

**Close Range
Photogrammetric
Applications for 3-D
realistic reconstruction of
objects using still images**

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March, 2013

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Dedicated to my parents.....

ABSTRACT

There are several methods by which 3D models of objects can be generated using close range photogrammetric software. Open source and free to use software are a low-cost alternative to the professional software available for cultural heritage documentation. These open source software are gaining popularity as their accuracy and efficiency is improving in close range photogrammetric applications.

This project evaluates the accuracy of three point cloud based modeling software, two open source and free to use software (PMVS and Autodesk 123D) and one professional software (PhotoModeler). The project also aims to apply CAD-like modeling for the reconstruction of Tibetan monastery using Autodesk ImageModeler. In CAD-like image based modeling comparative analysis of model and survey measurements of the building structure are assessed. Results show that the open source and free to used software are more accurate than the professional software. The Empirical accuracy of the two open source and free to used software is more than that of the professional software that was used.

The results for the CAD-like modeling revealed that the accuracy of the model created was very high which means that the difference between the 3D model and survey measurements was minimal. 3D primitives' generalization, orientation accuracy and measurement uncertainties influence the deviation between wireframe model and textured model of structure.

Keywords: Close range photogrammetry, Cultural heritage documentation, Point cloud, CAD-like modeling, primitives, image based modelling

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LIST OF ABBREVIATIONS

CRP: Close Range Photogrammetry
MVS: Multi-view stereo
PMVS: Patch Based Multi-view Stereo
RANSAC: Random sample consensus
CAD: Computer aided design
SIFT: scale invariant feature transform
SfM: Structure from Motion
SURF: Speed up robust features
CityGML: Citygeography markup language
TLS: Terrestrial laser scanning
DEM: Digital elevation model
SLR: Single Lens Reflex
GCP: Ground Control Points
GPS: Global Positioning System
CCD: Charged Coupled Device
CSG: Constructive Solid Geometry
ISO: International Organization for Standardization
DoGs: Difference of Gaussians
UTM: Universal Transverse Mercator
WGS: World Geodetic System
RMS: Root Mean Square
PCM: Point Cloud Mapper

1. INTRODUCTION

Advancement in computer vision and photogrammetry is changing human perception to examine and analyze objects in 3D virtual reality. Evolution of computer vision and photogrammetric technology has introduced flexibility and efficiency in the creation of 3D realistic models. In addition to this, easy availability of cheap hardware and software has driven development in the field of computer vision and digital photogrammetry in the technology sphere. Close range photogrammetric applications have made it possible to create 3-D realistic reconstructions of heritage buildings, archaeological monuments and other objects of interest. Virtual tourism, emergency response systems and urban planning are few of the areas where close range photogrammetric applications have been successfully applied.

A single camera, a stereo set of cameras, or a multi-camera system is used to collect image data of an object and then recover the 3D structure of the scene by using Structure from Motion (SfM) techniques[1]. This method of collecting data using a consumer camera is fast gaining popularity in projects that model and catalogue architecture and cultural heritage buildings as this technique is relatively low cost compared to the traditional methods like (survey, laser scanning) that are used in photogrammetry. Monuments that have significant cultural and historical value are of great worth as they symbolize the history of a certain culture of community. These important structures need to be protected and maintained. Close-range photogrammetry techniques for cultural heritage documentation have proven to be efficient in the maintenance and cataloguing of monuments. The structure used for this project on ‘Close Range Photogrammetric Applications for 3-D Realistic Reconstruction of Objects using still Images’ has several environmental issues that need to be addressed at the planning stage of the project. This is because the study area is situated in a region that experiences heavy monsoon rainfall and is also prone to earthquakes.

This project focuses on the cultural heritage documentation of a Tibetan Buddhist Monastery in India. The cultural heritage documentation is carried out using two methods. One is point cloud based 3D modeling (PMVS, Autodesk123D and PhotoModeler) and the other is CAD-like model reconstruction (Autodesk ImageModeler). The project also concentrates on two groups of software that reconstruct the model of one such culturally significant building. The empirical accuracy of software are compared to see whether they are similarly efficient in the 3D reconstruction of monuments. The first type of software is open source (PMVS) and free to use cloud based (Autodesk 123D) web application. The second is commercial software such as PhotoModeler for point cloud modelling and ImageModeler for CAD-like modelling. Point cloud modelling is used for volumetric measurements that are used in applications like cultural heritage building maintenance. The point cloud helps in understanding the volume of the object and how the different portions may have shifted over the years. CAD-like modelling, on the

other hand, can be used for creating virtual reality as it texture the model that is of high quality. PhotoModeler is able to create a photorealistic environment.

The first step is to construct a point cloud based 3D model using 123D, PMVS and PhotoModeler. The second step is to construct an image based 3D model using Autodesk ImageModeler.

Two assessments have been carried out in this project. The Empirical accuracy (internal/external) is compared of the various point cloud based models (PMVS, Autodesk 123D and PhotoModeler) for surface planarity. In CAD like image based modeling (Autodesk ImageModeler) comparative analysis of model and survey measurements of the building structure is assessed. The degree of generalization, measurement uncertainties and orientation accuracy are examined in primitive analysis. The image data used for both of these approaches will be the same.

1.1. Close Range Photogrammetry

Photogrammetry is basically a technique that involves extraction of 3D information from photographs. Photogrammetry has evolved in such a way that one can derive 3D information from any type of image (satellite, aerial or terrestrial) as long as there is an overlap between the images. The new digital cameras, computers and software that are available today have helped photogrammetry evolve as it can now be applied to a wider range of situations.

Close Range photogrammetry (CRP) is not entirely different from the traditional aerial photogrammetry and the same techniques used in aerial photogrammetry can also be applied to close range photogrammetry. The cost of the entire process of acquiring, processing and analyzing has been reduced dramatically over the years. Close-range photogrammetry has especially benefited from evolving low cost and efficient technology.

1.2. Motivation and Problem Statement

The main focus of this project is to assess the utility of open source tools and cloud based web applications in comparison to professional software. A 3D realistic model of a heritage building will be constructed utilizing 3D processing methods that employ both the free open source approach and professional software approach. The study will demonstrate qualitative analysis of both of these approaches for the cultural heritage documentation. Point cloud analysis will be assessed between 123D, PMVS¹ and PhotoModeler. The image based model of the building will also be reconstructed and assessed in ImageModeler² for measurement errors.

¹ <http://grail.cs.washington.edu/software/pmvs/>

² <http://usa.autodesk.com/adsk/servlet/pc/index?id=11390028&siteID=123112>

The commercial software available for the 3D modeling and cataloguing for cultural heritage documentation are expensive and therefore cannot be commonly used. Open source and point cloud based software such as Autodesk 123D and PMVS are also used for 3D reconstruction of objects. This project aims to compare the utility of open source/cloud based and professional tools in 3D processing by constructing 3D models using images from a consumer camera. It focuses on the low cost technologies for 3D realistic reconstruction of objects to advance the level of visualization and analysis and aims to provide a low cost alternative to the commercial software available today. The project also aims to assess the quality of point clouds of the 3D models. Another goal of this project is to carry out 3D reconstruction using CAD-like modelling. The CAD-like modelling is done to understand how primitives can be manipulated to come up with a complex model.

1.3. Research Identifications

1.3.1. Research Objectives

- To assess the quality for free to use software with professional softwares used in close range photogrammetry.
- Empirical accuracy assessment of 3D point clouds of building.
- Analysis of primitives in CAD-like model for realistic reconstruction of cultural heritage monument by applying close range photogrammetry.

1.3.2. Research Questions

1. What is the orientation accuracy of 123D model when local coordinate system is transformed to global coordinate system using transformation parameters?
2. How is qualitative relation of point clouds based on internal accuracy assessment?
3. How much is the external accuracy of point clouds using plane fitting method?
4. What is the accuracy of CAD like model compared to ground truth measurements?
5. How orientation accuracy, degree of generalisation and measurement uncertainties influence deviation of 3D primitives in modelling process?

1.4. Innovation Aimed at

Three point cloud modeling software for the cultural heritage documentation have been compared to evaluate whether open source and free to use software are as robust and efficient as professional software. CAD-like modeling software have also been used to model complex architectural buildings by manipulating basic primitive shapes. The effect of the manipulation of basic primitives on the deviation between wireframe model and texture model in terms of degree of generalization, measurements uncertainties and orientation accuracy has been assessed.

1.5. Thesis Structure

Open source and cloud based software such as Autodesk 123D and PMVS are used for 3D reconstruction of objects. This project aims to compare the utility of open source/cloud based and professional tools in 3D processing by constructing a 3D model using images from a consumer camera. It focuses on the low cost technologies for 3D realistic reconstruction of objects to advance the level of visualization and analysis. Chapter 2 looks at the various studies that have been carried out by other researchers in the same field. Chapter 3 introduces the study area and the dataset used in the current project. Chapter 4 presents the methodology and software used. It describes the strategies implemented in the generation of point cloud and CAD-like models. The results and discussion are presented in Chapter 5 and conclusion follows in Chapter 6. Chapter 7 gives recommendations for further research.

2. LITERATURE REVIEW

2.1. Introduction

Image based modeling is a process in which information about an object is extracted from two or more images in order to come up with a 3D model of an object of interest. The 3D model is then used for various purposes like recording of historical buildings, virtual museums, upkeep of monuments, etc. Image based modeling is becoming an essential tool in the planning of all architectural projects. This research on ‘Close Range Photogrammetric Applications for 3D realistic reconstruction of objects using still images’, focuses on the utility of open source tools and web-based services in comparison to professional software. The research constructs a 3D realistic model of a heritage building utilizing 3D processing methods that employs both the free to use and open source approach and professional software approach. It demonstrates qualitative analysis of both of these approaches for the cultural heritage documentation. The accuracy of image orientation parameters is compared using 123D³, and PhotoModeler⁴, while point cloud analysis is carried out and evaluated between 123D, PMVS⁵ and PhotoModeler. The image-based model of the building has also been reconstructed and assessed in ImageModeler⁶ for measurement errors.

2.2. Point Cloud Modelling

The paper written by Agarwal *et al.* [1] discusses the construction of 3D models of various cities using photographs that are updated by people on the net. Knowing camera angles can help in the triangulation of 3D points. Same features from across the images are matched in order to create a 3D version of them. This process is known as the feature matching process. Feature matching is able to retrieve camera positions and 3D points. The detection of various features leads to the generation of a sparse point cloud. The feature matching process is carried out using SfM (Structure from Motion) techniques which use SIFT (Scale Invariant Feature Transform) algorithm for detection of features. The depth estimation for all 3D points is done using a multi-view stereo algorithm (MVS). The impression of depth is created when the line of sight from two viewpoints intersects. MVS uses many viewpoints of the same feature to create an estimation of depth. It uses a window matching technique to match features in consecutive images. This type of matching is prone to various types of errors; the difference in the brightness of images causes them to not match or areas that are uniformly colour match even when they are not supposed to. These issues can be tackled by using robust matching. In order to make the point cloud denser,

³ <http://www.123dapp.com/catch>

⁴ <http://www.photomodeler.com/>

⁵ <http://grail.cs.washington.edu/software/pmvs/>

⁶ <http://usa.autodesk.com/adsk/servlet/pc/index?id=11390028&siteID=123112>

the depth for all of the pixels in all of the images is estimated. These 3D points are then added to the model. My study also uses the patch-based Multi-view Stereo (PMVS) method to detect and match features across images.

Khoshelham [2] paper on accuracy analysis of Kinect depth data discusses depth data that is obtained with the help of the Kinect sensor and the geometric quality of this data. Kinect, a recently launched range sensor by Microsoft is a low-cost alternative to laser scanners. The sensor is able to capture images with colour and depth at the same time. This combination of depth and colour creates a point cloud that includes approximately 300,000 points in a frame. This can be extremely helpful in the creation of an indoor point cloud in real time. It is essential to carry out an analysis of the systematic errors and random errors present in such sensors so that the complete potential of the sensor can be utilized. A mathematical model of depth measurement helps in measuring a theoretical error for the data. This theoretical error helps us analyze the various factors that have an influence on the accuracy of the data. The results illustrate that random error in depth measurement increases as distance from the sensor increases. The range of random error can be anywhere up till a maximum of 4 cm. Another major influencing factor that affects data accuracy in depth measurements is low resolution. The paper concludes that data for these sensors should be obtained inside a range of 1 to 3 m. Distances beyond this range result in lower resolution data with a higher level of noise. The mathematical model used by Khoshelham to study the depth accuracy of 3D planes is somewhat similar to the mathematical model used for calculating depth accuracy in the present study.

In their paper Fathi and Brilakis [3] present a low-cost alternative to the high cost, far-ranging spatial data collection methods that are generally used for obtaining geometric data on various infrastructures today. This method allows for an automated stereovision and creates a 3D point cloud of an object using two video streams. SURF feature matching algorithm is able to automatically detect and match a pair of stereo video frames. Triangulation is used to compute the 3D coordinates of the matching features. RANSAC is used to detect and remove those features or outliers from the images that do not match. The next step is to use the ‘quaternion motion estimation method’ as well as ‘bundle adjustment optimization’ in order to record all of the point clouds. The validation of these point clouds was carried out by randomly selecting various feature points and evaluating their spatial distance with the distance recorded using tape measurements. The current project (Close Range Photogrammetric Applications for 3D realistic reconstruction of objects using still images) also uses a RANSAC algorithm to detect and remove outliers. The difference is that the present study uses the RANSAC algorithm to remove the outliers from 3D planes of point clouds in Empirical Accuracy Assessment.

The paper by Bartelsen *et.al* [4] charts out a method of 3D reconstruction that is carried out using images that are taken from consumer cameras. The paper claims to have improved on several methods used in other studies. These methods include ‘least squares matching, RANSAC, scale-space maxima and bundle adjustment, for robust matching and parameter estimation’. The other

difference in their method is that the authors have used ‘wide-baseline image sets’ in their research. Their improved methods have made it possible for the user to orient images in conditions that are not optimal. The user can now orient images that have scale differences or even images in which illumination changes. The paper presents a method that uses wide baseline image sets to generate automatic orientation and dense reconstruction. Accuracy of image orientation will be analyzed in my study to make the 3D model finer in detail. This paper gives possible improved method to generate automatic image orientation of unordered terrestrial wide base line images using same algorithms (RANSAC etc.) employed in free software in 3D processing pipeline in my study.

