Utilization of Optical Systems in Generating 3D Point Cloud Data for Architectural Building Forensics

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Authors Note

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Abstract

An indispensable technology that has made its presence, both in industry and in academia, is 3d point cloud. There have been advancements that have made it accessible as well as being utilized in many different sectors. A variety of devices are used in obtaining visual data to support specialists in collecting and identifying features of buildings. Devices such as drones, laser scanners and different camera systems are researched in this paper in order to understand the limitations and the conditions in which each should be deployed. Beyond using sensors individually, different methods were developed in order to integrate the different visual data in order to develop a more comprehensive method of visually inspecting building features. This research is focused on developments in optical devices and sensors which have helped in aiding the evaluation of building defects.

Keywords: Forensic Architecture, Building Forensics, Architecture, Point Clouds, Thermal Infrared Imaging, Multispectral Imaging, Hyperspectral Imaging, Non-destructive Analysis.

Contents

1. Introduction

There many factors that threaten various cultural and historical assets, ranging from pests to earthquakes (Yang et al., 2022, p.6). Many interventions to renovate and repair buildings requires significant changes to the targeted site, which risks the loss of losing important cultural and historical elements. In order to reduce the risk of losing these important components of buildings, non-destructive methods are considered when inspecting historic buildings (Resende et al., 2022, p.2).

Cultural heritage preservation in the field of Forensic Architecture is a multi-disciplinary field that integrates a multitude of specializations that integrates art, archaeology, computer science, environmental science, applied physics and chemistry (Yang et al., 2022, p.1). Because of its multidisciplinary nature, its applications have been studied and utilized in many different areas of studies and industries. The application of 3D point cloud data in the domain of cultural heritage is gaining more attention in academia and industry (Yang et al., 2022, p.1). Many papers in the past decade have been published in various academic journal in regards to using point cloud data that includes construction, civil engineering, advanced engineering informatics, computer vision, photogrammetry and remote sensing (Wang & Kim, 2022, p.3). The number of academic journals being published on point cloud data in regards to construction has increased dramatically from 21 papers from 2005-2010, to 82 papers from 2010-2015 (Wang & Kim, 2022, p.4). In addition, image based 3d models has also gained increasing interest in the academic field, as a sizable portion of literature is available on the use of photogrammetric 3d point clouds (Sánchez-Aparicio et al., 2022, p.3).

The geometric properties of point clouds are an important feature, as over 50% of papers written about 3d point cloud regarding construction is about 3d model reconstruction. In which there are roughly 3 main categories of literature for 3d modeling reconstruction that include, construction site, building and their components, and civil infrastructures and their components (Wang & Kim, 2022, p.5). Besides only utilizing purely geometric data, several studies have shown the potential uses of using different sensors to obtain radiometric data in conjunction with 3d point cloud data in evaluating cultural heritage buildings (Sánchez-Aparicio et al., 2022, p.3).

1.1. Point Clouds

Point Clouds are a set of points defined by using the [X, Y, Z] 3D Cartesian coordinate system (Yang et al., 2022, p.1]. 3D point cloud data is vital for virtual reconstruction of cultural heritage which includes 3d spatial data acquired by laser scanning. The data mainly includes registration noise filtering, hole filling, surface reconstruction and texturing (Yang et al., 2022, p.3). Point cloud data also contains color information, which can be turned into a texture and applied to meshes. Point clouds can be used to generate meshes, which are different than point cloud data as 3d meshes are composed of interconnected vertices, edges and faces that define the shape of an object (Su et al., 2023, p.3).

The most popular parameters for point cloud quality are accuracy and spatial resolution (Wang & Kim, 2022, p.18). 3D point cloud is particularly important in the preservation and evaluation of buildings by its ability to capture and visually portray the geometric shapes, dimension, orientation and position of buildings (Sánchez-Aparicio et al., 2022, p.1).

Point Cloud inside Autodesk Recap. Captured by Trimble x7. Point clouds carrying RGB data. Scan: (Corbett, 2022)

3D mesh reconstruction inside 3ds Max. Created by interconnected vertex, faces, UV coordinates and textures. Model: (Her, 2023)

1.2.0. Optical Devices – Capturing and Displaying Point Clouds

In many cases, using a single method to acquire 3d point cloud data for a complete set of point cloud data is challenging (Yang et al., 2022, p.3-4). Due to this, many different devices are used in collecting point clouds. Data can be collected using 3D laser scanning technology and photogrammetry technology equipped with UAVS (Unmanned Aerial Vehicles), mobile vehicles, and other platforms. Recently, drones, handheld mobile 3d laser mapping systems, low-cost spherical cameras and smartphones with lidar sensors have been used for 3d surveying in the cultural and heritage domains (Yang et al., 2022, p.3). Low-cost hardware and methods have been shown to help supplement and update point cloud data (Hellmuth et al., 2020, p.12).

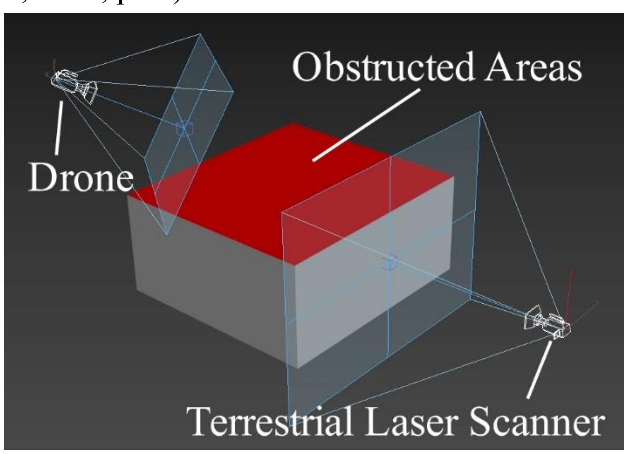
There are a variety of methods for generating 3D point cloud data. Different ways of capturing point cloud data are used according to the requirements and conditions of the target site and buildings for assessment. Point cloud data can be obtained by various sources such as laser scans, images and videos (Wang & Kim, 2022, p.6). Additionally, point clouds can be acquired using different devices and methods such as laser scanners, stereo cameras or structured light systems (Sánchez-Aparicio et al., 2022, p.2). Laser-Scanners dedicated for capturing 3d point cloud data, drones, reflex-cameras as well as a simple smartphone has its strengths, limitations, ease of use and expense.

Point clouds are compatible with many displays. They are also able to be combined with Virtual Reality to enhance construction safety. The generated 3d models from point clouds from construction sites are able to simulate safety hazard simulations in a virtual environment (Wang & Kim, 2022, p.14).

