an up-to-the-date as-built model, facility managers may need to capture 3D data from the existing building.

By emergence of the technology, many tools have been introduced to capture 3D data. Laser scanning is one of the most popular tools that has been used decades to capture the topography and provides geological maps. Recently it has been used for heritage building's documentation and many have used it to capture operational buildings as well. Although laser scanners are accurate and convenient tools to capture the 3D data, they have been considered expensive, bulky and not efficient on specific surfaces.

Photogrammetry is a tool which works by converting multiple 2D pictures into 3D objects. Development of computers and new algorithms such as structure from motion have made photogrammetry a reliable tool in heritage conservation field as well as agriculture industry. Many studies have compared photogrammetry and laser scanning

technologies which show each have their own advantages and disadvantages. Photogrammetry is considered as an affordable tool that can produce sufficient results as well. Studies have been done testing photogrammetry for operational buildings but none of them have considered capturing the whole interior spaces of buildings interior using existing tools. This study evaluated the practicality of using photogrammetry as a tool to capture the 3D data of an operational building's interior spaces. Furthermore, time was measured as an important factor to show the efficiency of the approach. Moreover, the accuracy of the 3D models was assessed to show the effectiveness of the final model.

The Francis Hall building at Texas A&M University campus was chosen as the case of the study. The building was divided into 22 sections. The photos were taken by placing the camera in the perimeter of each section looking toward the center of the space. 12 locations were specified for each section and 20 horizontal and vertical rotations were used to cover all surfaces in each location. The photos were uploaded on the Autodesk Recap site, which is a web-based image processing commercial application to produce 3D mesh models. Moreover, completed 3D mesh models were cropped, scaled and fixed using Autodesk Memento. Fixed models were imported into Unity 3D to be stitched and to create the 3D model of interior spaces of the Francis Hall building. Also, to verify the accuracy of this model, dimensions were collected from 6 different locations in the building. Each dimension was compared to the same element of the 3D model to evaluate the tolerance of the approach. The duration of each step of the process was recorded using a stopwatch.

The result of the test shows that despite many challenges in the process of creating the 3D model, it is possible to create the 3D model of the entire building interior using photogrammetry technology. However, the results show that the mesh model have many deficiencies. Some of them can be fixed in the process of creating the 3D model. This approach includes the manual processes which produce more errors and increase the duration of the process. The average duration of taking photos was 47.95 minutes for each section, and it took 647.05 minutes to process images to create its 3D model. In total, it took 14,469 minutes to create a 3D model of the entire first floor of the Francis Hall. Also, the results show most of the duration of the process was spent on image processing which can be reduced by improving computer systems. Moreover, the results show that the tolerance of the 3D models was 1 cm in average. Considering the length of the dimensions, this tolerance was 0.83 percent on average for all 108 measurements.

In conclusion, this study proves that it is possible to create a 3D model of the building interior using photogrammetry technology. It took 12 hours in average to produce the 3D model of a section in the building. As expected, the accuracy level of photogrammetry technology is lower than that of laser scanner technology, but the 3D model created from this study demonstrates only 0.83 percent of deficiency in average.

6.2. Limitations

1. This study was limited to one public educational building. Results of the study and existing challenges might be different in other buildings.
2. Specific equipment and applications were used in this study. Other equipment and applications can have different challenges.

6.3. Future research

Photogrammetry can be used as an affordable alternative to capture 3D data of buildings' interior spaces, however, there are issues that solving them can improve the quality of the final model and also decrease the total time for the process of creating the 3D model.

Studies can be done to evaluate the existing problems that have been found in this study such as the impact of furniture and texture-less surfaces to improve the quality of the model. Also, studies can be conducted to develop approaches to stitch 3D meshes automatically by computers.

Moreover, algorithms can be developed to detect building elements from 3D meshes and recreate information models automatically based on captured 3D data. Also by improving the accuracy, accurate as-built BIM can be created which can be updated by repeating the process by facility managers and building owners. Hence, the building information models can be current and updated easily in post construction stage of the building's lifecycle.

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APPENDIX A



Figure A.1: Section 3 camera placement diagram (B. R. W. Architects 2013)

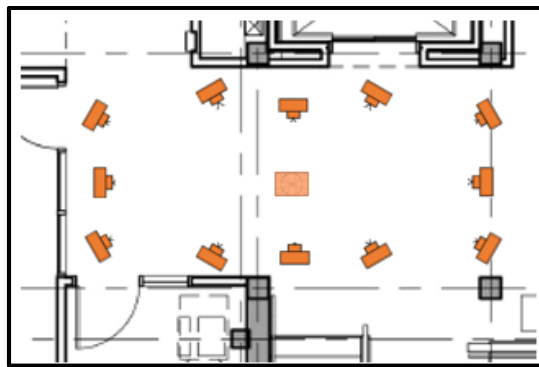


Figure A.2: Section 4 camera placement diagram (B. R. W. Architects 2013)

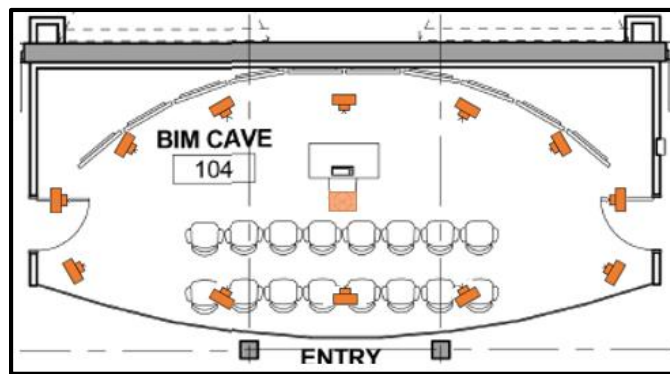


Figure A.3: Section 5 camera placement diagram (B. R. W. Architects 2013)