2.3. CAD-like Modeling

Fan *et al.* [5] present their paper on the advantages of City Geography Markup Language (CityGML). A generalization algorithm is used in integration with CityGML to decrease the storage space of 3D buildings significantly while retaining as much information about them as possible. Various algorithms that deal with the generalization of 3D objects in order to reduce storage space are available today but none of them take into account the semantic information related to these objects. This leads to the removal of vital visual information or can lead to the integration of features that do not belong together. CityGML does take into account the semantic information of the 3D objects, which is why even the small features of a building like its windows and door are modelled. Simplification and aggregation are used to generalize various features. The effects of generalization on the geometric objects of the building in 3D CAD-like model are considered my study.

Zhao *et al.* [6] discuss ‘detailed 3D modeling’ in their paper. The importance of ‘detailed 3D modeling’ in areas like cultural heritage documentation and ‘emergency management’ are discussed. Detailed models involve the modeling of complicated and elaborate feature of buildings, which leads to incredible amounts of data being generated. The existing ‘computational power of modern software’ cannot keep up with the pace at which 3D data is being generated today (Du *et al.*, 2008). Due to the high generation of data in detailed models users prefer more generalized depictions of structures. The current algorithms available for generalization of features are made for buildings that are more regular in shape. The paper by Zhao *et al.* gives a ‘mathematical morphology-based algorithm’ that is able to generalize in a more uniform way. The study applies this algorithm to buildings that are classically Chinese and to modern buildings as well to show the efficiency of the ‘mathematical morphology-based algorithm’. The generalized features of the building are also used in my present study.

The paper by Giordano *et al.* [7] discusses the importance of ‘flexible geometry’ in the documentation of structures that are both complex and realistic. ‘Flexible geometry’ is the answer to creating and maintaining details of a structure. They have used hypertext for the representation

of geometrical entities and simulations of possible structures. The management of the architectural geometry of cultural heritage using CAD-like reconstruction has been presented in detail in this paper.

2.4. Culture Heritage Restoration

The paper by Arias *et al.* [8] studies the maintenance of colossal buildings. Various methods of architectural documentation are discussed in this paper. The cultural value of these monumental buildings makes it necessary for us to preserve information on these buildings. Documented information is necessary for the upkeep for these monuments. Close-range photogrammetry methods help in documenting information on these heritage buildings. The computer and close-range photogrammetry methods discussed in this paper facilitate the detection and quantification of any displacement, in three dimensions, that may have occurred in such monuments of cultural interest. The information that is obtained from these methods is also continuous and is distributed evenly. The data provided from close-range photogrammetry techniques can be useful in the pre-processing stages as well as the post processing stages. Reconstruction is also another area in which photogrammetry methods can be of great value as they help in keeping the original geometry of the building intact. CAD-like modelling for cultural heritage restoration has been explored well by Arias *et al.* It is also the main theme of this current study. The difference is that the current study does not explore the structural problems faced in the documentation of cultural heritage buildings.

Butnariu *et al.* [9] have, in their paper, fashioned a 3D modeling methodology that can be used for the virtual restoration of various objects. The methodology follows an image based modeling technique. This technique generates a textured mesh for the 3D object using 2D images of that object. The first step is to acquire images of the object, then process those images and use them in the 3D reconstruction of the study object. The last step is to carry out restoration of the 3D virtual model. A variety of frameworks and tools are used in the 3D image-based modeling of objects. The main advantage of this process is that the methodology presented fashions the 3D modeling and virtual restoration process in a cost effective manner. A portion of the present study also focuses on the image-based modeling of objects for cultural heritage restoration. The similarity between this article and the present study is that both use a cost-effective methodology to generate 3D point clouds of their objects of interest.

The paper by Lerma *et al.* [10] focuses on the documentation of archaeological sites and objects. It does this by using terrestrial laser scanning technology. The study uses TLS to 3D model Palaeolithic caves with engravings on them. The authors have used TLS in order to generate 'digital surface models' of these caves. TLS, alone though, is not enough to create high-resolution models of these caves. Close range photogrammetry is used in addition to the TLS to create realistic views of the paintings in a 3D environment. The main focus of the paper is to study how well the integration of TLS and close range photogrammetry works in generating life like models

of complex structures. Studies such as this are useful in restoring and understanding the ancient art.

The use of 3D models for the reconstruction of objects has become progressively popular. This has only become possible because of the advancement in the computational power of modern software and hardware, photogrammetry techniques and modeling software. Photogrammetric techniques are the most commonly used but they are expensive and take too much time. The paper by El-Hakim *et al.* [11] applied such technologies for the purpose of cultural heritage documentation. The authors have used image based modeling to create the basics of the buildings and laser scanning is used to fill in details.

The cultural heritage documentation of the ‘agro-industrial buildings’ present in Galicia; Spain is vital in maintaining the cultural heritage of the area. Arias *et al.* [12] present a compilation of ‘graphic and metric documentation’ by various authors. Arias *et al.* have outlined a low cost cultural heritage documentation process that is easy to implement.

Useful tools in the field of cultural heritage are ‘game engines’. These are used for managing and maintaining urban environments in real time. The paper by Merlo *et al.* [13] studies one such place; Pescia in Italy. Merlo *et al.* used a tool that surveys and manages data that deals with the technical maintenance and historical and traditional understanding of cultural heritage buildings. Their work carries our surveys of historical buildings and then 3D models them which are similar to my study.

2.5. Close Range Photogrammetry

Close range photogrammetry has proved to be quite useful in several fields. Samad *et al.* [14] have described its use in ‘volume computation’ well in their paper. The results of the study show that their project was able to attain an accuracy of more than 90% which means that it proves that photogrammetry is a useful tool to compute volume. Another paper by Samad *et al.* [15] explores the role that ‘digital close-range photogrammetry’ can play in the mapping portion of ‘Geomatic Engineering’.

In their paper Ahmad and Rabiou [16] study the use of photogrammetry in the generation of 3D models of various structures. Their study uses photogrammetric techniques to generate a 3D model of the University of Technology, Malaysia using AutoCAD, Erdas, SpacEyes and Google SketchUp. These models were compared for efficiency and accuracy by comparing the model measurements to ground measurements and it was seen that Erdas is the most precise. In their paper Rusu *et al.* [17] have reconstructed a 3D point cloud model of objects and have fitted geometric primitives to this 3D point cloud to create a map that contains meshes and ‘3D shape coefficients’ that are obtained from ‘robust shape segmentation and triangulation of surfaces’. The geometric primitives help in reconstructing data that is missing. These studies relate my project as in them model measurements are compared with ground measurements and also various software

are applied to generate 3D models of same structure.

The paper by Hamdani *et al* [18] looks into the modeling of buildings using ‘Digital Close-Range Photogrammetry’. In this paper 3D points have been extracted from 2D photographs of buildings. These images have been fed into the close range photogrammetric method and the output is a 3D model of the building or the structure. The study shows that photogrammetry is an efficient way of measuring and modeling objects in 3D. It proved the user with an environment where they can navigate buildings in 3D. This paper applies low cost photogrammetry techniques to reconstruct 3D model of buildings is also similar to my study which low cost techniques to build models of heritage structure.

The paper by Sanz *et al.* [19] outlines a method of creating 3D models of petro glyphs. Low-cost software and consumer cameras are used to model these works of ancient art. The study carries out experiments in three different areas in Spain. The accuracy of the models is evaluated using a calliper. Their study reveals that the low-cost software available today is an economically advantageous alternative to traditional techniques of 3D modeling.

Yilmaz *et al.* [20] explore the application of close-range photogrammetry in ‘measured drawing projects’. Close-range photogrammetric (CRP) techniques reconstructed the ‘measured drawings’ of the façade of a building, which had been burnt. CRP techniques are important tools in the 3D reconstruction, restoration and documentation of buildings that have cultural significance.

The high-resolution surveys of areas that are inaccessible come with high costs. The paper by Westoby *et.al* [21] proposes an alternative low cost method to acquire high-resolution data on these landscapes. This is a photogrammetric method known as ‘Structure from Motion (SfM)’. SfM can provide the user with high-resolution data of an area at various scales. Most of the traditional photogrammetric techniques require the user to input the 3D points and positions of the camera that captures the object of interest. SfM on the other hand needs no such input and is able to compute the camera sensor geometry using a feature-matching algorithm. The paper provides an overview of SfM and how it creates ‘high-resolution digital elevation models (DEM)’ from numerous images. In order to assess the effectiveness of the DEM created by the SfM technique the authors compare it with a DEM that has been created using a terrestrial laser scanner. The results show that SfM can obtain high accuracy even for those areas that have a ‘complex topography’. ‘An exposed rocky coastal cliff, a breached moraine-dam complex and a glacially sculpted bedrock ridge’, are then modelled using SfM techniques to show their effectiveness in modeling various landscapes of differing topography. The paper demonstrates that SfM is a low cost photogrammetric technique that is able to model landscapes of various complexities in such a way where the user does not have to manually identify the camera positions and control points. This makes it easy for even an amateur to carry out 3D modeling of various objects and landscapes. The present study also applies SfM in low cost close range photogrammetry

3. STUDY AREA AND DATASET

3.1. Study area

The Tibetan Buddhist Mindrolling Monastery that has been modelled for this project is located in the Dehradun, which is a valley nestled between the Himalayan foothills and the Shiwalik hills of North India.

The valley is also situated between two of India's largest rivers – the Ganges and the Yamuna. Dehradun is famous for its various temples and green landscape. Clement Town is the area in Dehradun where the temple is located. This area is highly influenced by Tibetan culture as many Tibetan refugees from China have settled here. The monastery complex spans an area of 8,100 m² and is located at 30.27°N 78.07°E. The height of monastery is 56 meters.

The Mindrolling monastery is also known as Buddha Temple and it was built in the year 1965 as it took fifty artists to complete the temple. The monastery is constructed using Tibetan Buddhist Architecture which includes robust geometric shapes in the structure. The temple area also has a 103 feet tall golden statue of the Buddha. The temple itself is a dome shaped structure that is surrounded by a garden. The unobstructed view of the temple from all sides makes it easy for the temple to be modelled. The surrounding garden area is plain and has no structures that block the view of the temple therefore it is relatively easy to take photographs of the temple from various angles. The base length and standard height between the photographs can also be easily maintained as there are less occlusions situated in the near proximity of the temple making it is easy to walk around it.

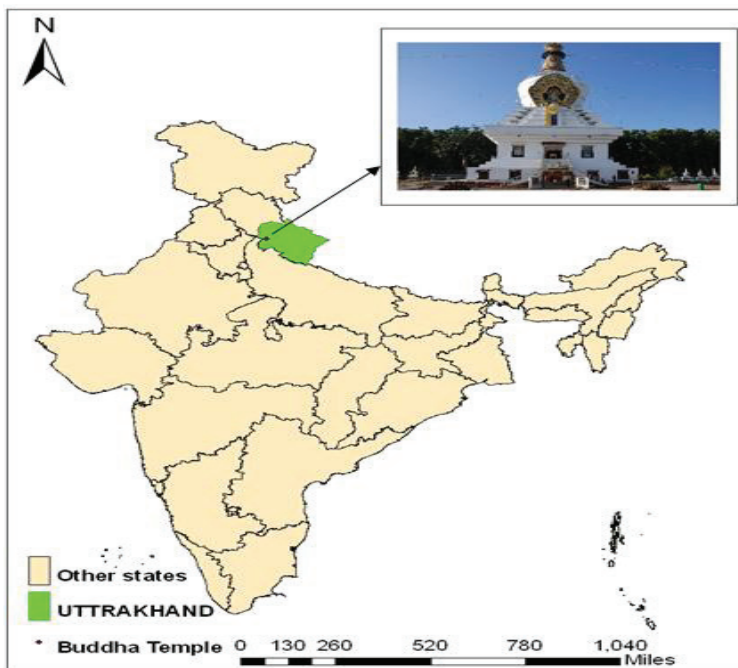


Figure 3-1 : Study Area

3.2. Dataset and Software used

Photographs of the Mindrolling monastery will be used to carry out 3D realistic reconstruction using Nikon D-80 SLR camera. The monastery is constructed in a typical Tibetan Buddhist architectural style. These photographs will be geo-referenced before they can be used for which the latitude and longitude of the objects will be collected using a GPS. Free software such as PMVS Autodesk 123D and PhotoModeler is used for 3D point cloud generation. Autodesk ImageModeler is used in CAD like image based modelling for cultural heritage documentation. Table 1 show the software and instruments used in this project.