There are also several papers that deal with damage detection collected off additional informational systems such as GIS and integrating them into point cloud. GIS (Geographic Information System) are computer systems that analyzes and displays referenced information. GIS is especially useful as it is able to contain a variety of maps that contains different kinds of information such as elevation, orthoimages, transportation and structures (United States Geological Survey, 2023). There are several proposals in using GIS methods to monitor structural displacements as well as converting data off GIS into 3D mesh to map damage (Yang et al., 2022, p.20). Models obtained from photogrammetry technology allowed the quantification of seismic deformation using a GIS based environment (Yang et al., 2022, p.6).

1.2.1. Terrestrial Laser Scanning

Laser scanned point cloud data is obtained by registering point clouds from laser scans aligned in a shared coordinate system (Wang & Kim, 2022, p.6). As for captured wave lengths, the values for photogrammetry were mainly within the visible spectrum, and the near infrared, around 1550nm in the case of laser scanning (Sánchez-Aparicio et al., 2022, p.3). 5 mm (The lower the number, the denser the point clouds) was the most common density found in publications, followed by 10mm density and only a few had the density of 50 mm (Sánchez-Aparicio et al., 2022, p.9). It is also possible to manipulate the intensity of laser scanners that can increase the precision and allow them to detect cracks smaller than 2mm (Sánchez-Aparicio et al., 2022, p.18).



The high precision of Terrestrial Laser Scanners in combination with the high mobility of drones are able to comprehensively survey sites. Drones are able to enter areas inaccessible to Terrestrial Laser Scanners, while Terrestrial Laser Scanners are fast, accurate and reliable sources of obtaining point clouds.
This image shows the mobile nature of UAVS, and Terrestrial Laser Scanners ability to scan large environments accurately and efficiently.

Due to its high accuracy, laser scanners are used in Architecture for many purposes including preservation. The approach of capturing accurate building geometries from 3d laser scanning to build BIM or HBIM is called Scan-to-BIM (Yang et al., 2022, p.5). Terrestrial laser scanner's capacity to capture reality with high density and accuracy allows visible detection of deflections and deformations in geometry (Sánchez-Aparicio et al., 2022, p.1). Laser scans are frequently used to identify and evaluate façade surface defects like edge and cracks from cultural heritage assets. Terrestrial Laser Scanners are able to detect crack defects that are caused by weather, aging, and the infiltration of solar radiation at a millimeter level. Many research papers show how laser scans are able to identify and quantify the surface damage of cultural relics caused by cracks or material loss. (Yang et al., 2022, p.4-5).

1.2.2. Structure from Motion

Images are important sources of data when evaluating buildings. Images aid experts in detecting changes, conduct conservation analysis and engage in historical study (Sánchez-Aparicio et al., 2022, p.3). Besides still images, the collection of images can also be used to generate point clouds through photogrammetry. Photogrammetry is a process of creating 3D point clouds from 2D data coming from sources like images and videos (Wang & Kim, 2022, p.6). It works by analyzing overlapping areas of multiple photos of the same object using the differences to triangulate the position of each point in 3d space (Su et al., 2023, p.3). Structure from Motion is a relatively new photogrammetric approach in creating high resolution mapping products like point clouds and orthoimages from overlapping images acquired by consumer-grade cameras (Javadnejad et al., 2020, p.5). Orthoimages are photographic maps with a uniform scale, that removes the effects of tilt and relief displacement (United States Geological Survey. (n.d.), 2023).

Structure from motion and photogrammetry are flexible and affordable means of generating 3d models. The general workflow of photogrammetry can be briefly summarized as first: acquiring images, detecting features, matching, densification, generating mesh surfaces, then projecting the textures (Sánchez-Aparicio et al., 2022, p.3). Aerial drones are able to capture images, used to create 3d photogrammetric point clouds, then are able to generate textured 3d meshes (Su et al., 2023, p.3). Furthermore, optical devices that capture images such as drones are capable of storing radiometric information that can detect additional damages such as moisture or crusts (Sánchez-Aparicio et al., 2022, p.1)

1.2.3. Sensors – Quality Differences

Although many devices are capable of generating point cloud data, the quality of the data is determined by the device it's being captured on as well as the software being used. Studies have shown there are differences in the quality of 3d data being collected by different sources. Dedicated reflex cameras have been shown to generate higher quality 3d models compared to 3d models generated by smartphones (Hellmuth et al., 2020). It is suggested that laser scanning and or other high quality and resolution image capturing devices such as reflex cameras should be used to obtain point cloud data as opposed to smartphones. The quality of data is diminished considerably when using smartphones (Hellmuth et al., 2020, p.9).

Laser Scanners have the ability to capture large environments accurately and relatively quickly. (Corbett, 2022).

1.2.4. Pros & Cons of Laser Scanning & Photogrammetry

Laser scanners are commonly used for structural analysis due to its high accuracy and fast data acquisition capabilities. Laser scanners are used opposed to photogrammetry because of its higher accuracy (Sánchez-Aparicio et al., 2022, p.23).

However, the versatility of photogrammetry is its strength, due to its ability to equip different sensors, as well its ability to traverse areas inaccessible to laser scanners. These sensors are able to detect various ranges of the electromagnetic spectrum, that aren't able to be detected by a standard camera. Point clouds generated by photogrammetric data can detect the normal geometric properties, colors of the primarily visible light, as well as radiometric data outside the visible light. (Sánchez-Aparicio et al., 2022, p.3).

1.2.5. Integration of 3D Point Cloud Data from Different Optical Devices

While Terrestrial Laser Scanners are usually used for obtaining information on building facades, and UAVS are useful tools in providing information on the roofs of buildings (Yang et al., 2022, p.3-4), it is possible to integrate laser scan data with photogrammetry, albeit photogrammetry meshes are far denser compared to laser scanned point cloud counterpart. Laser scans can efficiently scan large environmental models, while photogrammetry is ideally used for small scale object that requires high density point cloud data (Hellmuth et al., 2020). The integration of different sensors and methods allows for a more comprehensive point cloud, as drones and mobile cameras allows access to otherwise inaccessible places for laser scanners (Yang et al., 2022, p.4).

Although, the data obtain from ground lasers and aerial photogrammetry from drones are ideal in creating a more comprehensive point cloud, this however, requires significant time and effort in order to fuse the data (Sánchez-Aparicio et al., 2022, p.23).