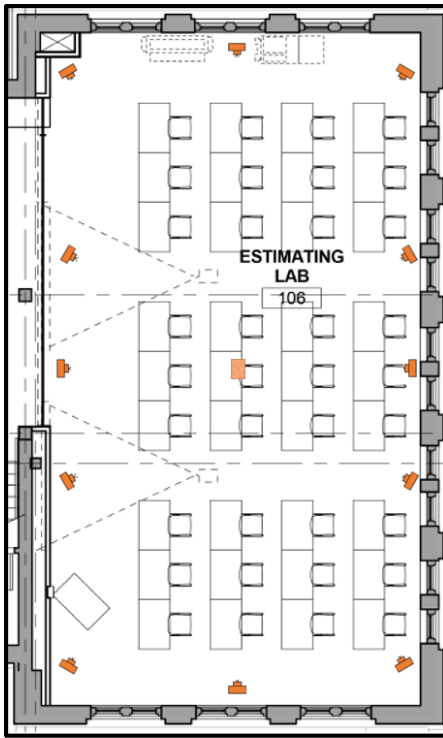


Figure A.4: Section 6 camera placement diagram (B. R. W. Architects 2013)

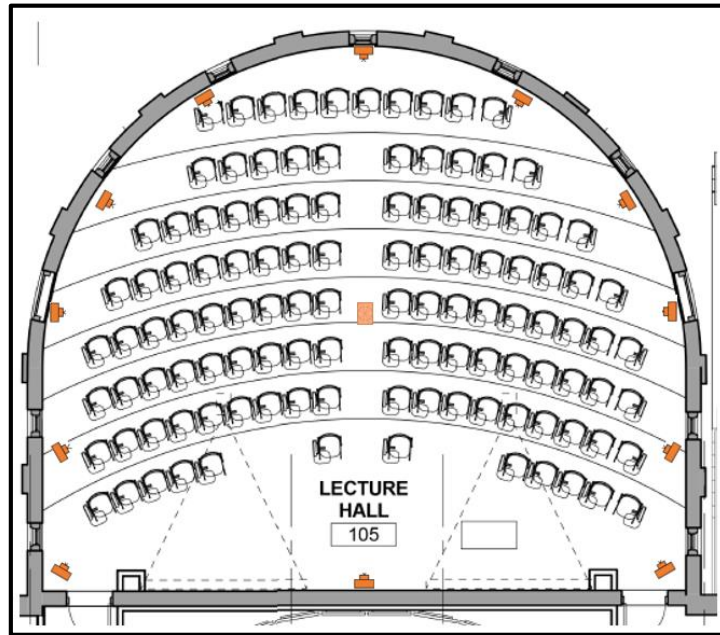


Figure A.5: Section 7 camera placement diagram (B. R. W. Architects 2013)

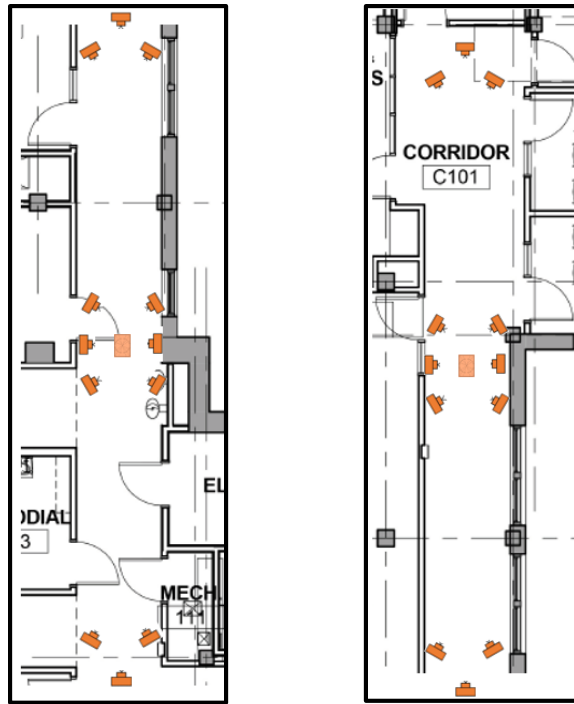


Figure A.6: Sections 8 and 9 camera placement diagrams (B. R. W. Architects 2013)

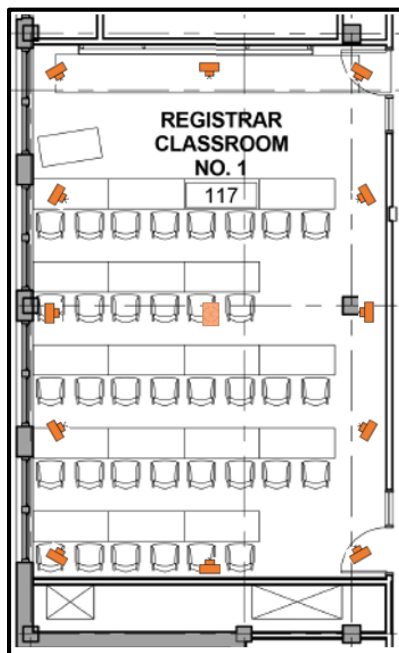


Figure A.7: Section 10 camera placement diagram (B. R. W. Architects 2013)



Figure A.8: Section 11 camera placement diagram (B. R. W. Architects 2013)

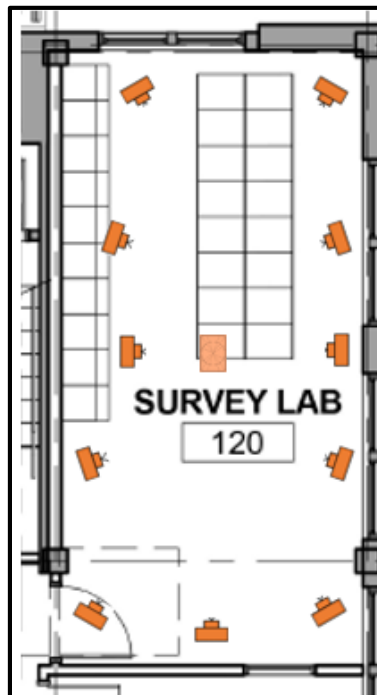


Figure A.9: Section 12 camera placement diagram (B. R. W. Architects 2013)

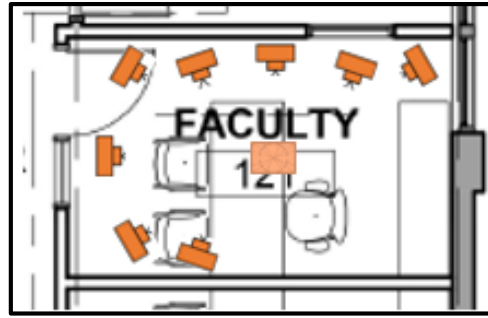


Figure A.10: Section 13 camera placement diagram (B. R. W. Architects 2013)

