

Creation of 3D models of objects using alternative applications

Master Thesis

Study programme: N2301 Mechanical Engineering
Study branch: Machines and Equipment Design

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Thesis Supervisors: Ing. Radomír Mendřický, Ph.D.
Department of Manufacturing Systems and Automation





Master Thesis Assignment Form

Creation of 3D models of objects using alternative applications

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Rules for Elaboration:

The main goal of this thesis will be to make a practical comparison of professional systems for 3D digitization and alternative approaches and applications for creating 3D models.

Recommended methods for elaboration:

1. Become familiar with the laboratory equipment needed to implement the practical part of the thesis (contactless 3D scanners, software for 3D digitization) and the principles of 3D digitization.
2. Research of works on a similar topic – an overview of the current state of knowledge (will be part of the theoretical part of the thesis). Research of available alternative applications and tools for creating 3D models (eg SW 123Catch, AgiSoft-PhotoScan, cheap hobby scanners, mobile applications).
3. Formulation of the solved problem and its analysis, proposal of a methodical approach to the solution.
4. Design of suitable models for digitization, practical implementation of experiments (digitization of models using individual systems and applications).
5. Processing and evaluation of obtained data. Analysis and interpretation of results, comparison of individual variants according to various criteria (quality and accuracy of the model, affordability, area of use, time consuming). Discussion, conclusion.
6. Prepare paper on this topic for publication in a technical journal or conference.

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- [1] ZHANG, S. *Handbook of 3D Machine Vision: Optical Metrology and Imaging*. Boca Raton: CRC Press, 2013. ISBN: 978-1-4398-7219-2.
- [2] GOM MbH. *GOM Software 2018: Inspection Basic*. Braunschweig (Germany): GOM MbH, 2018.
- [3] GOM MbH. *Atos III Triple Scan, User manual – Hardware*. Braunschweig (Germany): GOM MbH, 2017.
- [4] Agisoft LLC. *Agisoft PhotoScan User Manual, Professional Edition*, 2014.
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ABSTRACT

The main goal of the thesis is to compare the physical systems for 3D digitization with Photogrammetry software available in the market. Other important component taken into consideration is the type of cameras. Due to widely available cameras a critical comparison with Professional camera and mobile camera were considered. This study aims on identifying the suitable software and camera sensor for achieving a complete and accurate model. The model output from Photogrammetry Software is analyzed with the output from the ATOS Triple Scan system. To assess the Photogrammetry Software different available software in the market were taken into study and from that a feasible number were considered. Two open-source and two paid software were taken into this study. Nikon D500, Canon IXUS 220HS, iPhone 12 Pro camera were utilised to capture the images and corresponding 3D models were generated. In the end, a study based on the results from each software were computed and the best software from the four which has a good output as close to Optical Scan were shown. 3D printed models from the images generated from iPhone camera for the four photogrammetry software and ATOS Triple Scan were done.

Keywords: Photogrammetry, 3D Reconstruction, point cloud, 3D Scanning, Accuracy

ABSTRAKT

Hlavním cílem práce bylo porovnat profesionální systémy pro 3D digitalizaci objektů (tzv. 3D skenery) se softwary, které pro tvorbu modelu využívají principu fotogrammetrie. Jedním z hodnocených kritérií byl i typ použitého fotoaparátu, přičemž bylo provedeno srovnání s profesionální kamerou a kamerou mobilního telefonu. Práce si klade za cíl identifikovat vhodný software a kamerový senzor pro dosažení úplného a přesného modelu. Výstupní modely „fotogrammetrického“ softwaru byly porovnány s výstupem ze skenovacího systému ATOS III Triple Scan. Byla provedena rešerše softwarů dostupných na trhu, přičemž pro podrobnou analýzu byly vybrány čtyři softwary - dva open-source a dva placené. K zachycení snímků byly použity fotoaparáty Nikon D500, Canon IXUS 220HS, iPhone 12 Pro. V závěru byly vypočítány průměrné a maximální odchylky od referenčního modelu a byl ukázán nejlepší software, který má dobré výstupy - nejbližší optickému skenování. Pro vizualizaci kvality vypočítaných modelů jednotlivých softwarů byly pro fotoaparát iPhone a pro model vzniklý 3D skenováním vyrobeny fyzické kopie modelů metodou 3D tisku.