1.3. Point Cloud Processing Methods

1.3.1. Software Applications for Point Cloud Data.

Point clouds are processed in various programs. Many of these programs have graphical interfaces that enables users to see the millions of point cloud data into visible 3d graphics. These point clouds are capable of capturing the exterior location, geometric details and textures of objects (Yang et al., 2022, p.1). The data can then be imported into programs like FARO Scene, Leica Cyclone, BIM modeling applications like Autodesk Recap. Point Clouds can also be seen by using augmented reality and virtual reality commercial headsets like the Oculus Rift and HTC Vive. (Wang & Kim, 2022, p. 20).

1.3.2. Geometric & Semantic Modeling

The reconstruction of 3d models can be categorized into two categories, geometric and semantic modeling. Geometry modeling is the raw point cloud data that is generated directly from the devices that captured the images, videos or laser point cloud data. Point clouds are also used in semantic modeling, which is used in computational algorithms, artificial intelligence and machine learning that assists in 3d remodeling (Wang & Kim, 2022, p.7-8).

Geometric modeling is important in the visual inspection of buildings. The main purpose of geometric modeling is to transfer 2d data into 3d point clouds (Wang & Kim, 2022, p.7). Geometric models generate point cloud by using photogrammetry algorithms by finding distinct features from overlapping images or video frames, which are then used by aligning the geometric point cloud models with BIM models for quality inspection and tracking the construction of new buildings (Wang & Kim, 2022, p.7). The models are then used for geometry quality inspection of building and infrastructure which can be divided into three categories, Dimensional Quality Inspection, Surface Quality Inspection and Displacement Inspection (Wang & Kim, 2022, p.11). Geometric modeling is used in different stages of construction, including the operations and maintenance phase when point clouds are used to inspect concrete and steel structures. The ability to be used for risk assessment is also an important aspect as they are used for post-disaster buildings, heritage sites and landscape assessment (Wang & Kim, 2022, p.12).

Point clouds are also able to contribute to semantic models. There are four popular approaches to semantic model reconstruction from point cloud data which are geometric shape descriptor-based approach, hard coded knowledge-based approach, supervised learning-based approach and matching alignment with BIM based approach (Wang & Kim, 2022, p.8). Data is needed to use these methods for semantic modeling, for example, color information from point clouds is a widely utilized data for object recognition. HSI (Hue, Saturation and Intensity) are used for recognizing steel structural components and RGB values are used as features to obtain classifications of rebar and other objects. Color point clouds are used to detect secondary building components for example, door, windows, etc. (Wang & Kim, 2022, p.19-20). The ability to detect features of buildings increases the efficiency of assessing and reconstructing building.

The capability of detecting features in semantic modeling is also being applied to important fields like energy sustainability. Semantic modeling is being used to detect features of buildings in order to conduct energy analysis of buildings on an urban level. Research is being conducted by first gathering information from drones to create 3d models of buildings, using A.I. and machine learning algorithms to assess the window to wall ratios (Su et al., 2023, p.3). The 3d meshes generated from point clouds are then used to conduct research on machine learning to calculate the surface areas of windows on buildings for the potential of reconstructing the mesh using clean energy models (Su et al., 2023, p.5).

2.1 Current Applications of Point Clouds:

2.1.1 Point Cloud Data in Construction and Architecture.

Point clouds have proven itself to be a useful and versatile technology in the fields of Construction and Architecture. They are used in these fields for many different reasons which includes evaluating the geometric properties of buildings, civil infrastructures and tracking construction progress (Wang & Kim, 2022, p.3). The uses as well as stages of using point cloud technology in aiding construction demonstrates its versatility. Point clouds are used throughout many different processes of construction including fabrication, construction, operations and management among others (Wang & Kim, 2022, p.12). Additionally, they also used for existing buildings in order to plan renovations, retrofitting, refurbishing as well as assisting in renovating facades (Wang & Kim, 2022, p.14).

The use of 3d point cloud in construction is not always built precisely from the construction blueprints and BIM (Building Information Models) models. BIM is a 3D model-based approach that gives tools to engineering and construction professionals in order to design infrastructure efficiently (United States Department of Transportation, 2023). Point cloud data is used to inspect the alignment of the as-is buildings versus the BIM models and inspect the differences and the tolerances of the structure (Wang & Kim, 2022, p.12). In addition, they are also used in 4D BIM in construction to track progress of the construction of buildings and civil infrastructure (Wang & Kim, 2022, p.2). 4D BIM modeling is the process of comparing point cloud gathered on the construction site with the time-scheduled 3D BIM models to ensure timely construction. (Wang & Kim, 2022, p.13).

Point cloud used in geometric inspection has many uses in construction. One of these uses is inspecting the dimensions of precast and prefabricated elements, the dimensions of building façade elements, damages of building elements, and damages of heritage sites (Wang & Kim, 2022, p.11). As well as being used for surface quality inspection, the evaluation of surface cracks, spalling, flatness and deformation. The evaluation of displacement can also be obtained by focusing on the change of the position of structures and comparing the building's position from different time cycles (Wang & Kim, 2022, p.11). Point cloud's ability to capture dense and accurate data gives users the ability to inspect additional important details including earthwork and historical building ornaments (Wang & Kim, 2022, p.14). They are also used to evaluate construction parts such as precast and prefabricated components such as concrete and pipe spools to insure smooth assembly in the construction site during the fabrication phase of construction. (Wang & Kim, 2022, p.12).

Although the two major applications of point clouds are 3d model reconstruction and geometry quality inspection, there are more applications which includes construction progress tracking, building performance analysis, construction and safety management, building renovation, construction automation, heritage application and robot navigation (Wang & Kim 2022, p.4).

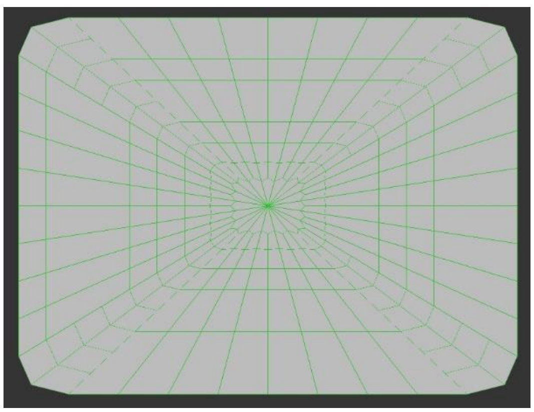
Besides the visual aspects of point clouds, they can also be used in numerical models such as conducting building performance analysis that includes mechanical, accessibility and energy building analysis. In accessibility analysis, steps from entrances can be evaluated in regards to the building's accessibility (Wang & Kim, 2022, p.14). In mechanical analysis, after generating 3d geometric masonry bridges, it is possible to use the geometry to conduct failure load estimation and stress distribution analysis (Wang & Kim, 2022, p.13-14).