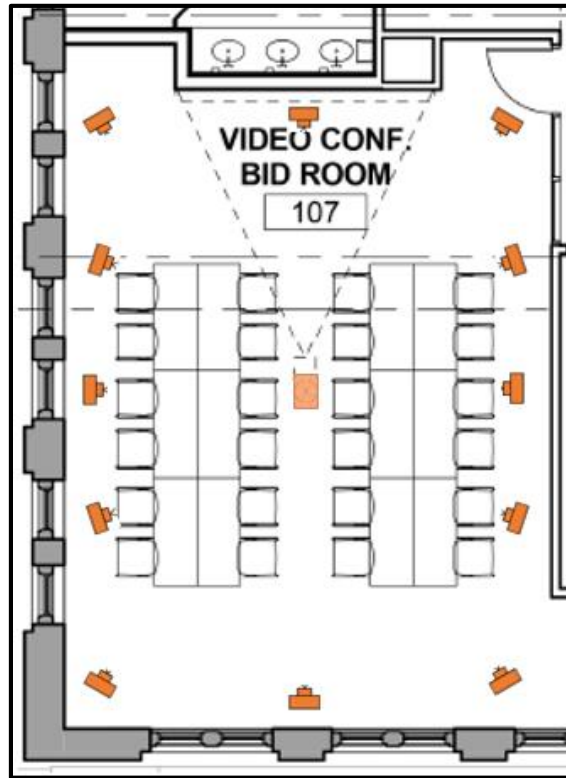


Figure A.11: Section 15 camera placement diagram (B. R. W. Architects 2013)

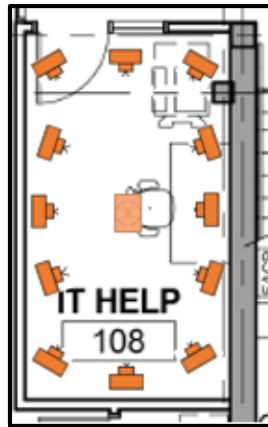


Figure A.12: Section 16 camera placement diagram (B. R. W. Architects 2013)

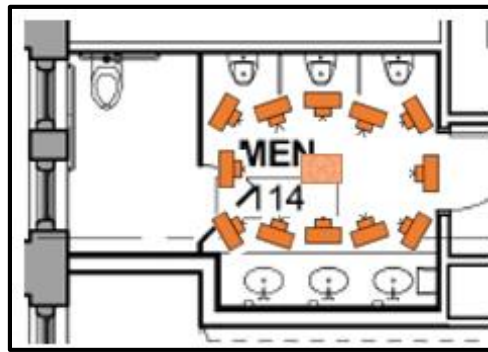


Figure A.13: Section 17 camera placement diagram (B. R. W. Architects 2013)

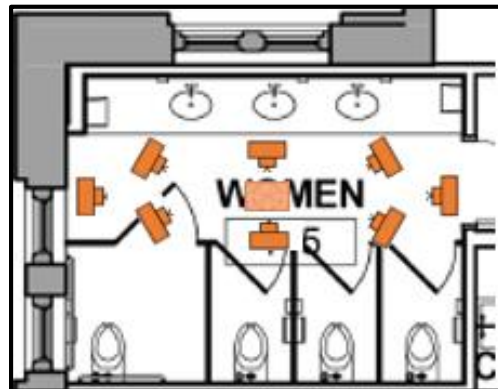


Figure A.14: Section 18 camera placement diagram (B. R. W. Architects 2013)

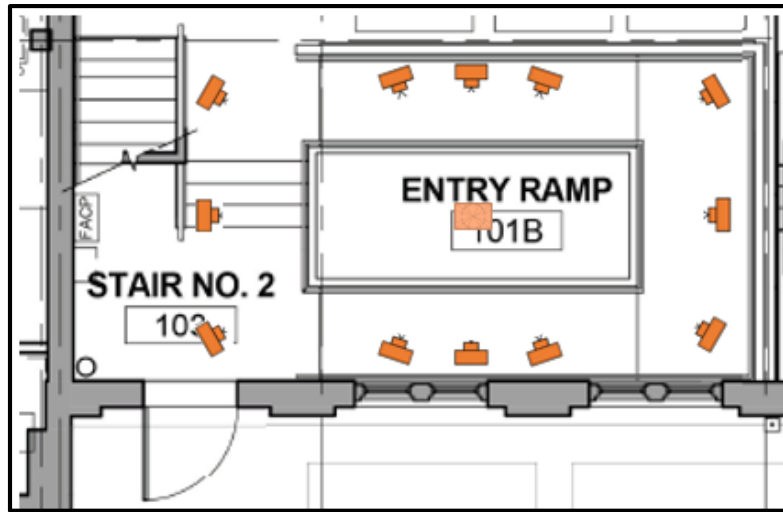


Figure A.15: Section 19 camera placement diagram (B. R. W. Architects 2013)



Figure A.16: Section 20 camera placement diagram (B. R. W. Architects 2013)

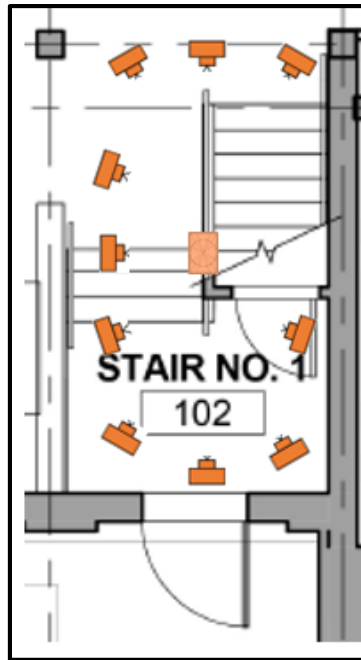


Figure A.17: Section 21 camera placement diagram (B. R. W. Architects 2013)