Table 1 : Software and Instruments Used

NO.	ITEM	USE
1	PMVS	POINT CLOUD
2	AUTODESK 123D	POINT CLOUD AND ORIENTATION
3	PHOTOMODELER	POINT CLOUD AND ORIENTATION
4	IMAGE MODELLER	CAD-LIKE IMAGE BASED MODELLING
5	MATLAB	STATISTICAL ANALYSIS
6	LEICA GPS	GPS POINTS
7	NIKON D-80 SLR CAMERA	IMAGES
8	POINT CLOUD MAPPER	VISUALIZATION
9	CLOUD COMPARE	VISUALIZATION

4. METHODOLOGY

4.1 Methodology Workflow

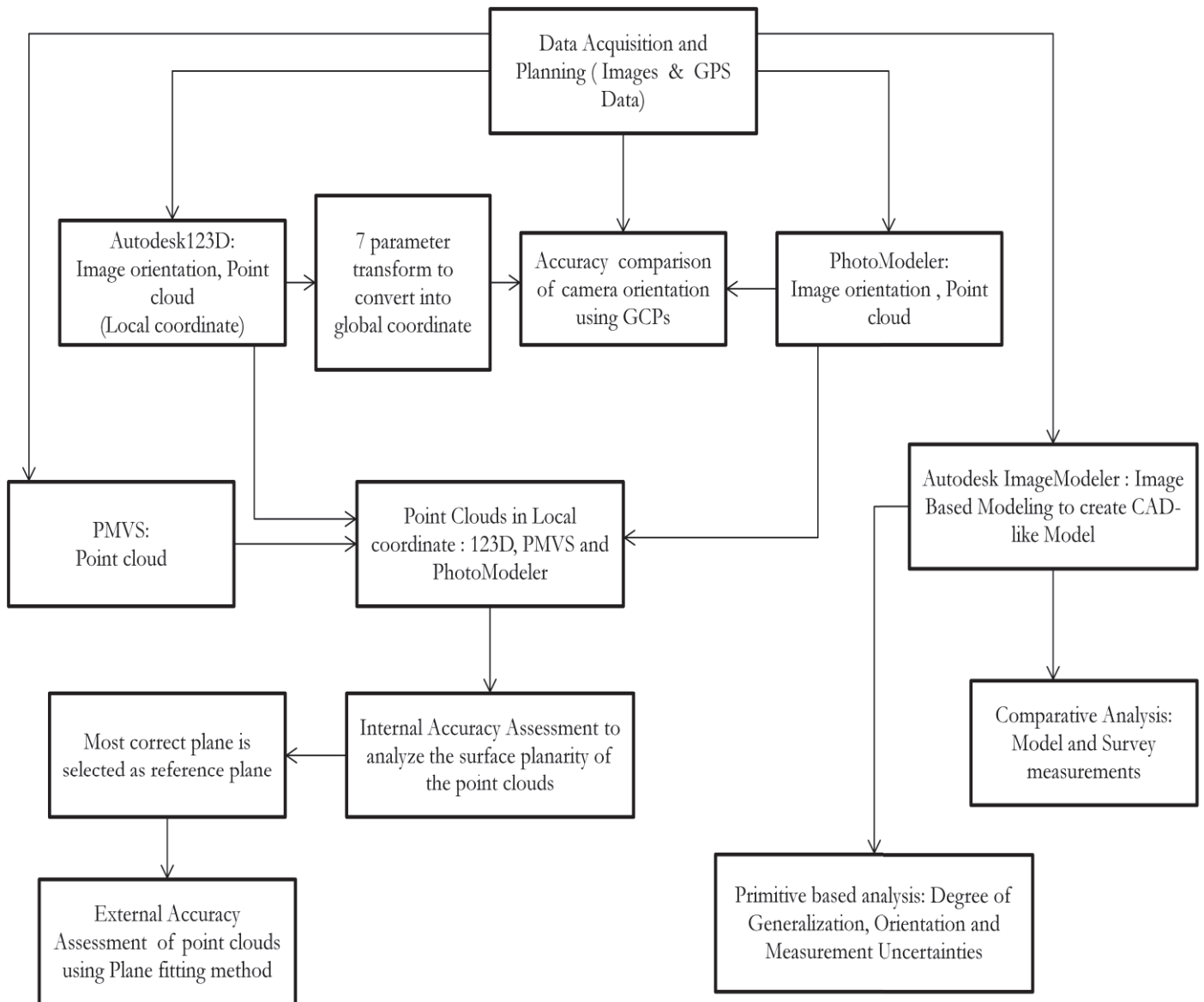


Figure 4-1 : Methodology Workflow Diagram

The first step to starting any project is data planning and acquisition. It is necessary to first realize the feasibility. The present project catalogues and models a cultural heritage building using PMVS, PhotoModeler, Autodesk 123D and Autodesk ImageModeler. The data that needs to be

obtained consists of taking terrestrial images of the monastery, a dome shaped building, using a Nikon D-80 SLR camera. GPS points for these images also need to be recorded using a GPS device. This is done in order to geo-reference the images for better model accuracy.

It is necessary to deliberate over which camera needs to be used for the data acquisition as it has a significant impact on the outcome of the project. The calibration of the camera also needs to be considered and its parameters and measurements need to be decided at the beginning of the project. The planning stage involves deciding on factors such as control points, photo locations, time needed to prepare the site. The close range photogrammetry plan is discussed in further detail later on in the report (section4.0).

Triangulation is vital to the principle of photogrammetry in 3D coordinates of a point in the space are recovered by spotting same point in the image using geometric method [22]. When images of an object are taken from two different angles, a line of sight can be developed using photogrammetric techniques. The photogrammetry process intersects the lines of sight and this result in the creation of 3D coordinate points of the object. Bundle Block adjustment is done to recover 3D point coordinates of the object and exterior orientation parameters [23], [24], [25]. Camera calibration is the very first step with which this process begins. In order to calibrate a camera, the digitizing scale (CCD format size of the digital camera), focal length of the lens and principal point need to be known. Overall residual RMS and the maximum residual determine the success of the camera calibration.

Autodesk123D, PhotoModeler and PMVS recover image orientation parameters from the image. In Autodesk 123D the images are oriented in local coordinate system and the model can then be transformed to global coordinate system with the help of GPS points using a seven parameter transform. In PhotoModeler, orientation parameters are recovered semi automatically using the GPS points as ground control points (GCP's). These GCP's acts as constraints in the bundle block adjustment.

Marking the calibration locators onto the 2D images carries out this process and in order to stabilize the calibration process the known the focal length of the camera is also fed into the software. On the other hand in Autodesk 123D camera orientation parameters are recovered fully automatically. Generating point residuals with the help of statistical analysis will help in assessing the orientation accuracy of the model in Autodesk 123D. Therefore, both free to use web application and professional software will be compared for image orientation. PhotoModeler, PMVS and 123D are software that generates point clouds of 3D models. Autodesk ImageModeler, on the other hand, is an image based modeling software that generates CAD-like 3D models.

A point cloud generated from Autodesk 123D and PhotoModeler will then be transformed into global coordinate system for assessment of orientation accuracy in point cloud analysis. The assessment of orientation accuracy is done in PhotoModeler itself and for 123D.

A point cloud generated from Autodesk 123D and PhotoModeler will then be transformed into global coordinate system for assessment of orientation accuracy. The assessment of orientation accuracy is done in PhotoModeler itself and for 123D 7 parameter transform is used to convert local coordinates into global coordinates and point residuals are generated to check orientation accuracy.

Point cloud analysis is applied under Empirical methods: internal accuracy and external accuracy in terms of quality aspects such as accuracy of individual points, occlusion of data points and point density [26]. Plane fitting method can be used to compare and assess the deviation of the point clouds in internal accuracy assessment but is relative to the object model. In external accuracy assessment, point cloud data will be compared with point cloud data of a higher accuracy using statistical analysis. Therefore point cloud analysis will be used to analyze and compare between free to use cloud based software (123D), open source software (PMVS) and professional software (PhotoModeler).

The image-based model of the building will be constructed by using the same images as the ones used for point cloud analysis. The images will first be calibrated in order to find camera pose estimation. A CAD-like model (wire frame model) using CSG based primitives will be formed in 3D image based modeling. The next step is to compare survey measurements with model measurements in order to analyze the accuracy of the entire 3D model. This was done as a ground truth analysis. The accuracy assessment is then carried out for the wire frame model and the 3D textured model (final result of the image based model). The accuracy assessment is done in order to evaluate the orientation accuracy, degree of generalization and measurement uncertainties present in the different modeling processes.

4.1. Close Range Photogrammetry (CRP) Project Plan

A CRP project begins with deciding the areas or objects that need to be photographed, the accessibility of the object, weather and light situation at the time, the accuracy of the final product, the format in which end product will be produced and various other requirements of the project. Once the requirements of the project have been decided one can begin the planning phase. The layout of the images is decided by analyzing the building and the obstructions around it. Then surveying is done to collect ground control points so that the end product can have a projection and coordinates to increase the accuracy of the final product. The GPS survey of the building is carried out and tape measurements of windows and walls of the building are also done for later references.

The terrestrial images acquired must be obtained in such a manner so that there are no oblique angles in the images. It also needs to be noted that the height of the camera must remain constant while capturing images of the object of interest from all sides so that a stereoscopic pairs can be produced. Various other parameters such as baseline, vertical opening angle, ground sample

distance and size of pixels are calculated in order to estimate a theoretical accuracy for the project so that the accuracy of the model can be later compared with the theoretical accuracy.

The theoretical accuracy is a benchmark for this close range photogrammetry project to assess Empirical accuracy of point clouds. There are two different approaches to estimate theoretical accuracy. The first is to decide certain accuracy and then planning according to that. The second is to plan according to the side constraints such as occlusions and base to height ratio and then estimate which accuracy is possible. The later approach was used in the current project. The reason for this is because there were numerous occlusions in front of the monastery. Another issue was the posterior side of the monastery has a low base to height ratio as the horizontal distance between the building and the camera sensor was very less due to space limitation. These side constraints were limitations that could not be overlooked and had to be modelled into the close range photogrammetry plan from the very beginning.

Point cloud errors are assessed based on the theoretical error budget and errors in observation. Theoretical accuracy has validated the 3D point cloud based models and CAD-like image based model for cultural heritage documentation.

4.1.1. Camera Technical Specifications

Camera Model: Nikon D80 Digital SLR Camera

Sensor: 10.2 million pixels and 23.6*15.8 mm CCD (DX Format)

Image Resolution: 3872*2597 (10.0MP)

Focal length: 18mm

Sensitivity: ISO 100-1600

Shutter Speed: 30 to 1/4000 sec

Image Format: JPEG and RAW

4.1.2. Camera Settings

The camera used for this close range project is a Nikon D80 digital SLR camera. SLR cameras are more likely to give improved results as they have lenses of higher quality as well as larger sensors as compared to compact digital cameras. The focal length of the camera is fixed at the beginning so that the process of capturing images can be more efficient. The focal length for this project was fixed at 18mm. The aperture of the camera was fixed at f10 in order to obtain a proper depth of field. The ISO range is approximately 100 for this particular CRP process. The ISO range of the camera defines the amount of light absorbed by the sensor. The photographs were stored in JPEG format.

Camera calibration is also done to adjust the camera with same settings as the stereo photos of the building. The camera is calibrated in order to compute the lens distortion and focal length, which affects the quality of the stereophotography. Calculating the lens distortion by calibrating the camera helps in accounting for and correcting the error the distortion may have caused. This camera calibration is done using PhotoModeler.

The flat sheet calibration method was used to calibrate the camera. The flat sheet is a sheet of target dots. Figure 4-2 shows the target sheet that was used in this project. The entire monastery is photographed at fixed 18mm focal length. The flat sheet is photographed from four different viewpoints and on every viewpoint two photographs were taken by rolling the camera at 90° . A total of eight photographs of the flat sheet were taken and were used to calibrate the camera in PhotoModeler.

The deciding factor for the fixed focal length to be at 18mm was the type and size of the building. The height of the building was 56m and the width was 28m. 18mm was the lowest focal length at which the entire building could be captured.

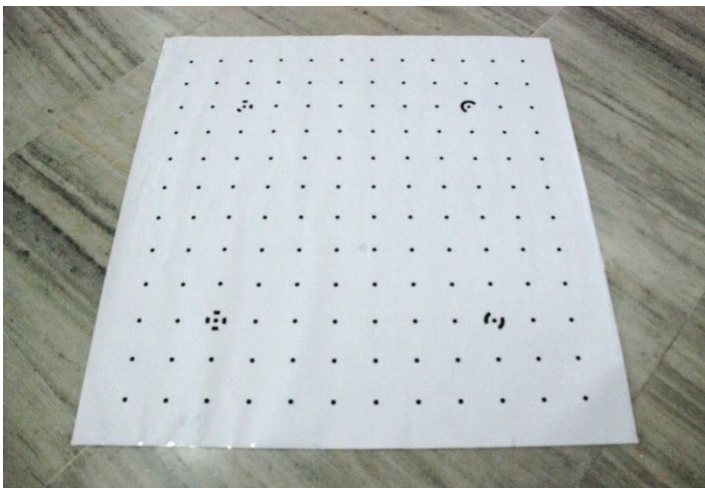


Figure 4-2 : Flat sheet for calibration

4.1.3. Terrestrial Based Data Acquisition

In terrestrial based data acquisition, images of the monastery are captured from all angles. During the acquisition process, height of the camera varies depending on the occlusions. Another measure that was maintained while carrying out this process is that the fixed focal length (18mm) of the camera was decided before the terrestrial based data acquisition.

It was tried that a distance of 30 m between the camera and the monastery should be maintained but this was not always possible due to occlusions and also due to a lack of space behind the monastery. To compensate the lack of space at the back, two photographs from different heights but the same position were captured using a pole on which the camera was mounted. Figure 4-2

shows a camera positions around the monastery. The images taken have an overlap of at least 60-70% in order to extract 3D information for reconstruction.

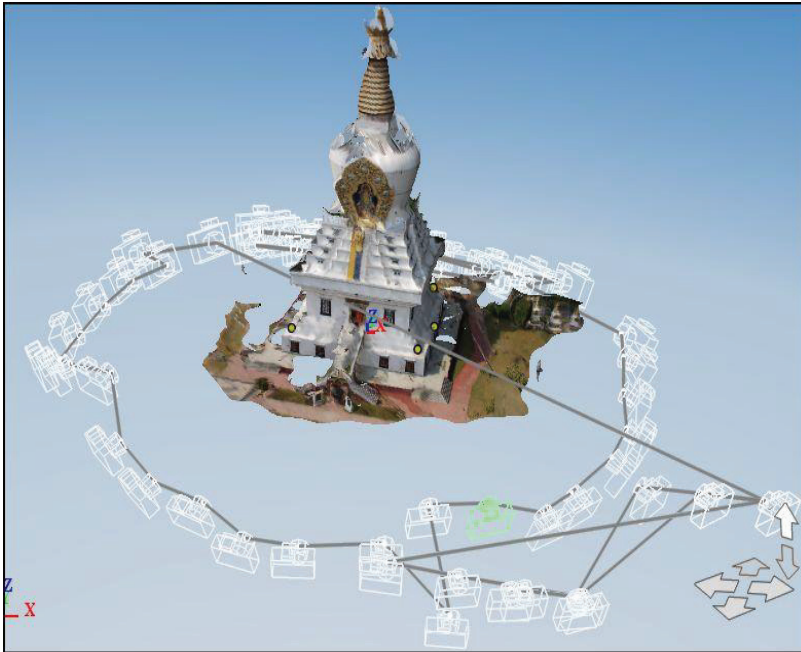


Figure 4-3 : Camera Sensor Geometry

4.2. Point cloud based Modelling

4.2.1. Point Cloud reconstruction with Autodesk 123D

Autodesk 123D catch is a cloud based web application that generates photorealistic 3D models from 2D digital images using cloud-computing technology. Cloud computing is a technology that brings together software, database services that are provided on the server (cloud), computation capabilities and access to data. Autodesk123D is able to generate 3D models from 2D photographs that are taken from an ordinary digital SLR camera. The captured images need to be uploaded onto the server through desktop client and 123D is able to create a 3D photorealistic model of the object. It does this by estimating the angle at which each image was taken and then generates geometry for that image. 123D even applies texture to the finished 3D model.