2.1.2: Heritage Structures

There are many variables that threatens heritage sites, some of these threats include climate change, human negligence, war and natural hazards. Natural environmental variables such as humidity, temperature, wind and soil characteristic contribute to natural deterioration including decay and erosion of perishable materials. The natural deterioration processes results in chemical, physical and biological degradations of the materials that the buildings are made from, as well as their decorations and artifacts (Sánchez-Aparicio et al., 2022, p.2). Due to these conditions, it is important to use technologies and find methods in the detection of elements that deteriorates the integrity of cultural and historical artifacts.

Point cloud data is a crucial source of information in the field of cultural heritage because of its ability to capture reality with high density and accuracy. The data is then commonly used as inputs for generating planimetries, BIM and used for numerical simulations (Sánchez-Aparicio et al., 2022, p.1). Planimetric maps are aerial maps without perspective distortions. Aerial images are influenced by the uneven altitude of landscapes, leading to image deformations such as relief displacement. As terrain elevation increases, the flying height decreases and photo scale increases, leading to perspective distortion. Planimetric views capture the ground positions from directly above. Orthoimages and topographic maps are said to be planimetrically correct (Pennsylvania State University, 2023).

Point cloud are used in both BIM as well as HBIM. The construction of BIM models based on 3d point cloud data allows the detection of changes in historical buildings (Yang et al., 2022, p.5). Cracks, deformations, detachment, features induced by material loss, discoloration and deposit and biological colonization and other building defects can be detected by point clouds and thermography (Sánchez-Aparicio et al., 2022, p.3). Heritage Building Information Modeling (HBIM), is a reverse modeling technique for point clouds that allows creating complete engineering drawings of historical buildings. Point cloud is an efficient way to manage complex historically and culturally significant buildings (Yang et al., 2022, p.5). HBIM focuses on the geometric structure and attributes of heritage buildings while GIS enables the integration of 3d models and geospatial information, which supports spatial analysis, risk & vulnerability analysis and heritage conservation (Yang et al., 2022, p.5). Beyond just preserving the original buildings, geometric models created from point clouds are able to be 3d printed for reproduction (Wang & Kim, 2022, p.14).



Orthogonal Image

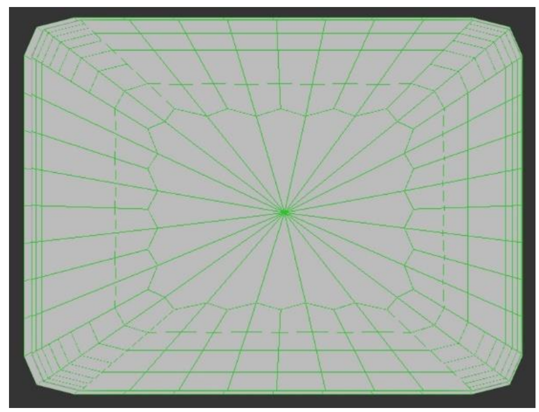
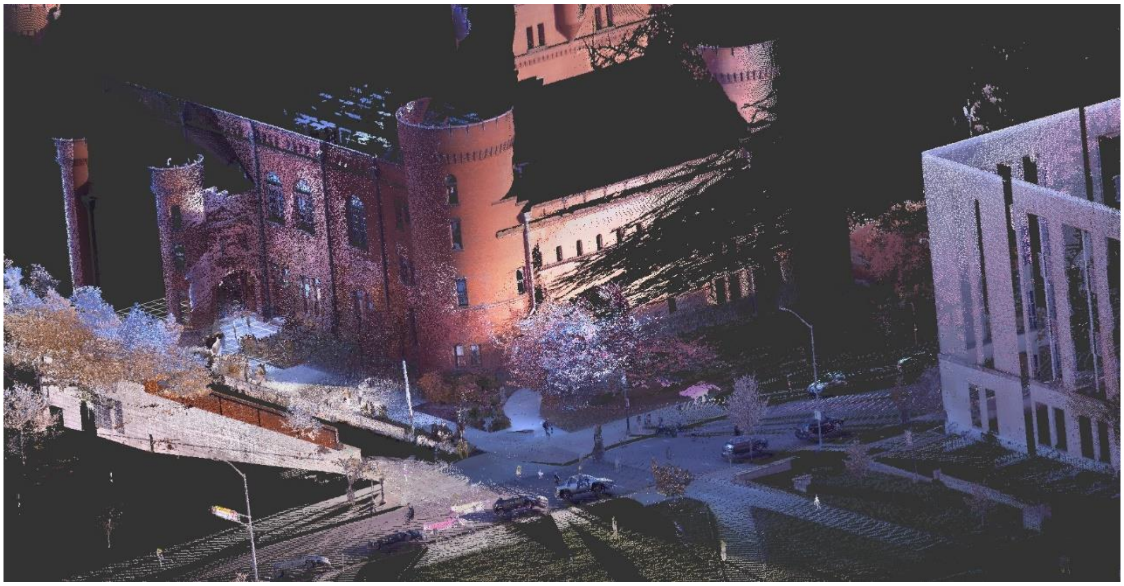


Image with Perspective Distortion

Point clouds are widely used for heritage related applications. Laser scanners are important in the geometric inspection in heritage building preservation such as being able to segment masonry units and mortar regions in cultural heritage buildings, which helps in surveying, repairing and maintenance of heritage buildings. (Wang & Kim, 2022, p.15). In addition to using point clouds only for geometric properties, studies have shown the potential of using the geometric and radiometric data of point clouds in order to analyze and assess heritage buildings. Using the properties of point cloud data allows for the detection of morphological characteristics of heritage buildings (Sánchez-Aparicio et al., 2022, p.3). They are also able to help detect chemical, biological and physical damages of heritage sites based on the combination of radiometric and geometric analysis using laser scanning data (Wang & Kim, 2022, p15).

There have been instances in which point clouds were used in order to virtually restore, as well as aided in rebuilding damaged heritage artifacts. Virtual restoration can also assist physical restoration to rebuild damaged heritage, restore visual assets and reconstruct artifacts. Point clouds gives users the ability to analyze the geometric shapes of culture relics based on 3d models and recovered details of each component (Yang et al., 2022, p.6).