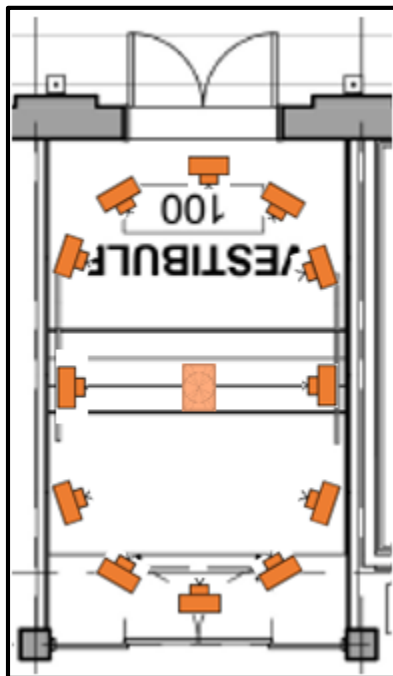


Figure A.18: Section 22 camera placement diagram (B. R. W. Architects 2013)

APPENDIX B



Figure B.1: Section 3 mesh model extracted from Autodesk Recap

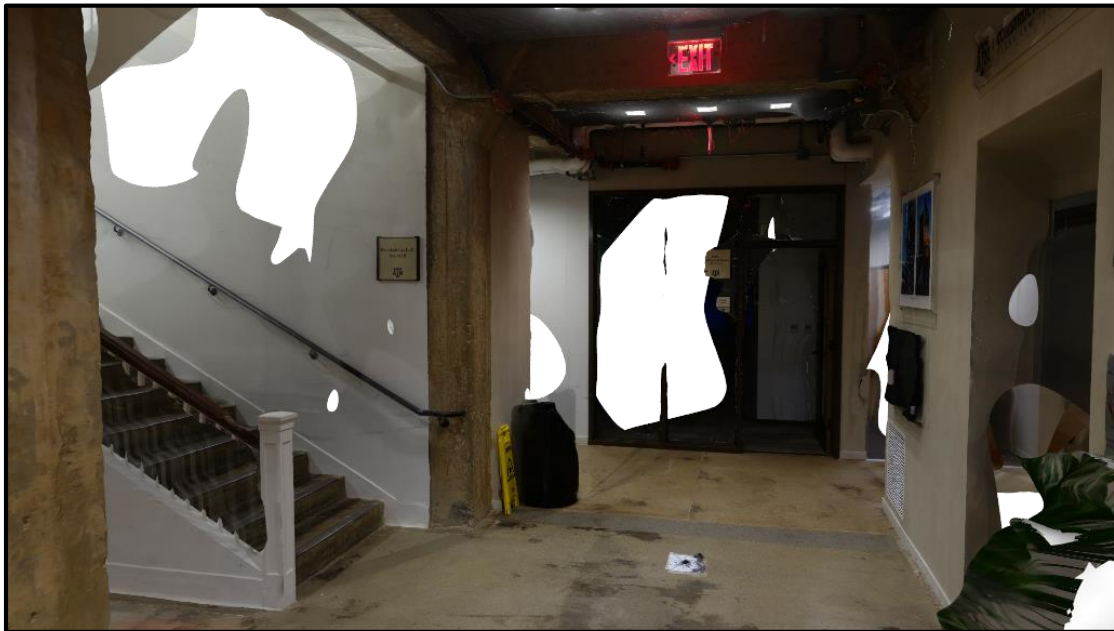


Figure B.2: Section 4 mesh model extracted from Autodesk Recap



Figure B.3: Section 5 mesh model extracted from Autodesk Recap



Figure B.4: Section 6 mesh model extracted from Autodesk Recap



Figure B.5: Section 7 mesh model extracted from Autodesk Recap



Figure B.6: Section 8 mesh model extracted from Autodesk Recap

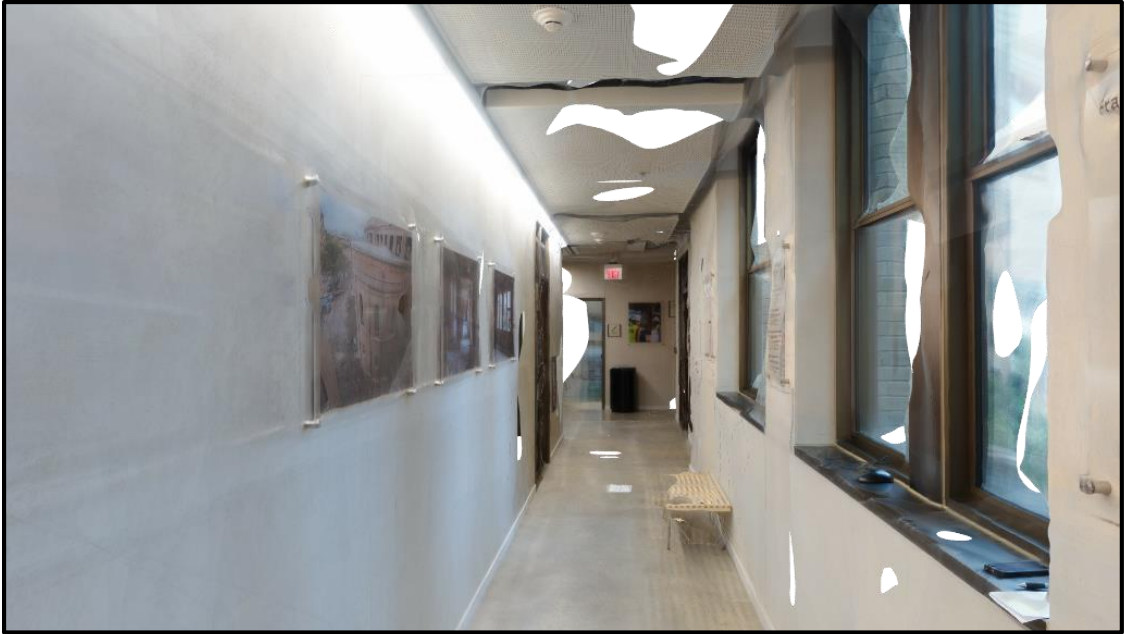


Figure B.7: Section 9 mesh model extracted from Autodesk Recap



Figure B.8: Section 10 mesh model extracted from Autodesk Recap



Figure B.9: Section 11 mesh model extracted from Autodesk Recap



Figure B.10: Section 12 mesh model extracted from Autodesk Recap