Klíčová slova: Fotogrammetrie, 3D rekonstrukce, Mračno bodů, 3D skenování, Přenosot

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1. INTRODUCTION

Generation of 3D models has become necessary for various industries. Different fields of engineering require 3D model from physical objects for the purpose of visualisation of the object. Two types of 3D model creation are used one is Image Based Modelling and Range based Modelling. Although the availability of 3D scanners has increased rapidly but it doesn't come in cheap cost. 3D Digitization using large or small scale laser sensor prove to be very expensive due to the external equipment which are required to generate the 3D model of the scanned object. It also requires high performing computer to accurately form the model & with increase in size it becomes heavier which makes it difficult to carry to remote places where scanning is required. The need for producing a low cost 3D model where general public can utilize the benefit of the Technology has paved way for many innovations in this area. Many advanced techniques are being developed to develop a more accurate & precise 3D reconstructed models. Photogrammetry and Laser Scanning are the most used techniques to obtain the 3D point cloud fast and accurate. They can be complementing each other in several aspects.

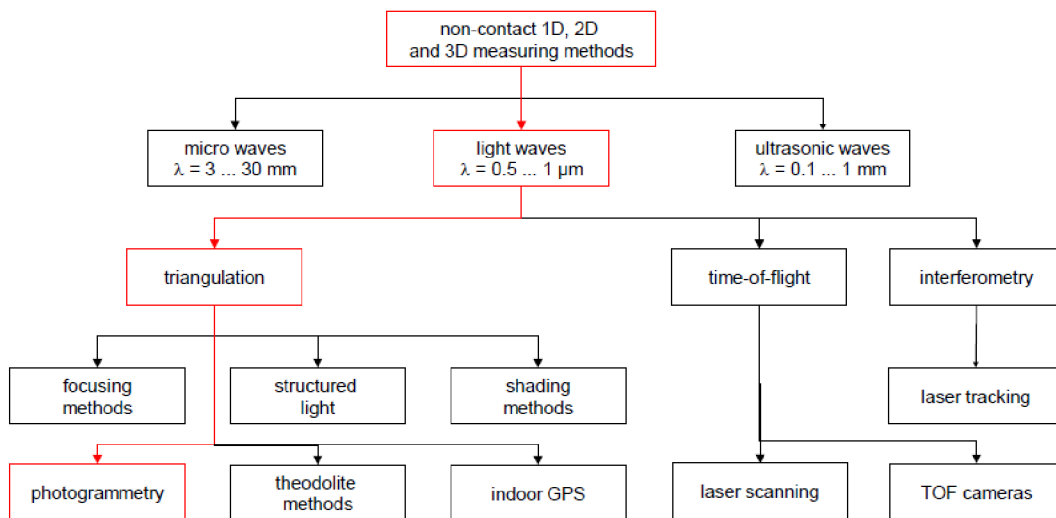


Figure 1: Non-contact Measuring Methods [1]

Laser Scanning of the real objects in order to obtain the 3D model is one of the technique of acquiring the 3D model. The quality of the end product increases only when the quality hardware is utilised i.e., best laser scanners, software. This in turn increases the costs multi-fold so the need for cost-effective generation of 3D model has brought to interest the low-cost software for creating these 3D models.

1.1 Brief Introduction to Photogrammetry

Photogrammetry is a technique where the object's geometric data is acquired from various photographic images. Photogrammetry was first developed during the 19th century. This technique provides a quantitative data instead of quality based data. From a 2D photo we can obtain only two-dimensional coordinates in order to get the three dimensional information from photogrammetry the so-called "stereoscopic viewing" principle is used. The creation of models using this technique prove to be inexpensive than many traditional scanners. Non-contact passive method of getting the data from images is also known as Photogrammetry. The photogrammetry technique leads to an innovation for cheap generating 3D reconstruction software for commercial use as well as research aspects. The basic principle is stitching together the overlapping photographs into a 2D mosaic. The photogrammetry takes into next step by identifying the position of the camera as it moves around the three-dimensional space to determine the X, Y, Z coordinates for each pixel of the original image which is also called as structure from motion (SfM).