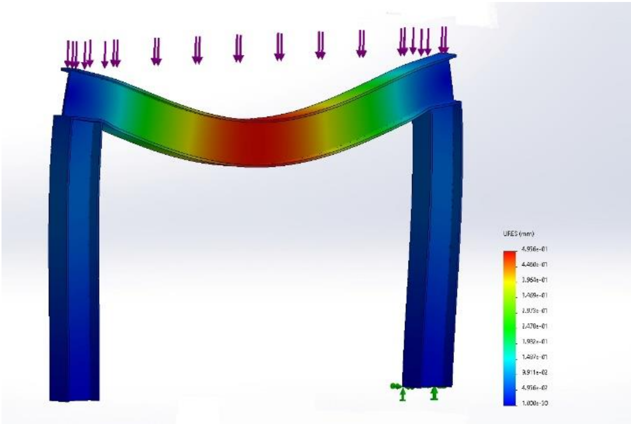


Point cloud data obtained by laser scanning using the Trimble x7 then imported into Autodesk Recap. The building scanned is the Red Gym, located in Madison, Wisconsin. (Corbett & Her, 2023).

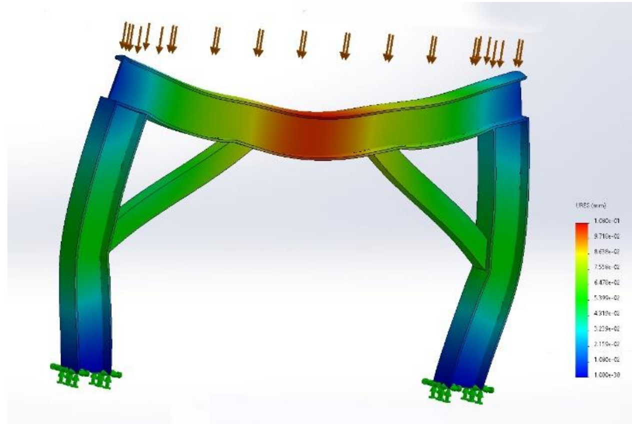
2.1.3. Structural Analysis Simulations

Many papers have been published on using 3d point cloud to find deformations of point clouds by integrating various numeric models and modeling strategies (Sánchez-Aparicio et al., 2022, p.20-21). The geometric models are able to be used in simulations. The generation of 3d finite element meshes from point clouds are able to be used to simulate and analyze the structural stability of buildings (Wang & Kim, 2022, p.15). Finite Element Modeling is a set of mathematical equations used for simulation, which is used to analyze deformations such as inclination in towers or out of plane deformations in walls (Sánchez-Aparicio et al., 2022, p.20). Scan-to-BIM models are able to generate structural finite element models of the built heritage buildings for dynamic simulations (Yang et al., 2022, p.5).

There are many programs that allow for structural analysis which includes Abaqus, Ansys, SolidWorks and Inventor Nastran, of which all of the programs are similar in results, with SolidWorks being one of the most diverse, as well as having different limitations. Many fields use Finite Element Analysis including engineering fields, mechanical, aerospace, civil and automotive in order to carry out dynamic, static, linear and non-linear analysis. (Магомедов & Sebaeva, 2020,p.1-2).



SOLIDWORKS® Simulation is a structural analysis tool that uses Finite Element Analysis (FEA) to predict real-world physical behavior. (*Solidworks Simulation,* 2023)



These images are examples of using Autodesk SolidWorks Simulation to conduct Finite Element Analysis on ASTM A36 steel beams. Images: (Corbett & Her, 2023)

3.0. Optical Sensors

Besides using the standard RGB data that is commonly used in commercial cameras, many different sensors had been added and used in conjunction with point cloud data in order to give additional information.

Many publications consist of non-destructive tests to complement 3d point cloud data, which includes 360-degree images, ultrasonic/sonic testing, vibration-based methods, radar interferometry, electric resistivity methods, chemical compositional tests, moisture tests, endoscopic tests, digital image correlation methods, multispectral cameras to compliment radiometric information of 3d point clouds (Sánchez-Aparicio et al., 2022, p.9).

Equipping UAVS with additional cameras assists in the detection of building defects. Cameras with different sensors are also able to be equipped to UAVS, increasing the possibility of gaining access to dangerous areas as well as enhancing building inspections (Dabetwar et al., 2022, p. 3). The different sensors enhance building inspections of their ability to detect different ranges in the electromagnetic spectrum using multispectral or thermal sensors (Sánchez-Aparicio et al., 2022, p.23). Several studies have demonstrated the potential of utilizing information stored in point cloud data including geometric and radiometric properties to assess heritage building surfaces. By understanding the surface data, the morphological characteristic of building surfaces and calculations of affected areas can reveal the environmental impacts or external factors (Sánchez-Aparicio et al., 2022, p.3).

Different sensors such as Ground Penetrating Radar (GPR), is another nondestructive method of producing images of subsurface interfaces and features by using the reflection of electromagnetic energy. The travel times of transmitted waves are analyzed to give depths, geometry and material type information (United States Department of Agriculture, 2021, p.1). Ground penetrating Radar sensors were used to capture the internal composition of buildings through electromagnetic signals. The sensors provided information about the building's foundations, the thickness of construction elements, and presence of damp areas (Sánchez-Aparicio et al., 2022, p.9). Ground Penetrating Radar data can be used to build detailed maps that indicate activities underneath areas, and even be created into 3d modules that depict dimensions and depth (United States Department of Agriculture, 2021, p.2)

3.0.1. Multispectral & Hyperspectral Imaging

New advancements in remote sensing and GIS have contributed towards the development of hyperspectral sensors (The University of Texas at Austin, 2023). Hyper spectral remote sensing is also known as spectroscopy, which is a relatively new technology that is being investigated by researchers and scientists in regards to detecting and identifying minerals, terrestrial vegetation, man-made materials and backgrounds. Hyperspectral data sets are composed of about 100-200 spectral bands or very narrow bandwidths of 5-10nm, while multi-spectral data sets are usually composed of about 5-10 bands of large bandwidths of around 70-400nm. Hyperspectral remote sensing is used for many purposes and within different fields including the Atmosphere, Ecological, Geological, Coastal Water, Biomass Burning and Commercial fields (The University of Texas at Austin, 2023).

UAVs are able to be equipped with multispectral sensors and combined with thermal images from separate UAV platforms. In addition to combining multispectral imaging to infrared images, 3d data are also capable of being generated from hyperspectral images using Structure from Motion (Javadnejad et al., 2020, p.7).

3.1.0. Infrared Radiation Sensors – Near, Mid, Far Infrared Radiation and FLIR

The resolution of thermal images come from sensors called Microbolometers, which detects infrared radiation (Resende et al., 2022, p.). Microbolometers work according to the thermal principles in which emitted infrared radiation from an object is absorbed by a thermally insulated membrane. The changes in electrical resistance are converted into a 16-bit signal to a readout circuit (*Microbolometers - Fraunhofer IMS,* 2022).