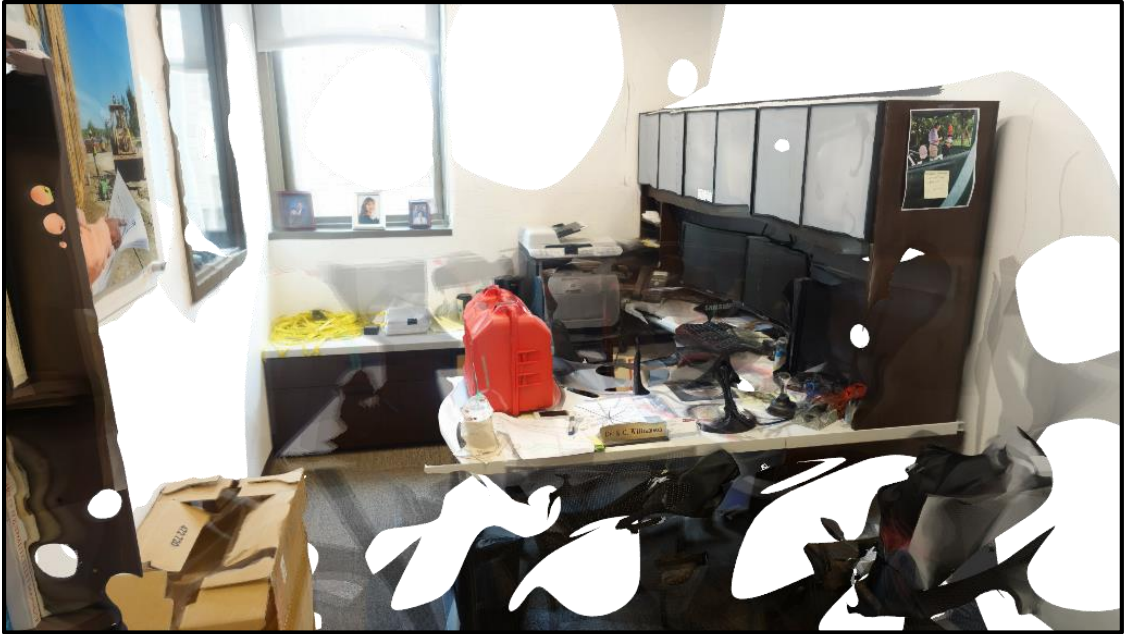


Figure B.11: Section 13 mesh model extracted from Autodesk Recap



Figure B.12: Section 14 mesh model extracted from Autodesk Recap



Figure B.13: Section 15 mesh model extracted from Autodesk Recap

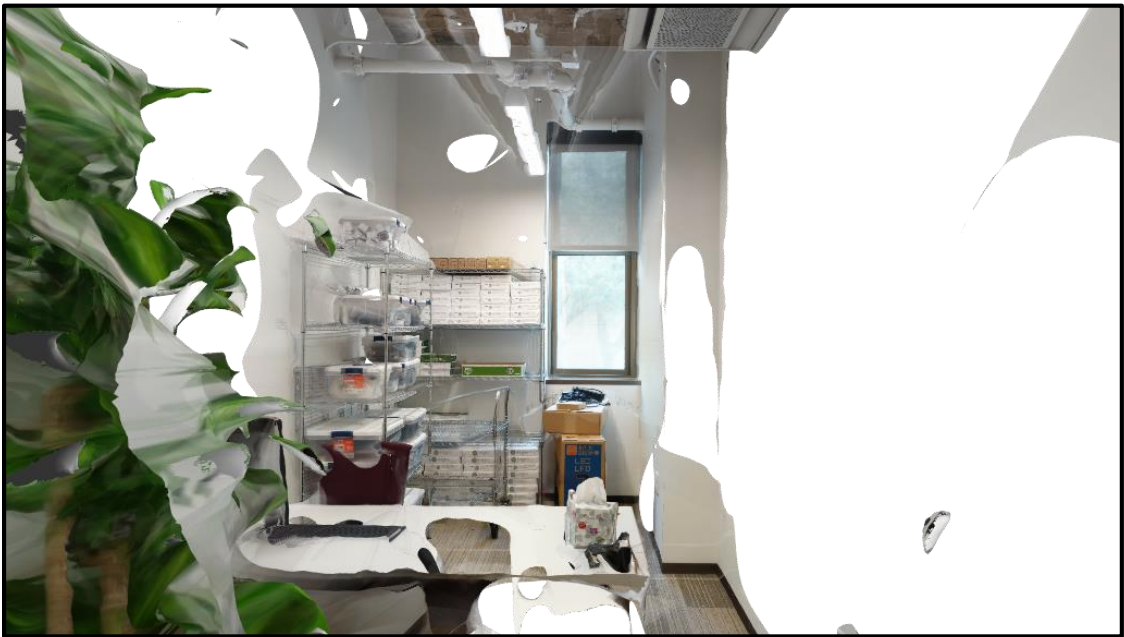


Figure B.14: Section 16 mesh model extracted from Autodesk Recap



Figure B.15: Section 17 mesh model extracted from Autodesk Recap



Figure B.16: Section 18 mesh model extracted from Autodesk Recap



Figure B.17: Section 19 mesh model extracted from Autodesk Recap



Figure B.18: Section 20 mesh model extracted from Autodesk Recap



Figure B.19: Section 21 mesh model extracted from Autodesk Recap



Figure B.20: Section 22 mesh model extracted from Autodesk Recap

APPENDIX C

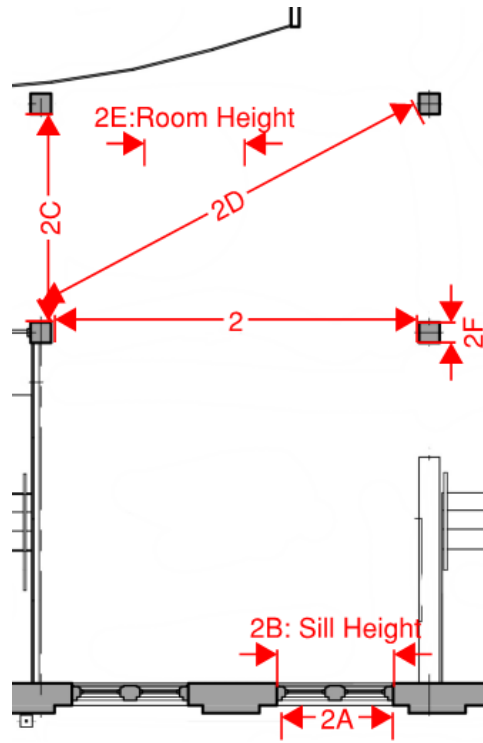


Figure C.1: Dimensions of section 2 (B. R. W. Architects 2013)