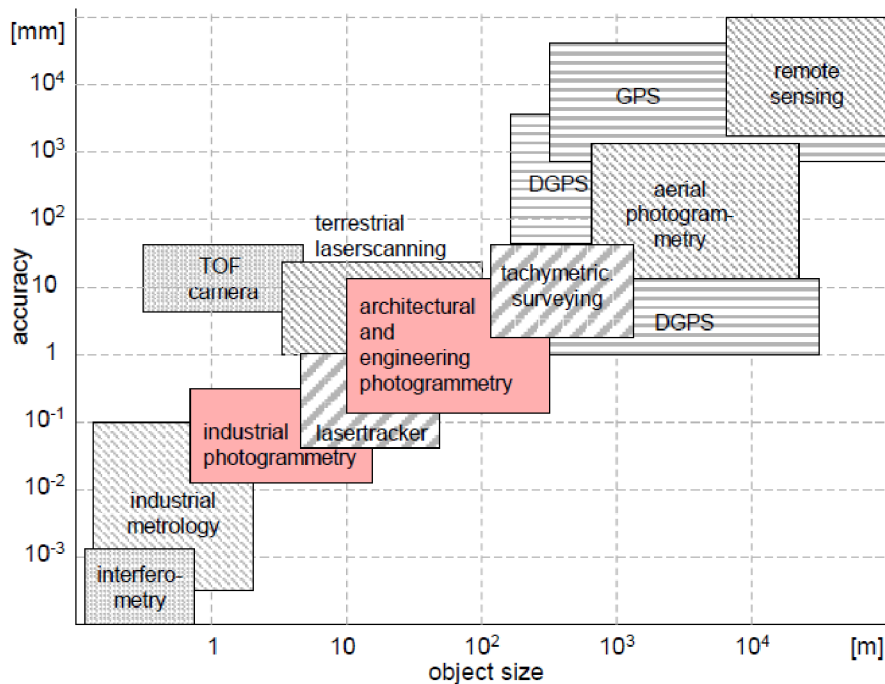


Figure 2: Relationship between measurement methods and object size and accuracy [1]

The Photogrammetry software working is mentioned as follows: The program automatically registers the shared points between every image and then calculates each and every point between them in the given 3D space. The output result is of a 3D point cloud that can be altered

into a 3D mesh. Some advanced version can provide a cleaning up the point cloud to enhance the overall quality.

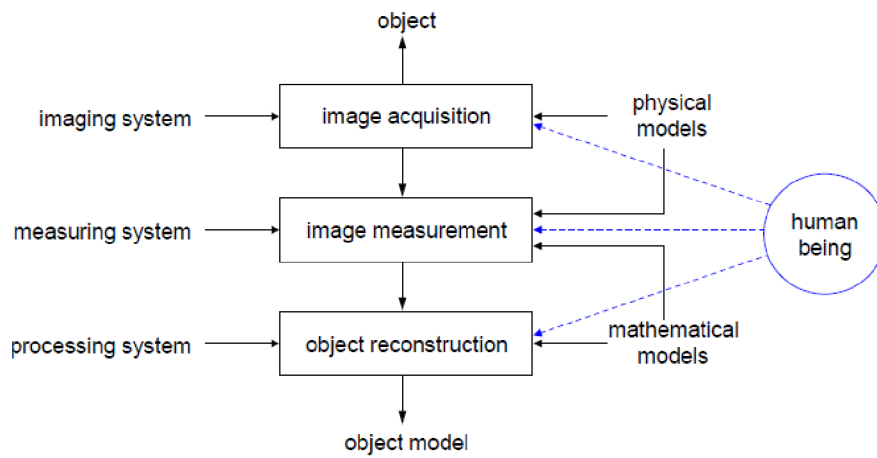


Figure 3: Photogrammetric process : Object to model [1]