Feature matching algorithms present on the cloud are able to identify certain points on the surface of the object that are unique. These unique points are those points that are identical in two successive photos. In order for this to happen there needs to be a certain amount of overlap between two consecutive images. Structure for Motion (SfM) techniques applied extract 3D structure of the building using camera motion and positions [26]. The minimum overlap between successive images should be at least 60%. Autodesk123D uses photogrammetric techniques to estimate camera positions. The orientation of the images helps in creating a 3D point cloud that models the object.

123D uses a SIFT (Scale Invariant Feature Transform) detector. This detector follows four steps which are, 'scale space extrema detection, key point localization, orientation and descriptor extraction' [27]. In the detection phase, key points are identified using difference of Gaussians (DoG). Gaussian images are produced at different scales. The neighbours in scale space are then used to compute DoGs [27]. The next step is to locate candidate key points using local extremas for which Hessian matrix is used to remove unstable key points and then an interpolation method is used on the remaining key points to localize them [27]. Next, all of the key points are oriented. Finally, a unique descriptor is assigned to each key point.

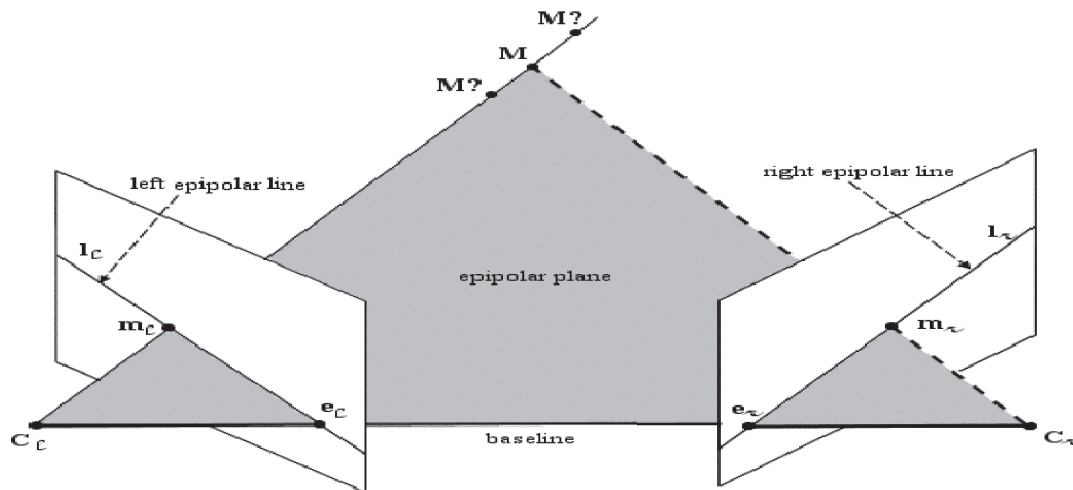


Figure 4-4 : Epipolar Geometry [28]

The photographs acquired from data acquisition are uploaded onto the server through the desktop client. Calibration, modeling, point cloud generation and texture mapping are managed on the server that has high-end 3D processing capabilities. Figure 4-4 [28] depicts epipolar geometry to estimate depth. The manual intensive labour that is required in other photogrammetric software is minimal in 123D. PhotoModeler, the professional software, on the other hand requires the user to carry out calibration, model point markings, point cloud creation, meshing and texture mapping manually. This is a lengthy process and can be done only by experienced users. 123D is able to create the model mostly of its own. The user only has to upload the photographs. The completed model on the server is directly downloadable to the desktop web application and can be accessed there. The same 3D model file can also be e-mailed to the user. A special format file, .3dp (file extension) is generated for the 3D model and this .3dp file can also be converted into other formats (.dxf, .obj, .rzi and .las). The .3dp file contains the XYZ coordinates of point cloud as well as the texture information for the 3D model. It also contains the topology of the points (mesh).

In this project a problem came up when twelve photographs out of a total of sixty-two images did not get oriented. The photographs that did not get oriented were those that were taken from the back of the monastery. Due to lack of space the base-to-height ratio was either too high or

too low. This discrepancy resulted in the software not orienting twelve of the images. In order to orient the entire dataset the twelve un-oriented images were manually stitched using the manual stitching tool. The manual stitching tool requires at least four locators to be marked on a single image. The placement of locators on the images allows the un-oriented images to be stitched onto the oriented dataset. The dataset is then processed again on the server side.

The final .3dp file is then converted into .las file format, which gives XYZ coordinates of all the points in the point cloud. Lastools is software that converts .las file into a text file containing XYZ coordinates. This text file can then be used in other software like Point Cloud Mapper for further analysis.

4.2.2. Point cloud reconstruction with PMVS

Patch Multi-View Stereo (PMVS) software is, as its name defines, multi-view stereo software. It uses camera parameters and images to reconstruct the 3D object present in the images. PMVS only takes into account and reconstructs rigid structure. Examples of rigid structures are buildings and non-rigid structures are people standing in front of the buildings. The software's output is a point cloud, which contains oriented points. PMVS does not create polygonal mesh models unlike 123D which does create mesh models.

The key elements of PMVS are patch model, which is a rectangular plane containing local tangent that is defined by the centre of object space and normal vector is oriented perpendicularly to the camera lens as well as the reference image [29]. Figure 4-5 shows the patch used in PMVS.

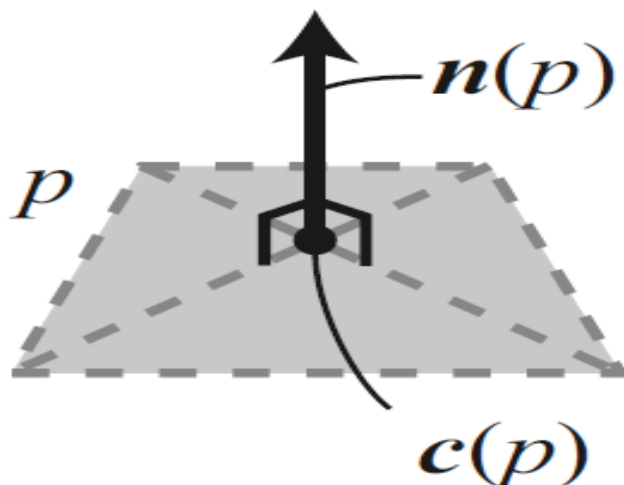


Figure 4-5 : Patch used in PMVS Algorithm [29]

Patch based MVS algorithm is divided into three steps for reconstruction of point cloud

1) Initial Feature matching :

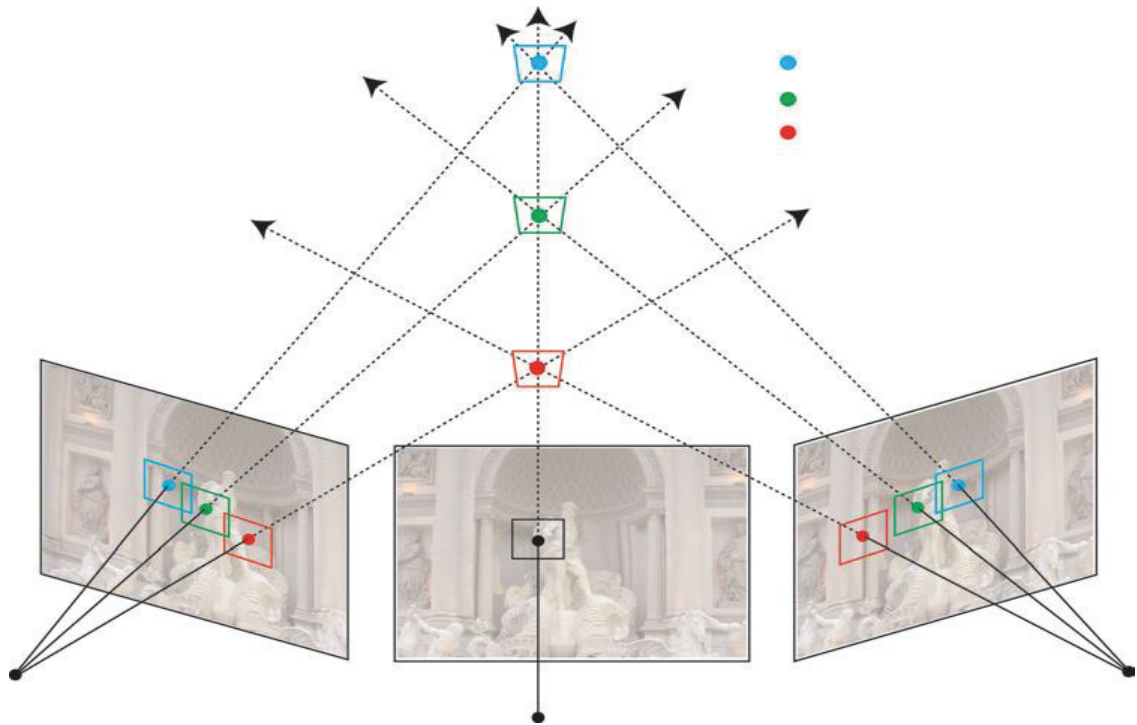


Figure 4-6 : PMVS Epipolar Geometry [1]

In initial feature matching the same features in corresponding images are matched using the patch based MVS algorithm. Figure 4-6 [1] shows the epipolar geometry for patch based MVS algorithm. Here, the first step is to detect the features. This is done using a corner detector, which helps in detecting the prominent point in all images. The corresponding points for all of the detected points are found in other images. The corresponding points are then triangulated into 3D points. Patch candidates are described by primary 3D point. The patch is defined by the matched images and it filters out those points that do not match. A patch is constructed for each image cell and is then matched in the corresponding images using SfM techniques [29].

2) Patch Expansion

An existing patch generates new patches which are allotted to neighbouring image cells, leading to the expansion of the patch. If there is a large discontinuity in the depth of the image or if a patch already exists in the neighbouring cells then new patches are not generated [29].

3) Patch Filtering

Filtering is used to remove the erroneous patches from corresponding images. Patched based MVS algorithm uses three patch filters to eliminate incorrect patches using visibility information. Patches are filtered out as outliers in depth map test.

4.2.3. Point cloud reconstruction with PhotoModeler

PhotoModeler is commercial photogrammetric software that allows for two types of modelling; Point cloud modelling and CAD-like modelling.

After the camera calibration, model locators are marked on corresponding 2D images of the object being modelled. A minimum of 8 points is identified in each of the images in order to triangulate 3D point data. The next step is to create point cloud from the images. PhotoModeler has an inbuilt set of dense surface modeling tools. These tools are able to extract a dense pattern of point clouds from the images. The photographs should be taken in pair stereo configuration.

The project should have at least two camera stations with appropriate base-to-height ratios and should begin with low residuals. The DSM algorithm identifies the stereo pairs of images that need to be processed. Each stereo pair should have at least 60% overlap. The resample images are aligned with the epipolar lines. DSM trims can be applied on the images to get the region of interest to be able to create a point cloud.

DSM algorithm is a patch based algorithm which uses an $N \times N$ patch that runs over the entire image searching for an appropriate match while in PMVS, feature matching is done by identifying corner points on every image and then searching for their corresponding matches in other images. For this the search range is defined by epipolar constraint. The point cloud in PhotoModeler can be created by controlling various parameters such as sampling rate, depth range, sub-pixel, super sampling factor, matching region radius and texture type. Sampling rate defines the distance between the 3D points that are created in the point clouds. In this project, the sampling rate for the 3D point cloud generated by PhotoModeler has been fixed at 8cm. Depth range is a co-relation search range. Increasing the depth range leads to removal of unexpected noise above and below the surface. Even small value changes in the depth range can lead to erroneous 3D point cloud therefore depth range values have to be managed with extreme care. Sub-pixel values help in generating accurate point clouds. Super sampling factor parameters are based on the sub-pixel method where the higher the factor less wavy is the surface of the point cloud.

4.3. CAD-like Modelling

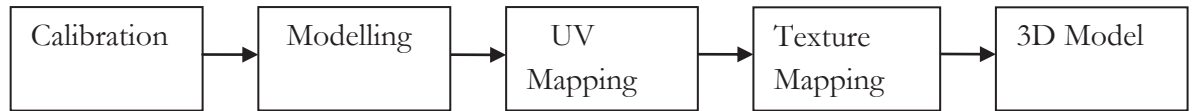


Figure 4-7 : CAD-like Modelling Workflow

4.3.1. Calibration

In this project, images were captured at 18.00 mm focal length. This focal length is taken into account as this pre-defined length eliminates the need for calculating the focal length from the images that is a lengthy and complex task and generally tends to reduce the accuracy of the model.

Next step is to generate markers on certain features of the structure in order to identify the position of 3D locators. The features selected are corners and edge intersections and markers are created at various depths and planes of the structure to improve the accuracy of the calibration process. Feature matching comes next. Camera parameters like position, focal length and lens distortion are calculated when identical features are marked in different images. It is also able to determine the 3D coordinates of the features and the objects marked. It is done in order to produce correspondences across consecutive images. A marker is created in the image and then same marker is placed at the very same point (corner) on the other image so that the markers may correspond on each consecutive image until the point is invisible. At least 8 different markers are created on a single image for successful calibration. In this process 19 3D calibration locators are specified on all images for calibration.