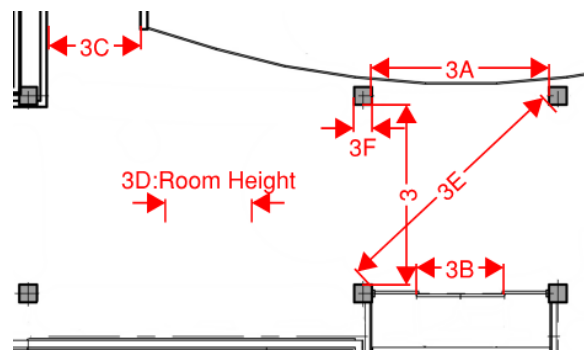


Figure C.2: Dimensions of section 3 (B. R. W. Architects 2013)

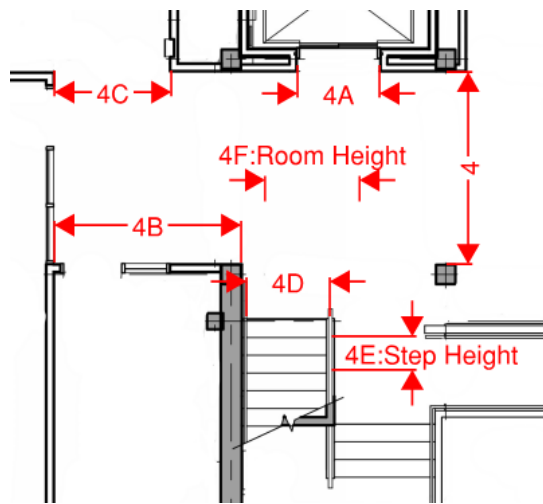


Figure C.3: Dimensions of section 4 (B. R. W. Architects 2013)

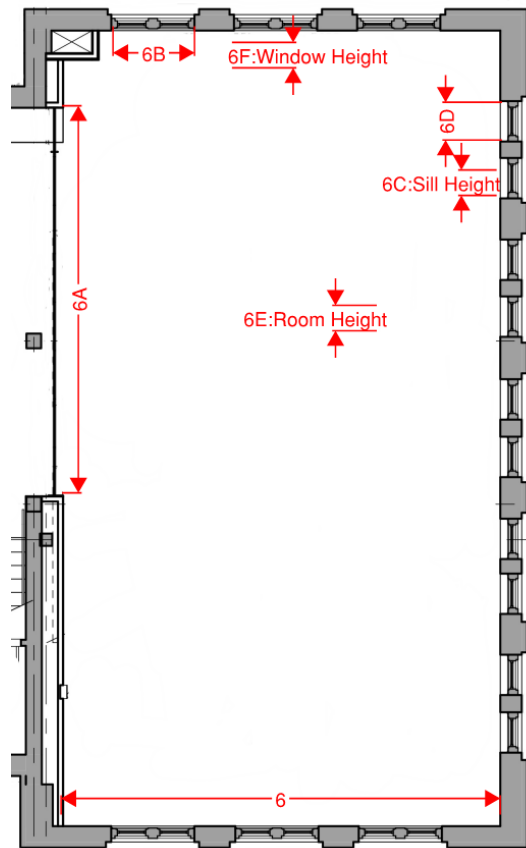


Figure C.4: Dimensions of section 6 (B. R. W. Architects 2013)

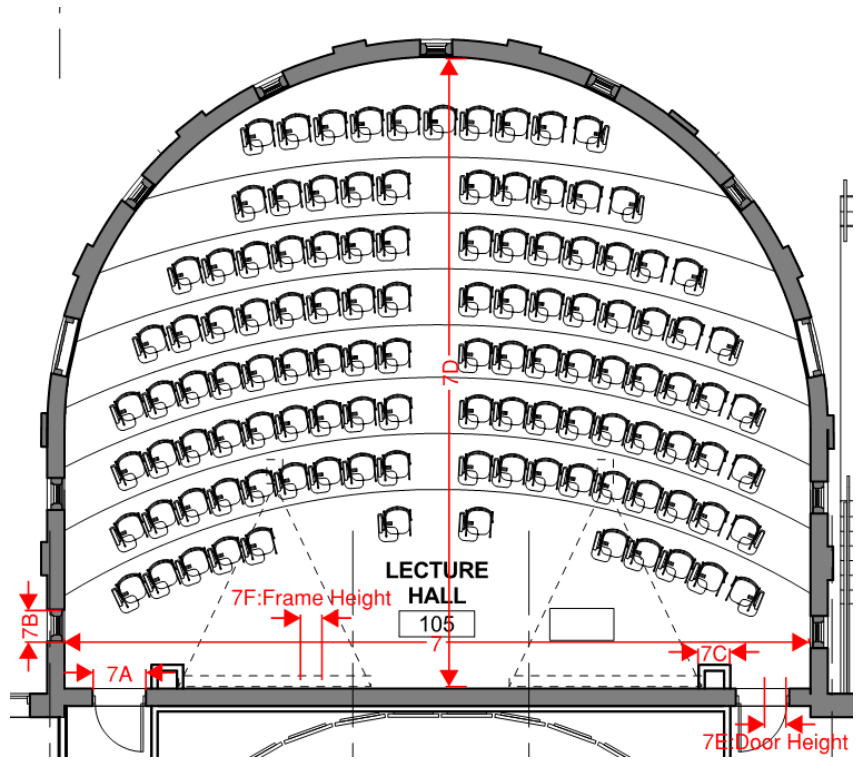


Figure C.5: Dimensions of section 7 (B. R. W. Architects 2013)