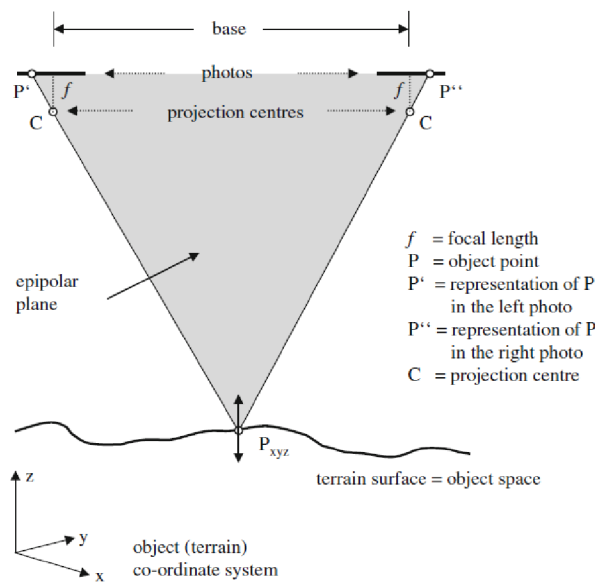


Figure 4: Stereoscopic Principle [2]

1.2 Classification in Photogrammetry

There are two classifications in photogrammetry they are terrestrial/aerial/long-range photogrammetry & close-range photogrammetry. As the name suggests, for aerial photogrammetry the camera is mounted on the aircraft/drone to photograph the large structures and then transform that data into 3D model. The drones have paved way for cheaper scanning of aerial photogrammetry. For close-range photogrammetry, the camera takes hundreds of

images to reconstruct the object later in the Computer. For obtaining high quality 3D model the pictures had to be overlapped by 80-90%.

Photogrammetry software can be grouped into three major categories: Web-based, Open-access, Commercial solution. Web-based allows limited amount of images getting uploaded into the cloud server whereas in Open-access the software can be used for free of cost & accessible to the public and for research. Commercial software is where the software gets perfectly integrated and ergonomically suitable for the users due to the demand the software offers. [3]



Figure 5: Close-Range Photogrammetry [4]

High quality digital cameras have become more popular these days also the price has been on the downward trend which have led to the recreation of precise 3D models for various applications involving Reverse Engineering of certain parts for the competitiveness in the Industry.

1.3 Review of previous work in relation with Photogrammetry

3D-reconstruction was done using various sensors such as Nikon D3200 camera, Fujifilm FinePix Real3D and iPhone 5s in comparison with the readily available software Open-source & paid. The comparisons were of two kinds, Comparison of cameras & Comparison of software (Metashape Agisoft, VisualSFM, SURE, Arc3D). The physical objects with a complexity in geometric shape can help determine the geometric accuracy. The evaluation criteria used to determine the accuracy was through point clouds. Four types of physical objects

were used such as Stone statue, Cylinder, Hexagon, Sphere. Under these software comparisons of algorithm used in these software was brought into consideration SURF (Speed Up Robust Feature) Algorithm, SIFT (Scale Invariant Feature Transform) Algorithm. The best results were obtained for the better camera lens (Nikon D3200 professional camera) used from the three and it proved to be obtain a more accurate model. Further research can be done for the camera lens parameters.[5]

This paper evaluates three photogrammetric software such as Agisoft Metashape, Bentley Context Capture, Reality Capture. This study involves small scale photogrammetry, the images were captured using Nikon D3400 camera and the data acquisition was completed. The processing time of each software was noted. The computational time plays a pivotal role in determining the best of three software. Upon comparing the process time Reality Capture(RC) was fastest & next is Context Capture(CC) final one was Agisoft Metashape. This study only considers the Processing time as a major parameter for comparison. Only thing to be noted is the manual editing availability in RC & Agisoft Metashape but lacks in CC. There is very limited research done on RC Software. The study suggests based upon the user preference & available resources one must choose the photogrammetric software.[6]

The article deals with two photogrammetric software Agisoft Photoscan (now called Agisoft Metashape) & Pix4D. Canon 5D Digital was used to capture the images. The research mainly composed of three levels of accuracy such as low, medium, high. Three parameters were compared to determine which is the best of two. The initial calibration differed for both the software, the next parameter was the linear and angular displacements measured during tachymetric measurement and coordinates measured by photogrammetric method. The investigation of angular shifts was done by determining the azimuthal angle & horizontal angle. Finally, visual analysis of the point cloud generated from both the software were correlated based upon number of points generated & visual appearance of the point cloud. The work states that it's not necessary to mark all photopoints for 3D photogrammetric study. [7]