4.3.2. Modelling

3D modeling involves the use of several types of geometric objects in order to create various shapes and forms. Basic modelling consists of first, creating an object then editing and revising those very objects. These edits can be made once a polygon mesh has been created. The objects can be moved, scaled and rotated. In primitives, faces are dived and extruded according to the geometric structure of the monastery.

The first step to creating an object is to add a primitive. Primitives or objects are fundamentally basic shapes such as cube, cylinder, sphere or plane that can be added to a certain scene. They basically initiate a polygon mesh on which the model can be started. The primitive can be added to any of the components of the mesh. The second step involves the adding of faces to objects

that have been built. Faces can be added through 3D points that are marked. These 3D points can be marked anywhere on the image plane. The primitives are sub-divided and manipulate to create the complex structure of the building such as dome.

The architectural style of the building plays an important role in the modelling process. In the reconstruction of the Mindrolling monastery, the base of the building is modelled by piling cubical primitives on top of each other. In order to create depth extrusions were applied to the cubical primitives in the middle portion of the building. Finally, the dome was created by modifying cylindrical and spherical primitives. Figure 4-8 [30] shows the various primitives used in the modelling of structure of the monastery.

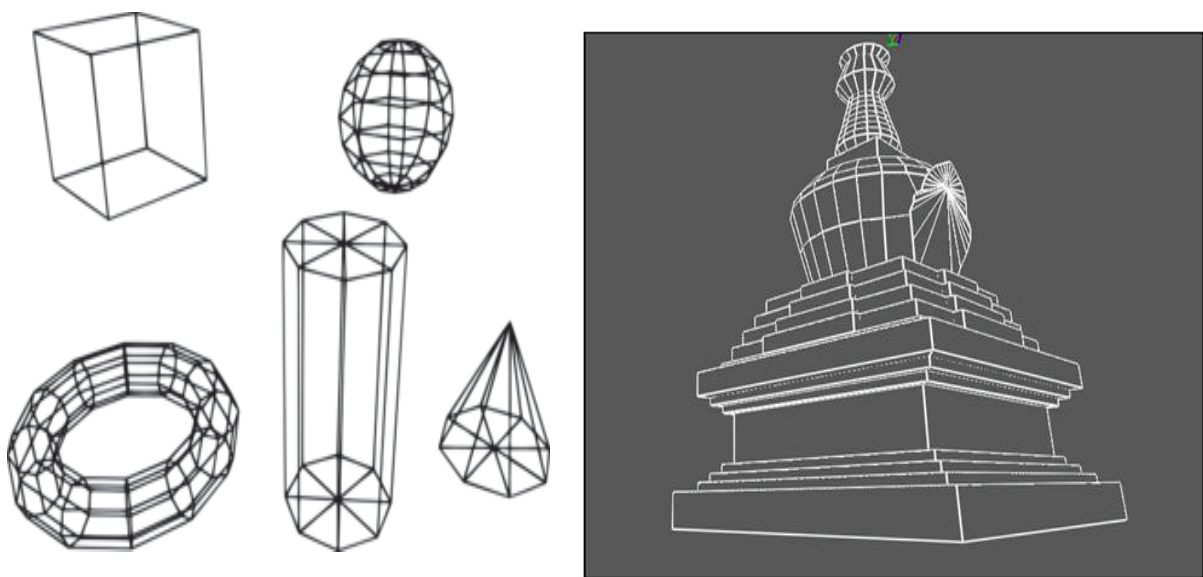


Figure 4-8: 3D Primitives used to build Wireframe Model of the monastery [30]

The shape and size of the primitives is modified to represent architecture of the monastery. Scaling of 3D primitives constrain the shape and size of the existing primitive. The primitives used for the monastery were modified to shape the geometric structure of the monastery.

There are three different coordinate systems; world coordinate system, object coordinate system and a defined selection. The monastery is reconstructed in the object coordinate system in which XYZ axes of the monastery are aligned with reference to the position in object space. A reference scale is also defined for the 3D model using survey measurement so that it can be scaled to real world. Right angle constraint is also applied to the primitive so to stabilize the 3D model at the corner of the building.

The number of faces of an object can also be increased. There are two ways in which this process can be carried out. The faces can be subdivided in order to increase their number. The edges subdivided vertically and horizontally. This leads to an increase in the detail of the model. There are again two ways of doing this. One is by splitting the faces. This done by adding edges to the face that result in the division of the face that leads to the creation of new faces with different shapes. The other way is to extrude faces. The process of extruding involves either protruding or projecting faces on the image plane. This allows the user to create a concept of depth in the 3D model. Objects can be extruded inside the object or even outside of the object.

4.3.3. UV Mapping

The principal steps to adding texture to a model are to first create mapping groups for all objects. UV mapping is done to define the UV texture coordinates that relate to points and vertices located in a 3D mesh. These help in placing the texture from the image onto the mesh. In UV mapping 3D primitive with XYZ coordinates is unwrapped to 2D UV plane with U and V coordinates. UV mapping assist texturing process for precise extraction of texture. Mapping of texture image to UV map and then wrapping on the 3D object is illustrated in the Figure 4-9 [31] below.

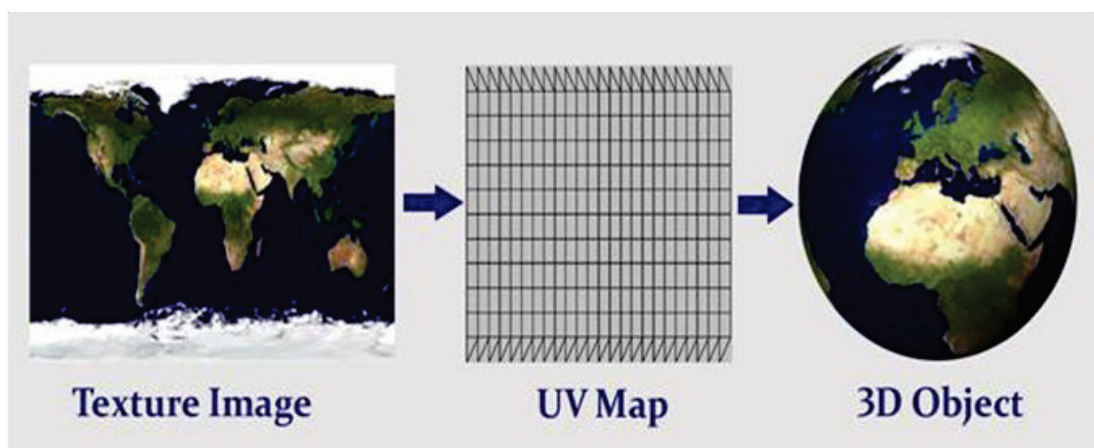


Figure 4-9 : Unwrap of model for UV mapping [31]

The next figure 4-10 shows a modified cylinder primitive with complex edges and corners is UV mapped according to the wireframe model in this project.

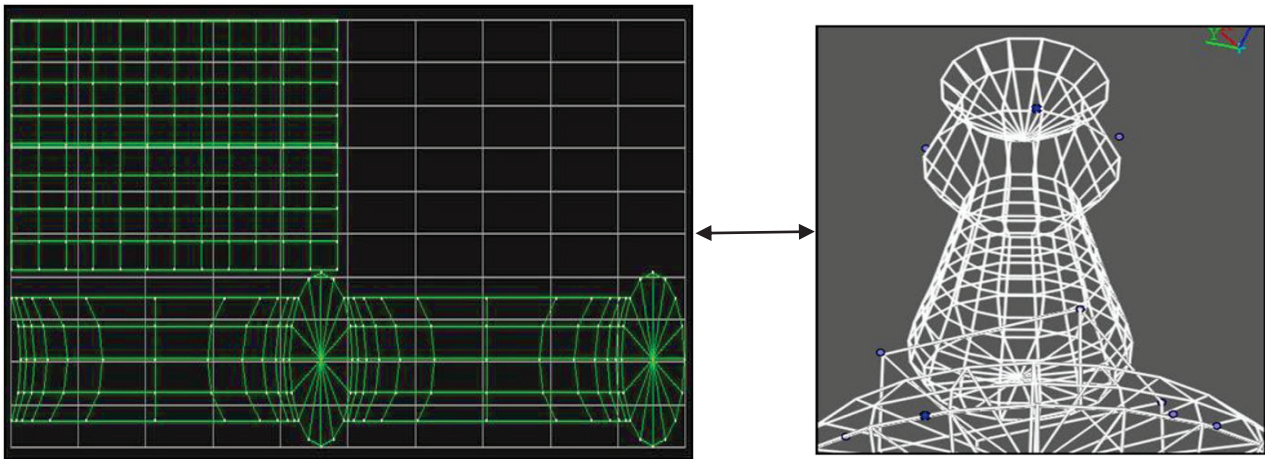


Figure 4-10 : UV map and Wireframe model of top part of the monastery

The UV primitives are divided into mapping groups to basically manipulate and develop connected 2D faces that belong to the same object. The mapping groups are linked to a certain set of faces and to a unique texture too. It is important to check the accuracy of the mapping group because it is the mapping group that defines the layout of the texture in a model.

4.3.4. Texturing Mapping

Texturing is a process where the user adds texture or material to the surface of the model. ImageModeler is able to lift off the texture from an image and use it to texture a model. There is default colour and texture that is added to all faces while modeling and further texture and colour can be added from photographs.

Texture from the calibrated images and for each face of the primitive one photograph is used to extract texture. This automatic addition of texture can be tricky though as not all of the calibrated shots are suitable for texture mapping as some of them maybe too dark or too bright. When choosing shots for texture mapping it is always better to use as many shots as using a larger number of shots results in the ImageModeler picking up more information about the texture of the object, final texture of any face is actually as blend of textures from various images [32]. This blending helps in eliminating all discontinuities.

The value for texture sizes that have been extracted is defined by pixels per surface unit and this

is known as the default texture density. Texture Boundary shows how well UV projection and the boundary of the UV map match. It measures this in pixel units. The first image is the most useful in the texture extraction procedure.

There are three types of extraction modes; area weighted, vertex weighted and all shots. Area weighted is a process in which the best photograph is chosen according to the image area and the amount of contribution it makes towards texture creation [32]. Area weighted texture extraction method is prefer because it gives the photorealistic texture.

5. RESULTS AND DISCUSSION

5.1. Calculation of parameters for Theoretical accuracy

In order to be able to acquire data that is accurate from consumer cameras, it is vital to outline various parameters that can model geometric characteristics [26].

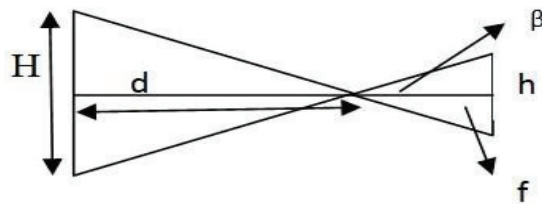


Figure 5-1 : Parameters of camera geometry and building structure [26]

Physical Sensor size: 23.6 * 15.8 mm

Image resolution: 3872 * 2592 pixels

Vertical opening angle: $\tan\beta = h/2 / f$ or $H/2/d$ as in [26]

- Focal length, $f = 18 \text{ mm}$,
- Height of the building , $H = 56 \text{ m}$
- Distance from building to capture photos $d = 30 \text{ m}$
- Physical sensor size $h = 15.8 \text{ mm} \approx 16 \text{ mm}$
- The scale of the photo, $s = d/f = 1666 \approx 1700$
- Pixel size $sx = 24 \text{ mm}/3500 \approx 6 \mu\text{m}$
- Double, the pixel size of the camera,
 $spx \approx 2 * sx \approx 2 * \text{pixelsize} = 12 \mu\text{m}$ as in [26]
- Therefore, the pixel size at the object will be: $Scale * 12 = 20\text{mm} = 0.02\text{m}$
- Baseline length, $b = 10 \text{ m}$

5.2. Theoretical Accuracy

Theoretical accuracy is a mathematical result from error propagation when the sensor geometry is given [26].

- $spx \approx 2 * sx \approx 2 * pixelsize = 12\mu m$ as in [26]
- $mb = d/f = 1700$ as in [26]
- $sH = \frac{d}{b} \cdot mb \cdot spx \approx 0.06m$ as in [26]
- $sX = mb \cdot sx \approx 0.01m$ as in [26]
- Depth accuracy, $sH \approx 60 mm = 6 cm$
- Parallel Accuracy, $sX \approx 10 mm = 1cm$

Depth accuracy is a depth range in which 3D points are created above and below the surface. Parallel accuracy is the accuracy of the surface or the plane, which is parallel to the camera sensor. The dimension of the plane that is parallel to the camera sensor and its measured accuracy is known as parallel accuracy 2D. The third dimension in the space creates depth and is known as the depth accuracy.

Depth and Parallel accuracies are used to calculate the errors in camera sensor geometry. They are used as references for checking the external and internal accuracies in point cloud and CAD-like modelling.

5.3. Orientation Accuracy

Orientation accuracy estimates the accuracy of camera positions and angles around the object of interest, which in this case is the Buddha temple. Six GPS points taken while surveying were converted to a global coordinate system (UTM/ WGS 84) and were then used as input parameters for accuracy assessment. The accuracy of the GPS is expected to be approximately 4-5 cm. This means that the results of the orientation accuracy will also be skewed due to lower accuracy of the GPS device.

5.3.1. Autodesk 123D

Autodesk 123D uses a seven-parameter transform that computes transformation parameters when local coordinates are transformed to global coordinates (UTM/WGS 84). It estimates a 3D rotation as well as a 3D translation between two sets of corresponding points by minimizing the distance between the points.

The point RMS residual is the difference in point locations that is generated when local coordinate points are converted to global coordinate points. This transformation from local to global coordinates helps in deducing the orientation accuracy of 123D. The locators that are placed in 123D are in local coordinate system. The position of these locators on the 3D model

corresponds to GPS points on ground. Next, a seven-parameter transform is used to convert these local coordinate 3D points into global coordinates. The residual that is generated from this conversion is known as the point residual.