The type of sensors used is the main factor in categorizing infrared images. Infrared wavelengths have longer wavelengths and are just beyond the visible light spectrum. Infrared radiation is usually divided into three spectral categories, near, mid and far-infrared (Institute for Computational Cosmology, Durham University, 2023, p.1).

Just beyond 1.1 microns, infrared emissions become primarily heat or thermal radiation. Near infrared wavelengths are generally considered from about 1.1 to 5 microns. The temperatures in the near infrared ranges from 872 F – 8900 F (740K-5200K). (Institute for Computational Cosmology, Durham University, 2023, p.2)

Earth radiates most strongly at about 10 microns, which places it in the mid infrared spectrum. Wavelengths ranging from 5-40 microns are considered to be mid-infrared, which ranges in temperatures from -293 F – 872 F (92.5K-740K) (Institute for Computational Cosmology, Durham University, 2023, p.2-3).

Far infrared sensors are capable of detecting very cold matter. Satellites equipped with far-infrared sensors are able to detect cold gas clouds and dust within our galaxies. Wavelengths between 25 to 350 microns are considered to be part of the far-infrared. The temperatures range within the far-infrared ranges from -440 F to -207.67 F (10.6K – 140K). (Institute for Computational Cosmology, Durham University, 2023, p.2, 4).

The wavelength of Forward-Looking Infrared Radiation (FLIR) ranges from 8-12nm. FLIR is used because the intensity of the objects it detects depends on its temperature and radiated heat and not influenced by light conditions and surface features (Sanna & Lamberti, 2014, p.2).

The collection and analysis of data from the infrared radiation electromagnetic spectrum from approximately 3 to 15 microns provides unique information for identifying, describing and monitoring objects and phenomena for a variety of remote sensing applications (Javadnejad et al., 2020, p.2).

3.1.1. Methods of Evaluating Damages from Infrared Data

Thermal images may be analyzed qualitatively and quantitatively. Infrared data may be analyzed qualitatively by visually interpreting images based on the technician's own knowledge and experiences. After, the thermal images can be compared to intact surfaces and inspected for any abnormalities and identify the defects (Resende et al., 2022, p.4).

Quantitative analysis can also be done in regard with using infrared data. The parameters required for an accurate quantitative analysis will require the emissivity of the surfaces (Ɛ), the transmittance of the object (τ), the radiation power (W), the reflected temperature (Trefl), the distance from the camera to the target object (d), the atmospheric temperature (Tatm), and the relative humidity (RH) (Resende et al., 2022, p.4).

3.1.2. Thermal Infrared Radiation Applications

Technological advancements have led to the important reduction in the cost of infrared light sensors, which have allowed researchers and industry to use IR sensors in conducting evaluations (Sanna & Lamberti, 2014, p.2). Thermal imaging is a non-destructive method in the evaluation of buildings. Other non-destructive evaluation methods include visual inspection, infrared thermal imaging, ultrasound wave propagation velocity, acoustic emission and electrical resistivity (Resende et al., 2022, p.2).

3d point clouds obtained from standard laser scanners or visible spectrum images can only obtain information about the surfaces of object, however, infrared data can provide information on the subsurface defects as well as environmental factors that have influenced structures such as water damage (Dabetwar et al., 2022, p.2). Aerial images from thermal cameras obtained from UAVS have shown great potential for close range, high resolution thermal remote sensing (Javadnejad et al., 2020, p.3). Thermal infrared radiation has the ability to detect subsurface defects based on abnormal distribution of temperatures on the surface of an object (Dabetwar et al., 2022, p.3).

Over the years, thermal imaging has been used in many fields and applications including medical imaging, remote sensing, monitoring of civil engineering structures, defect detection in concrete slabs and in the fields of structural health monitoring and nondestructive evaluation (Dabetwar et al., 2022, p.3). Thermography has also been used in many vision-based applications, from surveillance to vehicle navigation, driver assistance and activity recognition. (Sanna & Lamberti, 2014, p.1).

Thermal imaging has been used in detecting various features and defects of buildings. Consumer grade thermal cameras have been utilized in evaluating building heat efficiency, electrical inspection non-destructive testing and leak and fire detection (Javadnejad et al., 2020, p.3). Infrared imaging was used to evaluate murals and masonry and found damages to masonry murals caused by cracks and detachment of rendering mortar as well as finding discontinuities on walls, wooden beams used for wind protection, and finding critical points for repair (Resende et al., 2022, p.5). Many publications used radiometric information contained in 3d point clouds to manually map data. This approach was able to detect a wide variety of damages including cracks, features induced material loss, discoloration, deposit of biological colonization (Sánchez-Aparicio et al., 2022, p.18).

Thermal information can also be used for maintenance of buildings. Thermograms can be used to identify regions that can't be detected by visible light. Qualitative evaluation of thermograms allows for the identification of damage such as moisture, detachment of rendering mortar, mold growth and crack formations. Frequent inspections can be conducted to identify defects and to repair and preserve historical buildings (Resende et al., 2022, p.9-11). The presence of moisture and lack of maintenance programs leads to mold growth, vesicle formation, paint disintegration, frame corrosion and detachment of mortar. Thermal data gives the ability to detect the deterioration of building facades and erosion of decorative, historical and cultural elements of buildings (Resende et al., 2022, p.7).

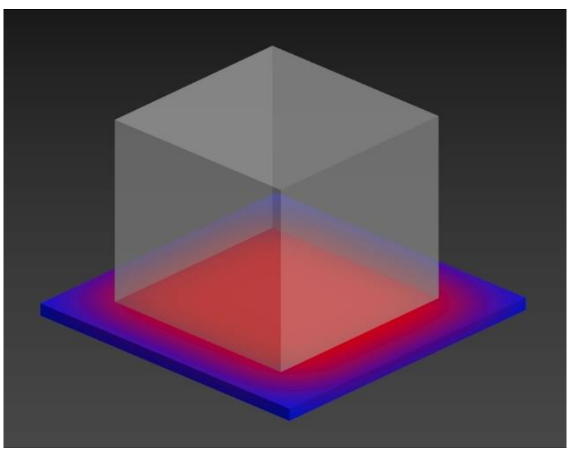
Radiometric data can be integrated into point clouds that help in the evaluation of buildings. Radiometric data and features integrated into point clouds such as intensity and color information assist in the evaluation of damages in a structure (Sánchez-Aparicio et al., 2022, p.16). Thermal point clouds can also be generated by combining 2d digital and thermal imagery in order to conduct energy performance analysis of buildings (Wang & Kim, 2022, p.20). \