Photogrammetry initially started to determine the geometric shape of large scale objects. This article delves into the topic called Digital Close Range Photogrammetry (DCRP). The integrated use of Digital cameras & commercial software paves way for accurate measurement of the object & 3D modelling. The research focussed upon calibration pattern obtained from OpenCV-open source calibration library. The hardware used in the study was Canon 400D camera which used to capture the images and generate a point cloud which in turn uploaded in

the software Agisoft for generating the 3D model. The approach was to explain a low accuracy Photogrammetric method compared to very costly micro scanning system using a powerful 3D digitization system.[8]

Structure-from-Motion(SfM) also known as multi-image photogrammetry is 2D to 3D modelling technique for digitizing of surfaces. The 3D models were generated using Agisoft Photoscan (now Metashape) and Autodesk ReCap Photo (now ReCap Pro). The research takes three things as selection factors for comparison such as availability, cost, ease of use (friendly GUI). The 3D models generated from the software whose point cloud data were extracted and inputted into software called CloudCompare were the cloud-cloud distance, average distances between the points and standard deviation were calculated. UAV Photography was employed to capture the landscape images and load into the software for the study. The final results suggested that the models generated using both the software are similar to each in terms of recreating the said model so the comparison came to be on the basis of the user experience. So some the shortcomings were considered to be the Autodesk ReCap software needs an internet connection because the model generation is done using the cloud storage so its inaccessible where no internet connection is present. So Agisoft proves to have an edge over ReCap of its versatility and easy to share features.[9]

The spatial data of the real world physical object can be obtained using the help of Digital Photogrammetry. In this study 5 Applications were selected based upon the image processing and analysis: VisualSFM, OSMBundler, Microsoft Photosynth, Photosynth Toolkit, Autodesk 123D Catch. The above open source applications were compared with a commercial photogrammetric software called Photomodeler Scanner(PMSC). There were certain conditions set for the scanning body such as shape-a regular geometric shape, dimensions-possibility of manufacturing and transportation, material-the type of texture and surface treatment. The SLR Pentax K-5 camera was used to capture the images. The result was compared in terms of the reconstruction density, completeness of point cloud and quality of photo texture. The differentiation in volume created by each of the software and the cross-sectional area were analysed. All these open-source software uses the fundamental principle called SfM method. The VisualSFM software appears to be best of all the five software in comparing the volume difference of the obtained 3D model. [10]

Image-based 3D modelling software proved to be a cost-effective method of creating a 3D model. In this research work the Free and Open Source Software (FOSS) compared with the Commercial software Agisoft Metashape for better evaluation of the obtained results. The generation of point cloud from the software were equated in Cloud Compare software. The software which were taken into consideration for the 3D reconstruction are VisualSFM, Python Photogrammetry Toolbox, COLMAP, Regard3D-FOSS. The study suggests a workflow procedure for inexperienced users to understand the general concept of the 3D reconstruction software. The steps are (1) Image acquisition, (2) Feature detection, matching, triangulation (3) Point cloud generation/sparse cloud (4) Dense cloud generation (5) Surface generation (6) Texture Generation. Selection of software packages are based upon platform independence, scalability, output format, accuracy, ease of use & installation, processing time. The default settings were used in all the Applications. An Operational consideration with a tabular format were categorized. The Camera used in are Canon EOS 600D. The final result suggested that Regard 3D as the best Open-source software from the five software.[11]

Multi-view image sets are used in reconstruction of 3D models utilising the software. Four of the most used software are taken into this study those are Agisoft Photoscan, Autodesk 123D Catch, VisualSFM with CMVS (Clustering Views for Multi-View Stereo), ARC 3D. The Digital camera used for this study is Camera Canon D60. The captured images were grouped into datasets are converted to JPEG format. The 3D models from the software are compared in the separate software MeshLab & Cloud Compare for the reconstruction density & meshing of the model. The MATLAB helped in solving the statistical data obtained from these findings. Also heat map of the software compared were found out. Quantitative analysis was performed to detect the Mean value, standard deviation, Time and plotted with the help of the graph. The graph involving empirical distribution function was plotted. The ranking for this research was not deduced since the results cannot be brought into a conclusion due to the broad aspect each and every software performs.[12]