R is a 3 * 3 rotation matrix and T is a 3 * 1 translation vector. S is the scale.

$$\text{Rotation (R)} = \begin{bmatrix} 0.9085 & 0.4168 & 0.0293 \\ 0.4178 & -0.9051 & -0.0783 \\ -0.0061 & 0.0834 & -0.9965 \end{bmatrix}$$

$$\text{Translate (T)} = (1.0e + 6) * \begin{bmatrix} 3.3516 \\ 0.7883 \\ 0.0006 \end{bmatrix}$$

$$\text{Scale (s)} = 1.012$$

5.3.2. PhotoModeler

The orientation accuracy of the 3D model created by PhotoModeler is carried out by transforming local coordinates into global coordinates by inputting GPS survey points into the PhotoModeler. The overall RMS residual of the points is then generated.

Total Error

First Error: 0.835

Last Error: 0.881

Point Residual

Overall RMS residual: 0.889

The overall RMS residual for Autodesk 123D is 0.865m and for PhotoModeler it is 0.889m. The expected accuracy was 4-5 cm as this is the approximate accuracy of the GPS with which the GPS points were obtained. The reason the orientation accuracy is low is because the GPS points were taken while standing right next to a wall at quite a height on the structure. This may have led to multi-path error which contributed to the low accuracy of the GPS points thus leading to a low orientation accuracy in Autodesk 123D and PhotoModeler.

Autodesk 123D has a higher orientation accuracy than PhotoModeler which means that the camera orientation is estimated more accurately in Autodesk 123D.

5.4. Point Cloud Analysis

5.4.1. PMVS



Figure 5-2 : PMVS point cloud in cloud compare

Figure (5-2) shows the PMVS point cloud of the Buddha temple. This point cloud has been generated using patch-based multi view stereo algorithm. The point cloud has been visualized using Cloud Compare software.

5.4.2. Autodesk 123D

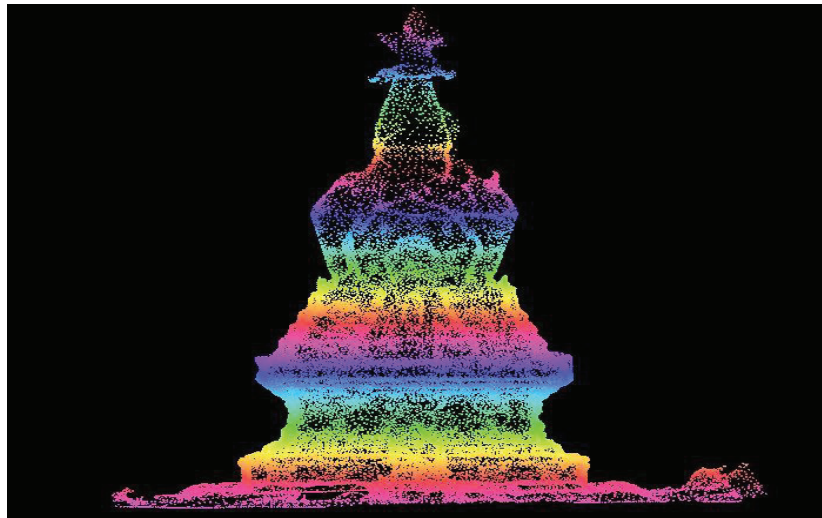


Figure 5-3 : Autodesk 123D point cloud in PCM

Figure (5-3) is a point cloud representation of the Buddha temple generated using Autodesk 123D. The point cloud has been exported to Point Cloud Mapper (PCM) software in order to visualize the point cloud. This point cloud was produced in standard quality. The 123D software has three quality options at which point clouds can be generated. These quality options decide on the point density at which the model should be created. The mobile option has the lowest point density, standard is medium and mesh has the highest.

5.4.3. PhotoModeler

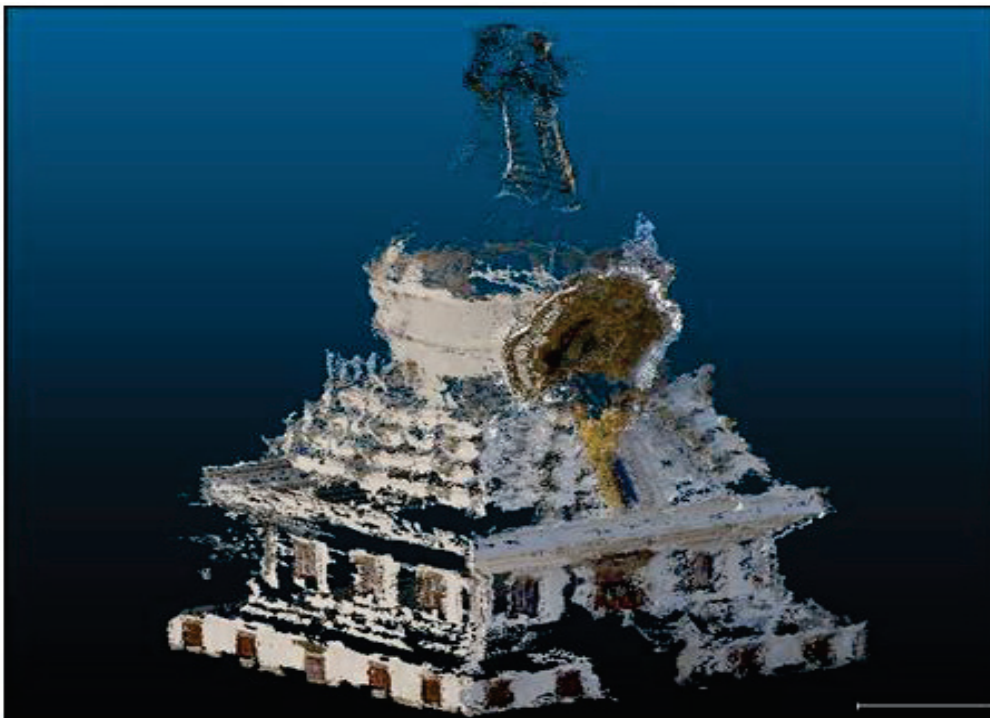


Figure 5-4 : PhotoModeler point cloud in cloud compare

Figure (5-4) is a representation of the Buddha temple generated by PhotoModeler, which is professional software. The point cloud is exported to Cloud Compare Software for the purpose of visualization.

5.4.4. Visual Analysis

The point clouds generated by Autodesk 123D and PMVS are the most visually appealing as compared to PhotoModeler. Autodesk 123D has the most even distribution of points and therefore it is able to capture the entire structure without any missing areas. PMVS, though visually impressive, has portions of the structure missing from the point cloud, as the points in it are not evenly distributed. PhotoModeler captures features like walls and windows very well but the dome of the monastery as well as the metallic features are missing in the point cloud.

The density of PhotoModeler is 4380 points per m². It is 1250 points per m² for PMVS and 1020 points per m² for 123D. This shows that the PhotoModeler point cloud is the densest whereas 123D and PMVS are quite sparse in comparison. Denser point clouds mean that the structural features are more defined and there are more details on the surface of the structure. Though most of the PhotoModeler point cloud is very well defined but some portions like the top are missing details, because the points are not evenly distributed.

Though the point cloud is sparse in 123D, the points in the point cloud are more evenly distributed throughout the model giving it uniform visual appearance. Overall feature details of the structure are retained in 123D. The point cloud generated by PMVS is slightly denser than 123D but the points are not as evenly spread along the surface of the structure compared to 123D and there are also more holes in the point cloud in PMVS.

At times denser point clouds tend to generate a higher degree of noise. The noise can be identified as outliers. Outliers are those points that lie outside of the surface plane. Outliers indicate measurement error when two planes are fitted to each other and they need to be removed.

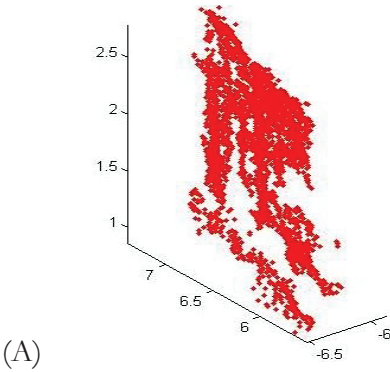
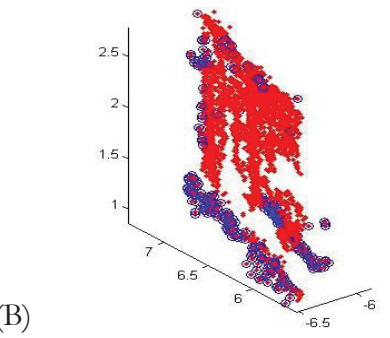
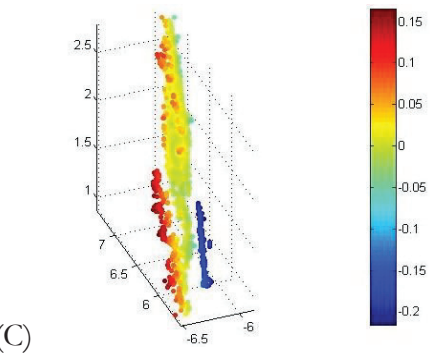
5.5. Internal Accuracy Assessment

Internal accuracy in this case assesses the planarity of planar surfaces. In order to find the internal accuracy the first step is to extract a plane, which represents the same feature of the structure from the three point clouds that have been generated. This plane is in local coordinate system and is used as an input for the internal accuracy assessment. A RANSAC (Random Sample Consensus) plane is then fitted to the plane being assessed. The RANSAC is able to determine the outliers of the plane being assessed. RANSAC is an iterative algorithm that repeatedly chooses samples of data till the maximum numbers of inliers are found. It then removes the outliers from that dataset. Thus, it helps in removal of outliers, which can influence the accuracy of the point cloud. RANSAC produces a best-fit plane, which is taken as the reference plane. The distance between the measured and the reference plane is then calculated. The output is an assessment of the surface planarity of the extracted planes. A statistical analysis of the planes is carried out to evaluate internal accuracy of the point clouds.

5.5.1. PMVS Plane

The image A of table 2 below illustrates the XYZ coordinate points in local coordinate system. Image B of table 2 shows the outliers of the PMVS plane. After fitting a RANSAC plane to the PMVS plane the outliers are deduced. Image C of table 2 shows the planarity of the surface of the PMVS plane.

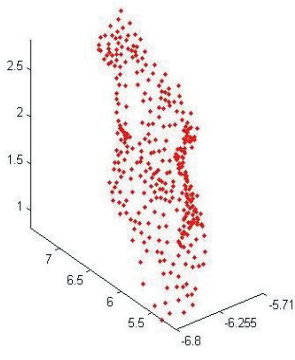
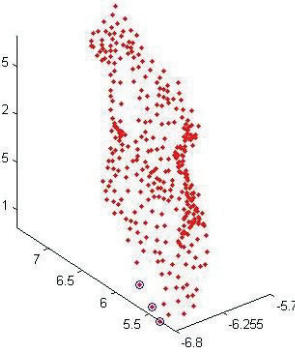
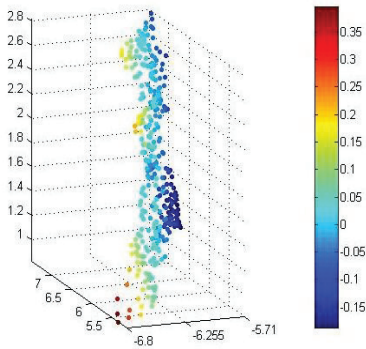
Table 2 : Visualization of PMVS plane for internal accuracy assessment

	PMVS Plane
Plane (Local coordinate)	 <p>(A)</p>
Outliers on the plane	 <p>(B)</p>
Surface Planarity	 <p>(C)</p>

5.5.2. Autodesk 123D Plane

The image A of table 3 below illustrates the XYZ coordinate points in local coordinate system. Image B of table 3 shows the outliers of the 123D plane. After fitting a RANSAC plane to the 123D plane the outliers are deduced. Image C of table 3 shows the planarity of the surface of the 123D plane.

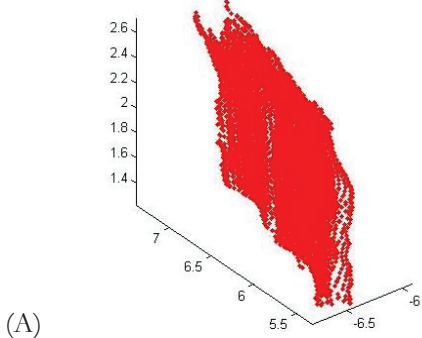
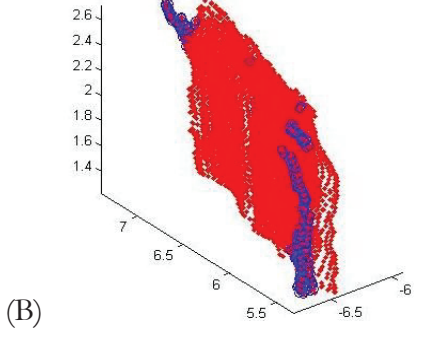
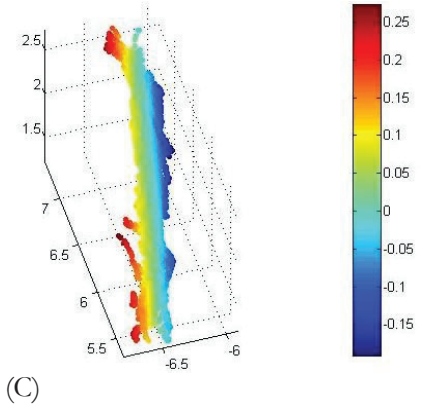
Table 3 : Visualization of 123D plane for internal accuracy assessment

	123D Plane
Plane (Local coordinate)	 <p>(A)</p>
Outliers on the plane	 <p>(B)</p>
Surface Planarity	 <p>(C)</p>

5.5.3. PhotoModeler Plane

The image A of table 4 below illustrates the XYZ coordinate points in local coordinate system. Image B of table 4 shows the outliers of the PhotoModeler plane. After fitting a RANSAC plane to the PhotoModeler plane the outliers are deduced. Image C of figure table 4 shows the planarity of the surface of the PhotoModeler plane.