3.1.3. Thermal Infrared Point Clouds Integration

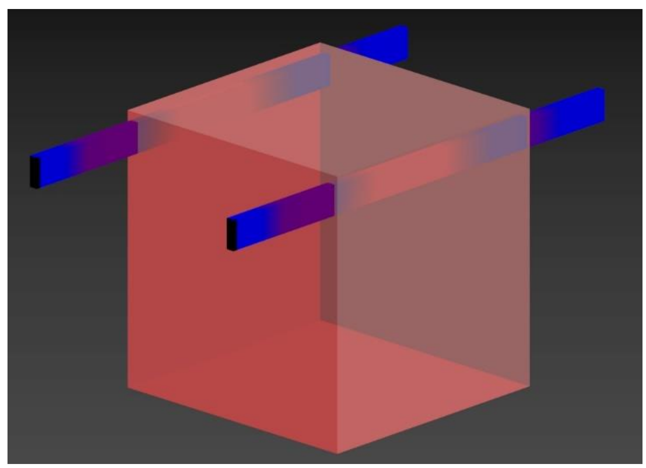
Photogrammetric thermal 3d point clouds are sources of information that highlights both radiometric qualities, color properties as well as its 3-dimensional geometric form (Sánchez-

Aparicio et al., 2022, p.3). There are dual-head consumer grade RGB and thermal infrared cameras that can be mounted on drones, in which the traditional RGB camera data can be used to construct 3d point cloud data, while the thermal data can be applied to the point clouds (Javadnejad et al., 2020, p.9). Point clouds are created by the RGB cameras due to its ability to generate high density points, then overlayed with the thermal data for visual data (Javadnejad et al., 2020, p.29). Thermal point clouds could be generated from using consumer-grade devices with commercial software by using georeferencing to identify ground control points from images (Javadnejad et al., 2020, p.19). Georeferencing is the process of aligning geographic imaging with real-world locations in GIS software (Carleton College, 2023). Research is being done on fusing infrared and RGB images collected from dual-head camera systems mounted on UAVS to generate 3d point cloud data with RGB and thermal data (Javadnejad et al., 2020, p.4).

Thermal infrared point clouds have found a variety of uses in structural assessments. The combination of thermal infrared radiation sensors, UAVS and point clouds are widely used in construction for inspection and assessing the condition of engineering systems (Dabetwar et al., 2022, p.2). Once integrated into a unified coordinate system, the thermal information captured by thermal imaging systems compliments the deformation of buildings by detecting cracks, features induced by material loss, identify discoloration, deposits and biological colonization and thermal bridges (Sánchez-Aparicio et al., 2022, p.9). Advancements in technologies and methodologies shows how thermal infrared radiation can be combined with structure from motion to assess changes in structures, by capturing data over time and evaluating the temperatures of selected points in the 3d models (Dabetwar et al., 2022, p.4).



Thermal bridges are areas of a building where heat flows from the interior towards the exterior due to discontinuity of construction materials or the building's geometry (University of Padova, 2023).



Materials are categorized by its thermal resistivity (R). Metals tend to have higher thermal conductivity (Boston University, 2023). Heat from the interior may be transferred outwards through metallic materials.

The integration of infrared thermography with lidar is common in building energy analysis (Javadnejad et al., 2020, p.6). Fused thermal and RGB 3d models offers great potential for mapping heat loss, supplementing non-destructive testing of structures and aiding inspection of electrical parts (Javadnejad et al., 2020, p.34). Infrared sensors are able to detect temperature profiles, which allows detection of differences in surface temperatures due to defects under materials that affect heat flow (Resende et al., 2022, p.4). In addition, infrared data with RGB obtained from UAVS enables the detection of heat loss from windows (Javadnejad et al., 2020, p.7).

3.1.4. Using Thermal Point Clouds to Reduce CO_2 Emissions

The energy used by the building sector in America accounts for 20% of the total energy worldwide and contributes to 36% of the nation's CO_2 emissions (Dabetwar et al., 2022, p.1). Built environments are responsible for 37% of global greenhouse gas emissions annually, reducing the building sector's emissions depends on addressing the energy consumption of existing buildings (Su et al., 2023, p.2]. It is therefore an important task in trying to lower carbon emissions created in the building sector. Lowering carbon emissions can be done by using improved energy assessment methods (Dabetwar et al., 2022, p.1).

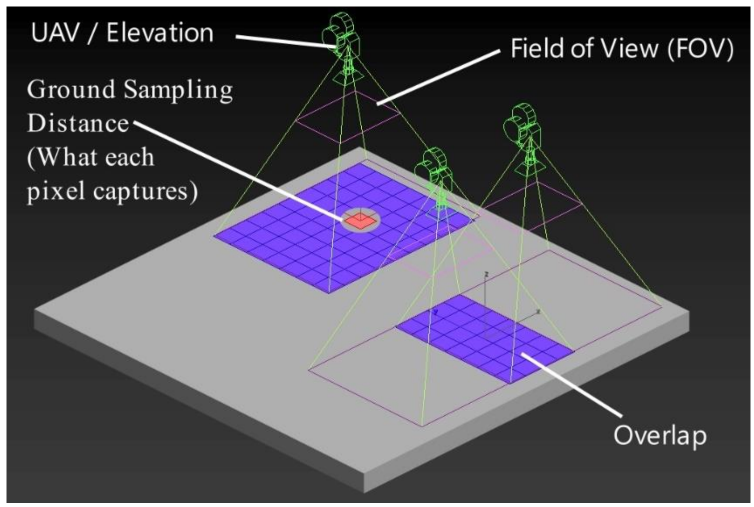
Although producing the necessary data for urban scale energy simulation purposes is time consuming and laborious, especially when reconstructing building geometry information (Su et al., 2023, p.7), Thermal point clouds are being researched in order to reconstruct 3d models in urban scales that can be helpful in surveying building facades for energy assessment (Su et al., 2023, p.6).