The research study delves into topic of Laser Scanning and Photogrammetry. The article shares the successful implementation of photogrammetry in industry has some issues those are;

- Imaging Sensor- Camera lens parameters & Image processing
- Focussing & Illumination -Object shape, environment, lighting
- Imaging Configuration-Datum definition, Image size, Object Orientation & Calibration
- 3D reconstruction- methods of determination 3D coordinates & error statistics

The cameras used in this study are SLR camera, Digital SLR camera, High-speed camera (PCO dimax), Metric camera (GSI INCA 3), Multi camera (AXIOS 3D CamBarB2).The paper suggests an industrial photogrammetry where the static and dynamic camera are brought to comparison .Only a very few researchers are working in the field of Close-range Photogrammetry.[13]

1.4 Parameters needed to evaluate 3D Reconstruction Software

1. Reconstruction Density / Quality of Reconstruction[6, 11, 14]
2. Completeness of the point cloud[7]
3. Surface Quality[5]
4. Degree of deviations from reference data
5. Total Processing time[15]
6. Alignment Rate with & without control points [15]
7. Determination & Analysis of angular and linear displacements
8. Image Orientation: No of aligned images, Re-projection error, Error on scale bars[3]
9. Mesh Reconstruction Time[6, 14]
10. Geometric Accuracy

1.5 Camera Sensors

In Modern Photogrammetry, digital image capture is used with a camera hardware Digital Single Lens Reflex(DSLR) camera to transform the 2-D images into three-dimensional models. The camera sensor plays a pivotal role in reconstruction of 3D models.

The better the camera sensor better results can be obtained from the camera hardware. The 3D reconstruction software is influenced by the camera sensors.

For the 3D point cloud GSD (Ground Sampling Distance) of the sensors are evaluated as one of the criteria[5] to compare the sensors of the various sensors such as Mobile sensor, Professional sensors etc.,

The important camera parameters noted to be GSD, Pixel Size, Focal length, Sensor size, Sensor type, Resolution, Signal-to-Noise Ratio, Dynamic Range. GSD is the distance between pixel centers in each camera which is measured in object space. Smaller GSD is better for 3D reconstruction.

Table 1: List of Photogrammetry software available [16]

3D scanning software	License	Output File Formats
AGISOFT(Metashape)	Available at University	fbx
AUTODESK RECAP PHOTO	Free Trial 30 days	asc, cl3, clr, e57, fls, fws, isproj, las, pcg, ptg, pts, ptx, rds, txt, xyb, xyz, zfs, zfprij
Visual SFM	Open Source	ply
Photo Modeler	Free Trial 30 days	3ds, 3dm, dxf, igs, kml, kmz, las, ma, ms, obj, pts, byu, facet, iv, ply, stl, txt, wrl
Clustering Views for Multi- view Stereo (CMVS)	Open Source	ply
Reality Capture	Pricing	pg, png, XYZ, XYZRGB, tiff, bmp, dib, rle, jpeg, jpe, jfif, exif, exr, tif, wdp, jxr, dds, KML, KMZ, obj, ply, partlist, fbx, dxf, dae, bvh, htr, trc, asf, amc, c3d, aoa, mcd, wmv, mp4
SURE	Educational License	
ARC3D	Free	ply
Context Capture Mobile (Bentley Systems)	Pricing	3ms, 3sm, kml, dae, fbx, obj, dae, stl
COLMAP	Free	ply, vrml
Meshroom	Free	abc, obj
MicMac	Free	geotiff, ply, xml
Multi-View Environment	Free	MVE
Regard3D	Free	obj, ply

1.6 Some of the Photogrammetry Software

- Agisoft Metashape
- Mesh room
- AUTODESK RECAP PHOTO-Trial Version/Educational Version
- Visual SFM
- COLMAP
- Regard3D