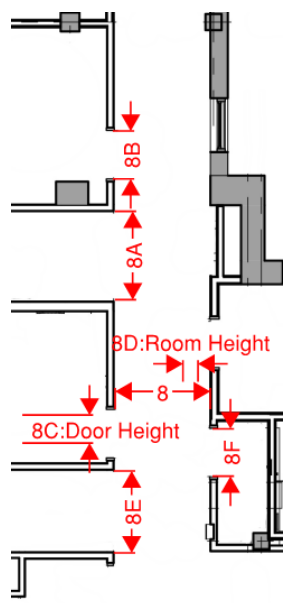


Figure C.6: Dimensions of section 8 (B. R. W. Architects 2013)

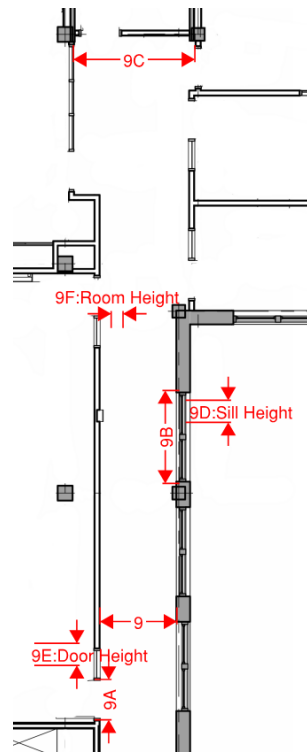


Figure C.7: Dimensions of section 9 (B. R. W. Architects 2013)

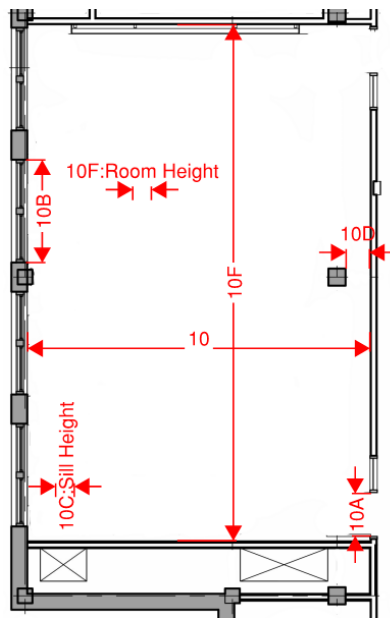


Figure C.8: Dimensions of section 10 (B. R. W. Architects 2013)

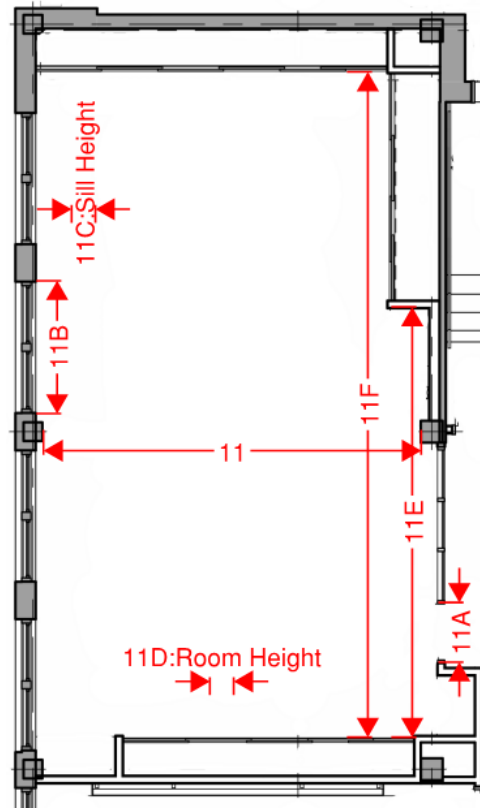


Figure C.9: Dimensions of section 11 (B. R. W. Architects 2013)

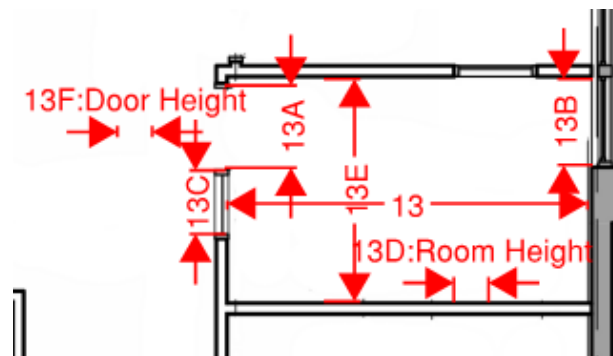


Figure C.10: Dimensions of section 13 (B. R. W. Architects 2013)

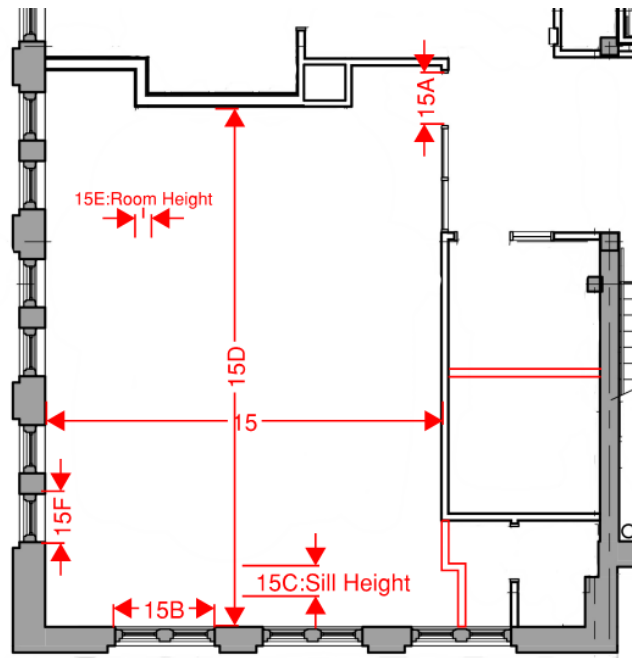


Figure C.11: Dimensions of section 15 (B. R. W. Architects 2013)