Table 4 : Visualization of PhotoModeler plane for internal accuracy assessment

	PhotoModeler plane
Plane (Local coordinate)	 <p>(A)</p>
Outliers on the plane	 <p>(B)</p>
Surface Planarity	 <p>(C)</p>

5.5.4. Statistical Results of Internal accuracy

Table 5 : Statistical results of internal accuracy of PMVS, 123D and PhotoModeler

	PMVS	123D	PhotoModeler
Mean	0.0006	0.0015	0.0044
Standard deviation	0.0501	0.0992	0.0512

Table 5 presents the results of the statistical values of the various point cloud based software planes. The PMVS plane has the lowest mean at 0.0006m, followed by 123D at 0.0015 and the mean for PhotoModeler is the highest at 0.0044m. The standard deviation demonstrates the precision of the 3D points. As seen from the table, the standard deviation for PMVS, 123D and PhotoModeler are 0.0501m, 0.0992m and 0.0512m respectively.

A lower mean value means that the surface of the extracted plane is smooth and a higher value suggests undulations in the plane's surface. Mean and standard deviation implies the quality of point measurement in the plane. Lower mean values imply higher internal accuracy. RANSAC fitting removes the outliers of the plane and then plane with inliers is left. Mean and standard deviation are directly proportional to the random noise in the plane. High random noise reduces the surface planarity or evenness of points in the plane. Therefore the PMVS plane is the most accurate in terms of internal accuracy followed by 123D. The internal accuracy of PhotoModeler is the lowest as its point cloud, though dense, is highly irregular. These statistical observations relate to visual observations. The point clouds generated by PMVS and 123D are reconstructed evenly while the PhotoModeler point cloud has many missing portions and its surface is irregular. The PMVS plane is for this reason taken as a reference plane when evaluating external accuracy.

5.6. External Accuracy Assessment

External accuracy is a relative comparison of two point clouds of the same object. Here the point cloud with the lower internal accuracy is compared with the higher internal accuracy point cloud. The extracted lower accuracy plane is taken as the measured plane and higher accuracy plane is taken as the reference plane.

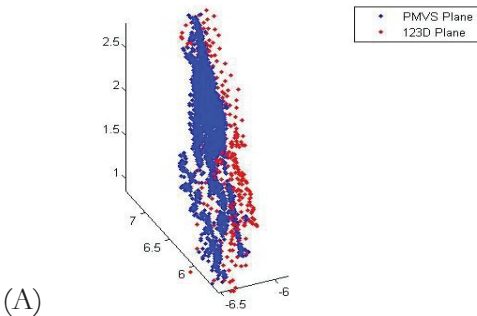
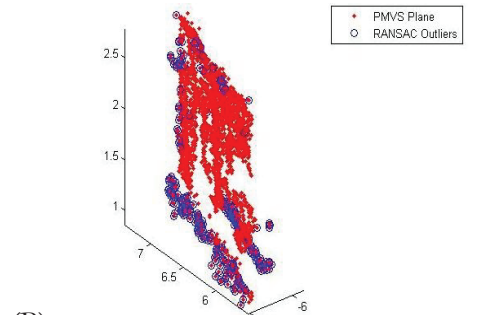
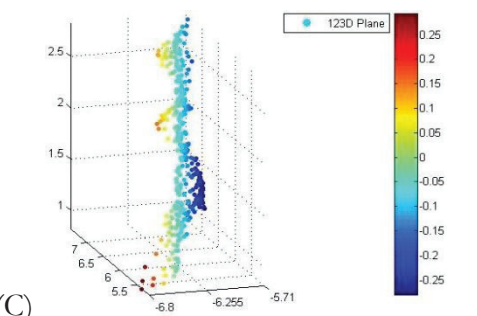
In this case the PMVS point cloud is used as a reference point cloud. This is because the internal accuracy of the PMVS has been computed to be the highest among the three point clouds generated. The purpose of finding external accuracy is that it compares the relative accuracy between two point clouds of the same object generated by different software.

In order to evaluate the external accuracy, the extracted planes of two different point clouds are fitted to each other to check the shift between them. The plane that is an outcome of the RANSAC fitting in which outliers are identified and removed is fitted to the measured plane as a reference plane. The distances of 3D points of the measured plane from the reference plane are then calculated. The distance between the measured plane and the reference plane is directly proportional to the external accuracy of the measured plane.

5.6.1. Autodesk 123D with PMVS Plane

Image A of table 6 presents the shift between 123D plane and the PMVS plane which has a higher accuracy. As the image shows, the shift between 123D and PMVS planes is quite less. Image B of table 6 show the outliers in the PMVS plane when RANSAC is fitted to it. Image C of table 6 shows the distance of the 123D plane from the PMVS reference plane. The points of the 123D plane are colour based on their distance from the PMVS reference plane. The darker colours represent wider distances whereas the lighter colours represent smaller distances. The red points denote the 123D plane and the blue one are the PMVS plane.

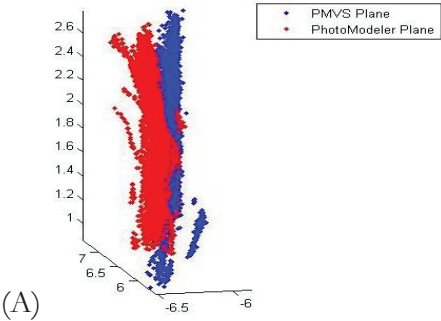
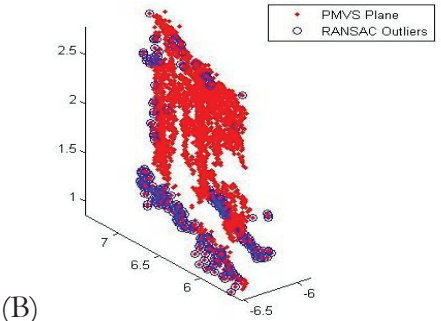
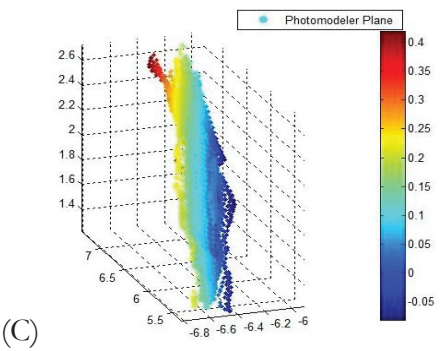
Table 6 : Visualization of 123D with PMVS plane for external accuracy

123D with PMVS	
Shift between the 123D plane and PMVS plane	 <p>(A)</p>
Outliers on the plane	 <p>(B)</p>
Distance of 123D plane from reference plane	 <p>(C)</p>

5.5.2 PhotoModeler with PMVS

Image A of table 7 presents the shift between PhotoModeler plane and the PMVS plane which has a higher accuracy. As the image shows, the shift between PhotoModeler and PMVS planes is quite less. Image B of table 7 show the outliers of the PMVS plane when RANSAC plane is fitted to it. Image C of table 7 shows the distance of the PhotoModeler plane from the PMVS reference plane. The points of the PhotoModeler plane are colour based on their distance from the PMVS reference plane. The darker colours represent wider distance whereas the lighter colours represent smaller distances. The red points represent the PhotoModeler plane and the blue ones are the PMVS plane.

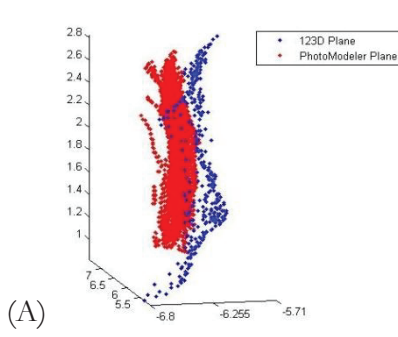
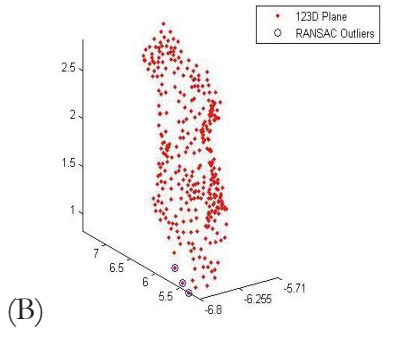
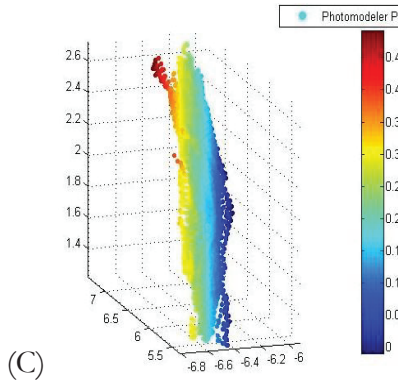
Table 7 : Visualization of PhotoModeler with PMVS plane for external accuracy

PhotoModeler with PMVS	
Shift between the PhotoModeler plane and PMVS plane	 <p>(A)</p>
Outliers on the plane	 <p>(B)</p>
Distance of PhotoModeler plane from reference plane	 <p>(C)</p>

5.6.2. PhotoModeler with 123D plane

Image A of table 8 presents the shift between PhotoModeler plane and the 123D plane, which has a higher accuracy. As the image shows, the shift between PhotoModeler and 123D planes is quite less. Image B of table 8 show the outliers of the 123D plane when RANSAC plane is fitted to it. Image C of table 8 shows the distance of the PhotoModeler plane from the 123D reference plane. The points of the PhotoModeler plane are colour based on their distance from the 123D reference plane. The darker colours represent wider distance whereas the lighter colours represent smaller distances. The red points represent the PhotoModeler plane and the blue ones represent the 123D plane.

Table 8 : Visualization of PhotoModeler with 123D plane for external accuracy

	PhotoModeler with 123D plane
Shift between the PhotoModeler plane and 123D plane	 <p>(A)</p>
Outliers on the plane	 <p>(B)</p>
Distance of PhotoModeler plane from reference plane	 <p>(C)</p>

5.6.3. Statistical Results of External accuracy

Table 9 : Statistical results of external accuracy for various planes

	123D with PMVS (m)	PhotoModeler with PMVS (m)	PhotoModeler with 123D (m)
Mean	0.0836	0.0984	0.1783
Standard deviation	0.0993	0.0627	0.0608

Table 9 presents the results of the statistical values of the various point cloud based software planes in comparison to a reference plane of higher accuracy. The given statistical mean value is an average of the distance of 3D points in measured plane from the reference plane. The 123D plane has a lower mean than the PhotoModeler when both of the measured planes are compared with the PMVS reference plane. The theoretical depth accuracy calculated in section 5.1 was 0.06m. This implies that the mean of the external accuracy should fall within 0.06m.

The mean distance between 123D and PMVS is 0.0836m, mean distance between PhotoModeler and PMVS is 0.0984m and mean distance between PhotoModeler and 123D is 0.1783m. Mean characterize the extent of systematic errors in the plane due to the change in the camera orientation. Comparing the mean values demonstrates that 123D has higher external accuracy than PhotoModeler. PhotoModeler uses photo pairs to generate the point cloud which are decided by user, use of incorrect photo pairs can be reason behind its low external accuracy. PMVS is used as the reference plane and therefore its external accuracy cannot be calculated, as there is no other more accurate plane that it can be compared with.

The standard deviation is also calculated for the measured planes in relation to the reference planes. Standard deviation calculates the deviation of 3D points from the mean value. High standard deviation means low precision. High standard deviation contributes to the increased random noise or error in the plane. PhotoModeler plane has a low value of standard deviation because PhotoModeler point cloud has a high point density. Also comparing means and standard deviations with depth accuracy 0.06 m (theoretical accuracy) shows that the point cloud accuracy is in close proximity to theoretical accuracy.

5.7. CAD-like Modelling

5.7.1. Wireframe model

The first step in CAD-like modeling is to calibrate images of the structure. The calibration process also orients the camera positions and angles. A bottom to top approach is used in the modeling of the monastery. Figure 5-5 clearly shows that the bottom part of the structure is cubical in shape. For this cube primitives are used to give a structural shape to the 3D model. The cubes are placed on top of each other in ascending order by size in order to give a stair case impression in the base of the model. In the middle portions of the monastery, the faces are split in order to extrude box primitives. This gives an impression of depth.

Tibetan monasteries are designed in a way in which the cubical base is crowned by a dome shape structure. This dome is half cylindrical and half spherical making it a complex structure to model. In order to model the dome, the cylindrical primitive is modified in accordance with the bottom half of the dome. The top half is given a spherical shape using the sphere primitive. The very top of the monastery is modelled by creating cylindrical extrusions in the original cylindrical primitive.

Manipulating various primitives, to suit the architectural style of the monastery, completed the wireframe model. The next step is to UV map the wireframe model so that texture mapping can be carried out easily. The texture is then added to model using the area weighted approach to give a photorealistic look to the building.

Figure 5-5 below is a wireframe model generated using ImageModeler. It shows the various primitives that have been used such as cylinders, spheres, cubes and planes.