There have been many advancements in using thermal point clouds in assessing a building's energy efficiency which can lead to maintenance and improvements in a building's design. Thermal 3d point clouds can generate renderings of inefficient heating in aging structures aiding energy efficiency assessment (Dabetwar et al., 2022, p.1). By locating places of heat loss, maintenance plans can be made to reduce heat loss and retrofitting damages early in the structure's life (Dabetwar et al., 2022, p.2). Thermal infrared radiation point cloud data has been used for energy audits, but in the future can be used for structural assessment and inspection to create efficient building maintenance plans and structural health monitoring (Dabetwar et al., 2022, p.3) Thermal inefficiencies can be conducted by using drones and surveying areas for water infiltration and heat leaks (Dabetwar et al., 2022). Thermal point clouds had shown the ability to find heat exhausts underneath roofs of buildings and leaking underground steam pipelines. It is also capable of creating high definition 3d models of targeted structures where heat leaks from multiple locations can be seen. Thermal point clouds allow the detection of heat leaks from multiple regions and detects subsurface defects that results in energy leaks. Research demonstrates 3d model generations can assist in determining the location and severity of energy loss (Dabetwar et al., 2022, p.20)

4.0. Difficulties of Thermal Infrared Radiation Data

There are many factors that make using infrared data difficult. Temperature differences play a significant role in the identification of the type and size of defects (Dabetwar et al., 2022, p.13). Infrared images have also been observed to show different temperatures based on angles of approach, affecting the accuracy of the point clouds (Dabetwar et al., 2022, p.2). Many variables of the cameras affect the quality of the thermal images which includes, thermal resolution, the angle related to the camera lens, geometric resolution of the field of view (Resende et al., 2022). The objects within the images also affect the accuracy of thermal images that includes, the emissivity, distance from the camera, reflections, temperature and relative humidity. All of these variables affect the accuracy and interpretation of thermograms. Radiation emitted by objects are attenuated by the atmosphere, the presence of water vapor, temperature variation and ambient temperature influences accuracy (Resende et al., 2022, p.4).

Infrared cameras tend to have lower resolution and fewer features than cameras capturing the visible-spectrum. Traditionally, structure from motion relies of detecting features like edges, shapes, colors or textures, which are abundant in RGB images (Dabetwar et al., 2022, p.6). The resolutions of infrared images are still poor compared to traditional RGB images. Reflectance, low resolutions and sensing errors are still a barrier impacting the accuracy of infrared point clouds (Dabetwar et al., 2022, p.4). The low resolution of infrared cameras produce imagery with coarse ground sampling distance that reduces details and impacts the accuracy of 3d models (Javadnejad et al., 2020, p.4). Ground sampling distance is the distance between the UAV and the ground, and the ratio between each pixel distance from the captured ground distance (Fraundorfer, 2023). The higher up the UAV from the ground, the more ground is captured at the cost of spatial resolution. Overlap, camera resolution, focal length and the altitude of the UAV's flight path affects the spatial resolution of ground objects (Fraundorfer, 2023). FLIR images from surveillance cameras and UAVS are still limited by poor resolution and contrast and have low signal to noise ratio (Sanna & Lamberti, 2014, p.2). There are still considerable differences in the quality and accuracy between traditional RGB images with thermal infrared images (Javadnejad et al., 2020, p.27).



Drone flight path & image captured variables

In addition, overlapping is another factor that impacts the accuracy and precision of thermal point clouds. Point clouds only generated from infrared images still faces difficulties because of overlapping point clouds with different thermal values resulting in lower accuracy (Javadnejad et al., 2020, p.35). Inaccurate thermal readings and thermal drift can cause overlapping infrared images resulting in different thermal values at the same location (Javadnejad et al., 2020, p.30), therefore, technological advancements are still needed for meeting accuracy standards. RGB images are able to create quality point cloud data, but thermal infrared images still have a high failure rate and poorer accuracy in comparison (Javadnejad et al., 2020, p.35).

There are some proposals on improving the plausibility of thermal point clouds. Some methods were used in order to reduce external factors influencing thermal images for example conducting surveys after sunset to reduce the effects of solar radiation that could result in shallow or locally heated areas in the images (Dabetwar et al., 2022, p.19). There are also devices that are capable in creating thermal point clouds. Developments of hybrid LiDAR systems can construct 3d thermal models consisting of point clouds of building geometry data on each point (Wang & Kim, 2022, p.20). However, professional laser scanners are still inaccessible to the general public due to their high costs.

Further research still needs to be conducted. Thermal infrared point cloud data still needs to be standardized and the quantification of energy loss of structures is an involved process and not a trivial task (Dabetwar et al., 2022, p.22). There is still additional research needed to determine the optimal flight paths for accurate infrared point cloud building reconstructions (Dabetwar et al., 2022, p.1). Lastly, direct Structure from Motion processing of only thermal infrared radiation images is challenging and has a low chance of success (Javadnejad et al., 2020, p.27).

4.1. Difficulties of 3D Point Cloud Data

Processing point clouds still require manual intervention that requires a significant amount of time and effort. Point cloud processing requires users to understand and have access to commercial and open-source software. Automation in this field is still in development to improve efficiency. Limitations of technology and software development makes processing point clouds time-consuming and costly (Sánchez-Aparicio et al., 2022, p.23).

The success rate and quality of 3d models generated from point cloud data is varied based on images and the complexity of the objects being reconstructed. The most commonly encountered issues are related to vegetation partially covering the building. Sharp shadows, sunlit shiny surfaces or leafless vegetation can influence the photogrammetry algorithms leading to flawed camera alignment and degraded models (Su et al., 2023, p.3). External factors like vegetation and weather conditions like snow can create artifacts in texture maps and may negatively impact the accuracy of 3d models being generated by the point clouds (Su et al., 2023, p.6). Complex decorations, distortions and highly reflective materials will reduce the accuracy of model generation and result in inaccurate geometry or poorly mapped textures as well as high-contrast shadows will also influence the accuracy of photogrammetric models (Su et al., 2023, p. 6).

Optimization is still a barrier in regards to using point clouds. Having more points in a cloud does not necessarily equate to having better quality. In real applications, computational efficiency and optimization is important to reduce workload and processing time (Dabetwar et al., 2022). A factor that influences processing time is flight paths. Flight paths influence the quality of point cloud data and having more images may only add on more redundant point cloud data that will slow the processing time (Dabetwar et al., 2022, p.14). Some programs like CloudCompare may be used to measure image redundancies (Dabetwar et al., 2022, p.15). If flight height is increased the number of images collected for the same area is reduced which results in decrease in the quality of images. Lens distortion amplifies when flying at higher altitude and thermal cameras used results in fish eye distortion and lowers the quality of thermal point clouds (Dabetwar et al., 2022, p.18).

5.0. Research Proposals

Most of the papers researched were concerned with the exteriors of buildings. Using thermal point clouds in building interiors to evaluate the building's internal thermal dynamics would be helpful in inspecting a building's heating, ventilation and air conditioning (HVAC) inefficiencies. Locating heat flows within a building may help detect moisture and mold buildups in buildings.

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