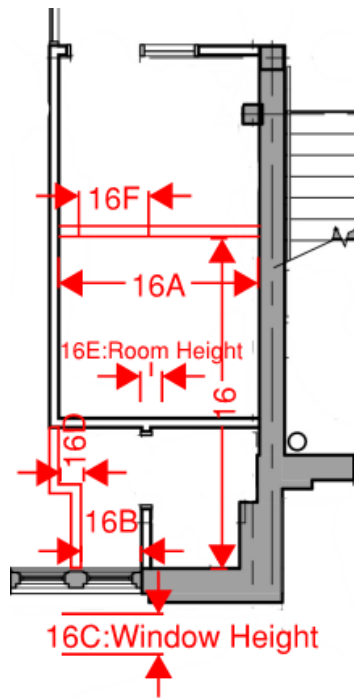


Figure C.12: Dimensions of section 16 (B. R. W. Architects 2013)

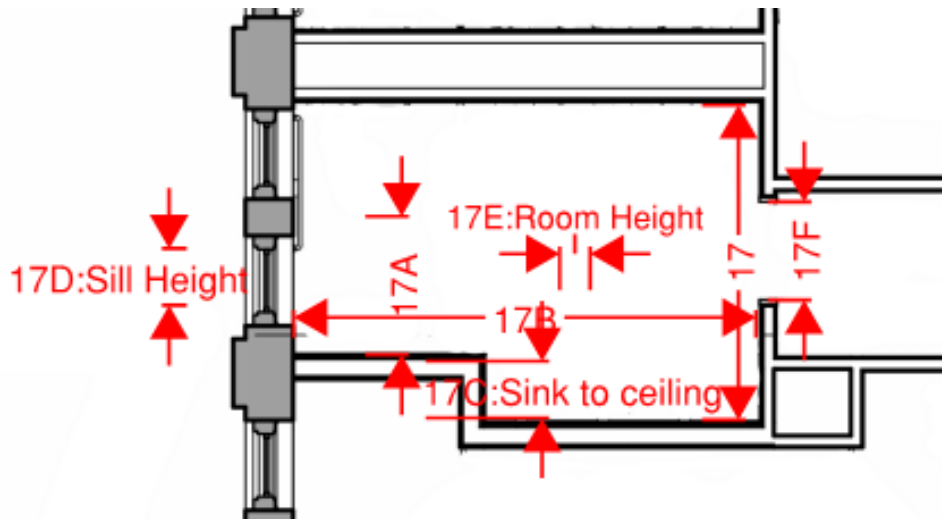


Figure C.13: Dimensions of section 17 (B. R. W. Architects 2013)

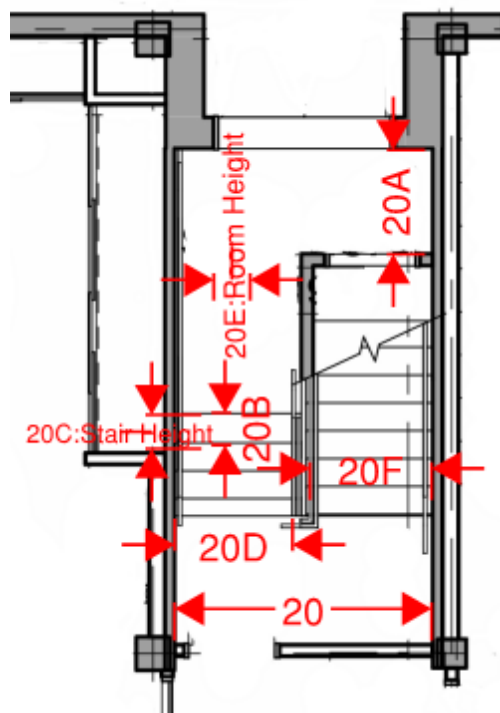


Figure C.14: Dimensions of section 20 (B. R. W. Architects 2013)

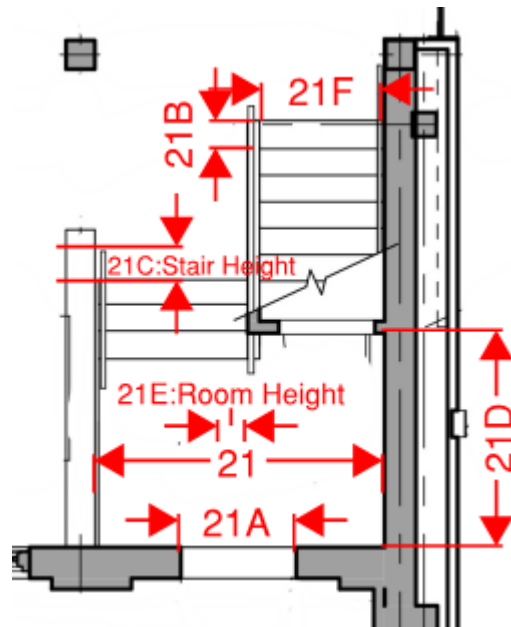


Figure C.15: Dimensions of section 21 (B. R. W. Architects 2013)

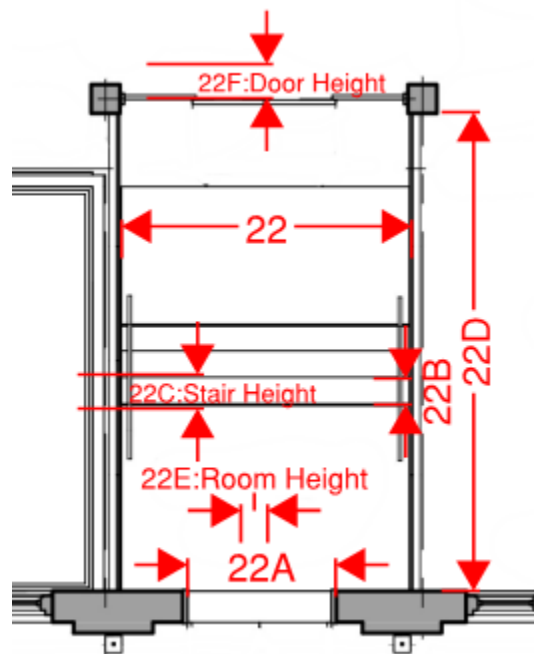


Figure C.16: Dimensions of section 22 (B. R. W. Architects 2013)