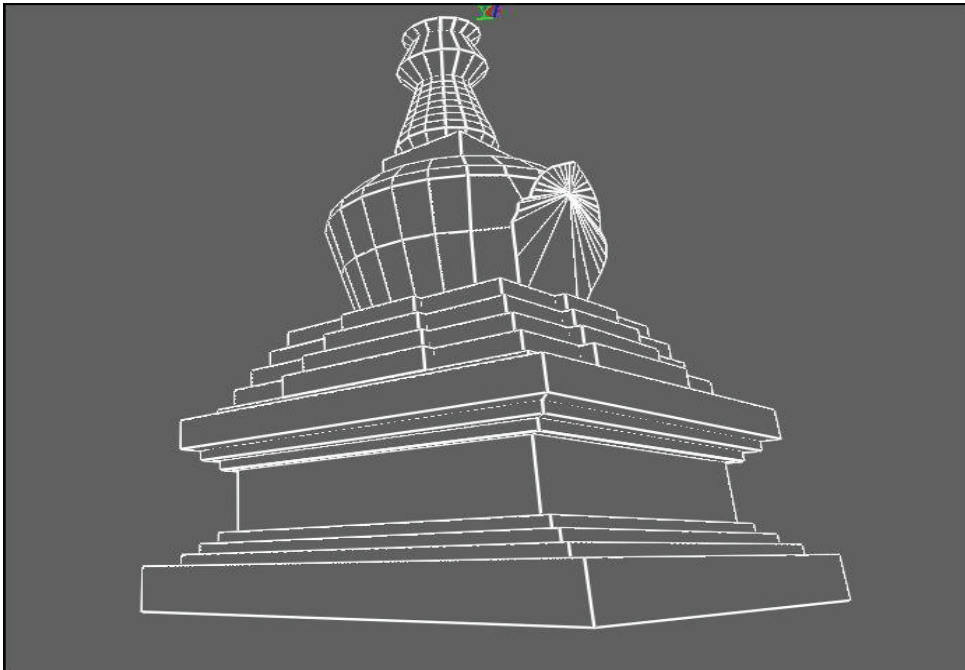


Figure 5-5 : Wireframe Model

Figure 5-6 illustrates all of the primitives used in the CAD-like modeling of the Buddha temple.

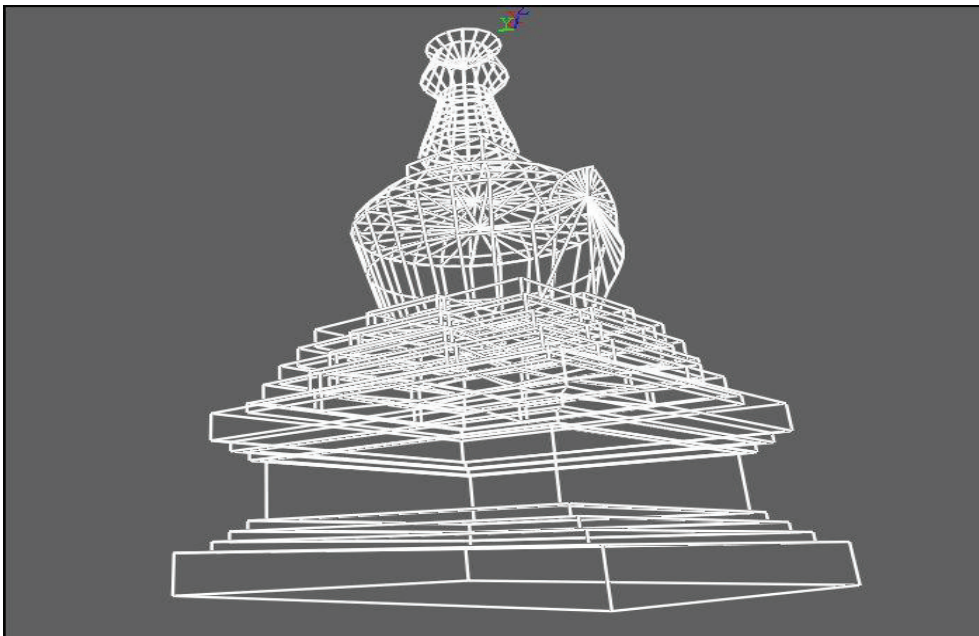


Figure 5-6 : Wireframe model with all primitives

5.7.2. Textured model

The figure 5-7 shows the wireframe model after texture has been applied to it. The texture applied to this model is extracted from the photos in order to give a photorealistic appearance to the 3D model. Texture is captured from single image using because texture from multiple images caused the disorientation of the texture on the face of the primitive. Dome of the monastery have many subdivision in the cylindrical primitive used as seen in Figure 5-6, extraction of the texture from the images caused jumble of texture in the model thus a matching texture is extorted from different part of the building to give a uniform look to the dome.



Figure 5-7 : Photorealistic Texture Model

5.7.3. Structural Length Accuracy

Table 10 displays the model and survey (tape) measurements of various parts of the structure. The model measurements are those that are computed using the measuring tool on the CAD-like 3D model. The survey measurements are those that are measured on ground using an inch tape. The spatial distance on the model is compare with the tape measurements to assess the accuracy of the 3D CAD-like model. The total mean of the differences between survey measurements and model measurements is 0.029 m or 2.9 cm. The expected accuracy (as calculated by theoretical accuracy) is a parallel accuracy of 1 cm and depth accuracy of 6 cm. The model accuracy is coming to 2.9 cm, which means that the model accuracy is close to the theoretical accuracy. The reason that model accuracy is close to the theoretical accuracy for CAD-like modelling is because 30m distance between the camera and the building is used in the mathematical model but in reality the distance kept changing due to occlusions and lack of space at the back.

Table 10 : Results for structural length accuracy

Structure	Model Measurements (in meters)	Survey Measurements (in meters)	Error
Level 1 right	27.36	27.39	0.03
Level 2 right	24.37	24.36	0.01
Level 3 right	22.87	22.90	0.03
Level 4 right	21.36	21.40	0.04
Level 1 left	27.36	27.39	0.03
Level 4 left	21.37	21.39	0.02
Level 2 back	24.41	24.36	0.05
Level 4 back	21.39	21.39	0.00
Level 1 Front	27.33	27.39	0.06
Level 2 Front	24.41	24.36	0.05
Level 3 Front	22.92	22.90	0.02
Level 4 Front	21.39	21.40	0.01
Mean Error = 0.029 m			

5.7.4. Deviation of Primitives between Wireframe Model and Textured Model

In order to measure the deviation of the primitives in the wireframe model with the texture model the corners of the monastery is measured with a point tool this point will deviate from the modelled corner. The size of the deviation depends on image orientation accuracy, degree of generalization and the measurement of uncertainties.

Table 11 shows the XYZ coordinates of 3D measured points and the XYZ coordinates of 3D model points. It also shows the distance between 3D measured points of the wire frame model and the 3D modelled points of the texture model.

Table 11 : Distance between Measured 3D point and Modelled 3D point

Primitives	Measured 3D Point			Modelled 3D point			Distance (in meters)
	X	Y	Z	X	Y	Z	
Level 1 cube	-20.797	24.606	-29.100	-20.805	24.619	-29.075	0.0285
Level 3 cube	-20.307	21.180	-28.218	-20.310	21.192	-28.200	0.0314
Level 4 cube	-19.902	20.005	-27.782	-19.899	19.995	-27.793	0.0152
Level 6 cube	-23.636	6.653	-7.574	-23.641	6.643	-7.582	0.0134
Level 7 cube	-11.884	18.099	-23.751	-11.913	18.135	-23.711	0.0610
Level 8 cube	-9.685	15.596	-22.257	-9.689	15.599	-22.259	0.0059
Mean Error = 0.0259 m							

During the modeling process the primitives are stacked on top of the actual building of the image. The size and shape of primitives are generalized to fit the shape and size of the building structure. This can be seen in figure 5-8. This degree of generalization leads to deviation between the wireframe model and texture model, this happens due to the simplification of the semantics of the 3D primitive. The purpose of generalization is to decrease complexity for the primitives and also eventually it reduces the storage space for 3D model which can be beneficial for

catalogue of cultural heritage structure. This deviation is also a result of the orientation of the images, which can help in understanding how well the camera has been oriented around the structure. The deviation in the models is the source of uncertainties in the measurement. Measurement uncertainties can be observed on the texture model when spatial distance measurements on the 3D model are taken from the acute angles, though these uncertainties are very small but it proves the deviation between models.

The mean error is the deviation between the 3D modelled points in wireframe model and 3D measured points in the texture model. The mean error is 0.0259m, which means that there is a deviation of 2.59 cm between the models. This amount of deviation is quite minimal and it shows that the quality of the 3D model is relatively good.

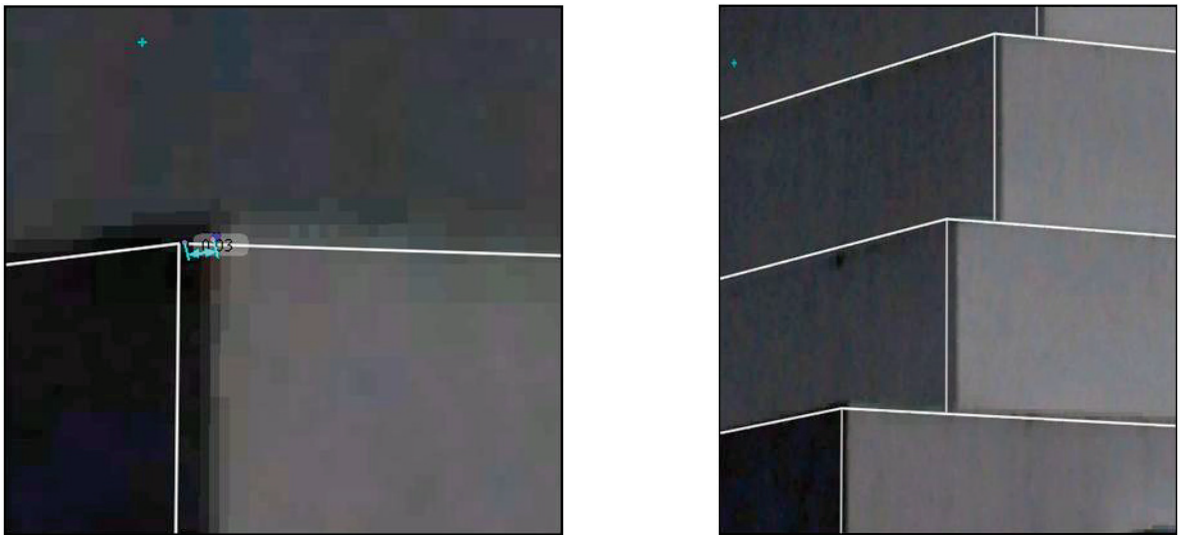


Figure 5-8 : Difference in distance between wireframe model and texture model

6. CONCLUSION AND RECOMMENDATIONS

The quality of free to use software in comparison with professional software has been evaluated. The results show that for the purpose of cultural heritage documentation, PMVS and 123D are the most suitable software options as they are able to model most of the structure. PhotoModeler tends to generate dense point clouds but is unable to reconstruct the entire building. The internal accuracy of PMVS is the highest. This shows that the model generated by PMVS has low random errors and noise. PMVS only requires camera orientation parameters and images to create a point cloud. Autodesk 123D only required images to be uploaded on the server. This takes the labour out of process of modeling and amateur users can also create 3D models that have high accuracy. It is finally assessed that the overall Empirical accuracy of open source and free to use software is better than professional software.

The orientation accuracy of Autodesk 123D (open source) is higher than that of PhotoModeler, which is professional point cloud modeling software. This shows that open source and free to use software is a low-cost alternative to expensive professional software that is currently used commercially for cultural heritage documentation. Not only is the open source an economically beneficial alternative, the accuracy of the software is also at par and even better than the professional software.

A benefit of PhotoModeler, professional software is that the user is able to generate and visualize both, point cloud based models and CAD-like models in a single environment. Another benefit is that the user is able to manipulate the process of modelling a lot more as it is done manually in PhotoModeler.

Orientation accuracy and degree of generalization result in the deviation of primitives between the wireframe model and texture model, introducing measurement uncertainties into the model. CAD-like modeling is also used to generate a 3D model of the monastery. The accuracy of the model is 2.9 cm. This is within close proximity of the theoretical accuracy, which was calculated to be 1cm as parallel accuracy and 6 cm as depth accuracy. This shows that CAD-like model of monastery created is highly accurate for cultural heritage documentation.

6.1. Recommendations

- Further work can be done on CAD-like modeling by carrying out a comparison between open source and free to use software and professional software
- The assessment of 3D primitives for generalization can be studied further in cultural heritage documentation to minimize the data storage space.

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APPENDICES

Appendix A:

Resolution Analysis for CAD-like Modelling:

Table 1: Deviation of wireframe model at different resolutions

Primitive (Corner)	Deviation (in meters) Resolution 512 pixel	Deviation (in meters) Resolution 1024 pixel	Deviation (in meters) Resolution 2048 pixel	Deviation (in meters) Resolution 4096
Level 1 cube	0.05	0.03	0.03	0.02
Level 2 cube	0.05	0.02	0.02	0.02
Level 3 cube	0.08	0.02	0.017	0.014
Level 4 cube	0.06	0.04	0.03	0.01
Level 5 cube	0.08	0.07	0.05	0.04
Level 6 cube	0.05	0.04	0.03	0.03
Level 7 cube	0.05	0.03	0.03	0.02
Level 8 cube	0.05	0.02	0.01	0.02
Level 9 cube	0.04	0.03	0.02	0.02
Level 10 cube	0.02	0.03	0.04	0.05
Level 11 cube	0.03	0.03	0.03	0.04
Dome cylinder	0.06	0.03	0.02	0.02
Level 12 cube	0.09	0.05	0.04	0.03
Top cylinder	0.10	0.05	0.04	0.04
Mean	0.05	0.035	0.029	0.026
Standard Deviation	0.022	0.014	0.010	0.011

Appendix B:

GPS points used in orientation accuracy:

Table 2: GPS points for coordinate transformation

S.N.	Mode	Carrier	Frequency	Northing	Easting	Height
1	Static	Phase	L1	30° 15' 42.36978" N	77° 59' 47.19467" E	577.8637
3	Static	Phase	L1	30° 15' 43.49161" N	77° 59' 47.15890" E	577.8554
4	Static	Phase	L1	30° 15' 42.94803" N	77° 59' 47.82460" E	577.8819
5	Static	Phase	L1	30° 15' 43.22289" N	77° 59' 47.57133" E	577.1112
9	Static	Phase	L1	30° 15' 43.48656" N	77° 59' 47.18488" E	579.6256
10	Static	Phase	L1	30° 15' 42.97527" N	77° 59' 47.80778" E	579.6458
11	Static	Phase	L1	30° 15' 42.60235" N	77° 59' 46.88796" E	578.1281