1.7 Factors Affecting the Photogrammetry Accuracy

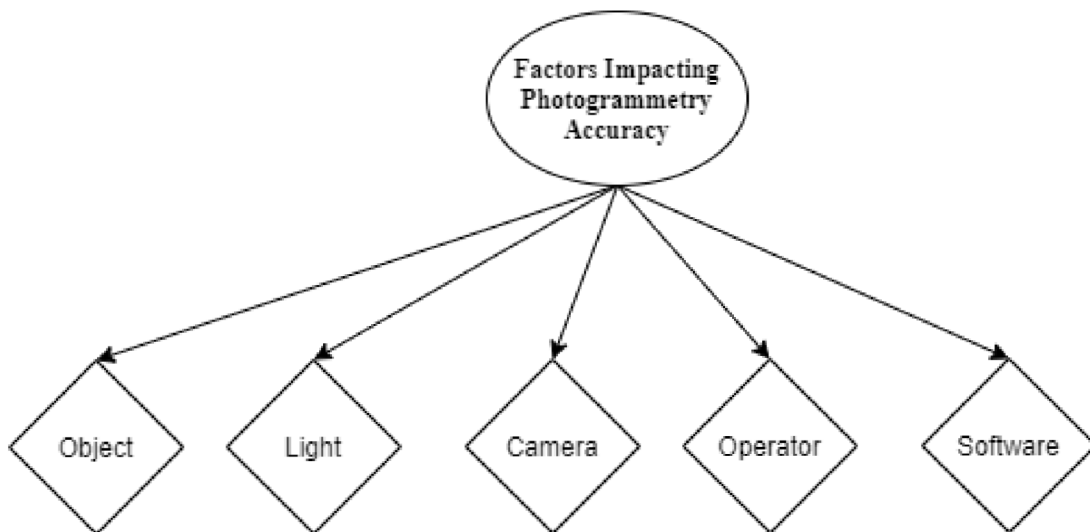


Figure 6: Factors affecting in creating a model using Photogrammetry

The user can create a 3D model using the 2D images and stitching all together. The image should contain a minimum amount shadows as well as the images should overlap as minimum of 60% as possible.

Based on the Figure 6: Factors affecting in creating a model using Photogrammetry the five factors are accounted for the overall accuracy of the Photogrammetry model.[17]

- Object-The object which needs to be scanned or photographed should not be transparent since the image gets reflected when capturing.
- Light- The lighting of the object properly makes great difference when capturing the images for the Photogrammetry.

- Camera- A in-depth analysis of the camera is described in the previous paragraph about the Camera Sensors.
- Operator- The foremost important thing to be observed is the skill of the photographer who requires utmost stabilization also proper knowledge in capturing the images for the Photogrammetry. This also involves the camera hardware which accounts for the main quality analysis for the photogrammetry software.
- Software- The quality of the software increases based upon the price it is offered. Well this research analyses each and every aspect of the software irrespective of the cost it is based upon.

1.8 Transformation of images into 3D printed models

Each photogrammetry software has different file as their output, some have extensions as *.obj, *.nvm, *.ply, *.rcm etc. These files with extensions are imported to other software such as MeshLab, GOM Inspect and are repaired and exported into a STL file for 3D printing.

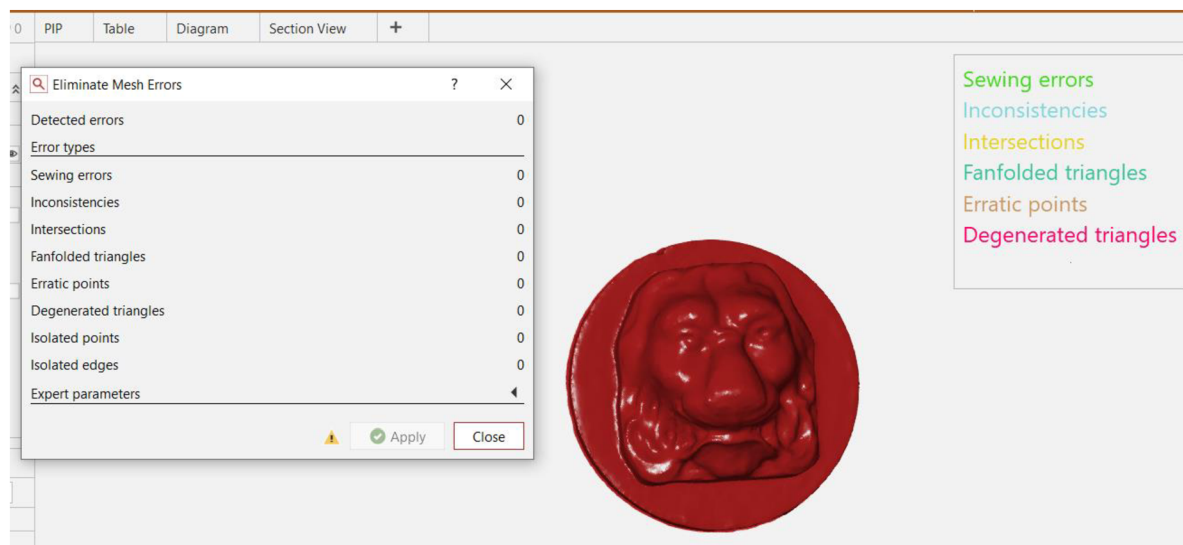


Figure 7: Detection of mesh errors before 3D printing

The STL file is then imported into a 3D printing software for generating a sliced model for 3D printing. [18]

The next step in the process after reconstructing the models digitally is to 3D print the models and check how it performs on the basis of the surface smoothness, completeness of the generated model.

This on the basis creates application in which this photogrammetry can be used instead of Laser Scanners and can even prove to be better alternatives where the laser scanners cannot be utilised in a way current generation cameras are used.

Before the 3D printing the models the reconstruction needs to look out for any kinds of mesh errors which affects the 3D printing of model. Figure 7 depicts how the GOM Inspect software detects several errors created during reconstruction phase and eliminates any errors present in the model without any issues.

This study involves 3D printing of the reconstructed models in a scaled version which compares in accordance with the Laser scanner based 3D printed model to understand the shortcomings in the 3D printed models generated from the photogrammetry software.

The 3D printer used in this study to evaluate and the print the stl model files is Prusa 3D printer. The material used for generating the physical 3D model is PLA. The layer thickness is around 0.15mm.



Figure 8: 3D printed model from ATOS Triple Scan

The 3D printed model which is a 1:1 version of Lion statue from ATOS Triple Scan is shown in Figure 8 taken as the nominal model to evaluate the photogrammetric models for proper evaluation in this study.

2. EVALUATION OF IMAGE-BASED 3D SOFTWARE

The selected seven Image based software whose introduction is described in this section. Also a short description of the software is given. For the convenience of the reader the basic workflow of the selected applications is described first. Further details about the software can be found in the reference papers. After the image acquisition stage in order to run each software some parameters need to be fixed for easy creation of the 3D model.

2.1 AGISOFT METASHAPE

The Agisoft Metashape is an independent software product which can generate large dataset of images in a short period of time into a 3-D model. It was founded by Agisoft LLC, Russia in 2006.

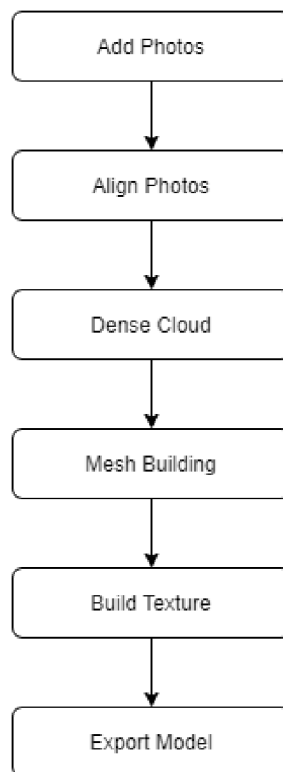


Figure 9: Agisoft Work Flow process chart

The image processing is entirely automated. The creation of texturized 3-D model is the main aim of the current work. Agisoft offers multiple licensing options (stand-alone, floating and educational) with price points depending on the license of choice.

The Metashape automatically builds precise textured 3D model using Digital images/photographs of an object. This program works with Windows, Mac-OS and Linux Operating system. The work-flow of the Agisoft Software is mentioned below.

The first step in the workflow is adding the captured photos to Agisoft software (step 1), image alignment of the photos is needed for the computation (step 2). Metashape computes the photographs and builds the geometry of object virtually (step 3). The density of the point cloud can be varied using Mesh building (step 4). The geometry gets constructed finally unwanted surfaces and textures can be removed by the user in the Build texture (step 5). Exporting the model is the next step in the process (step 6).

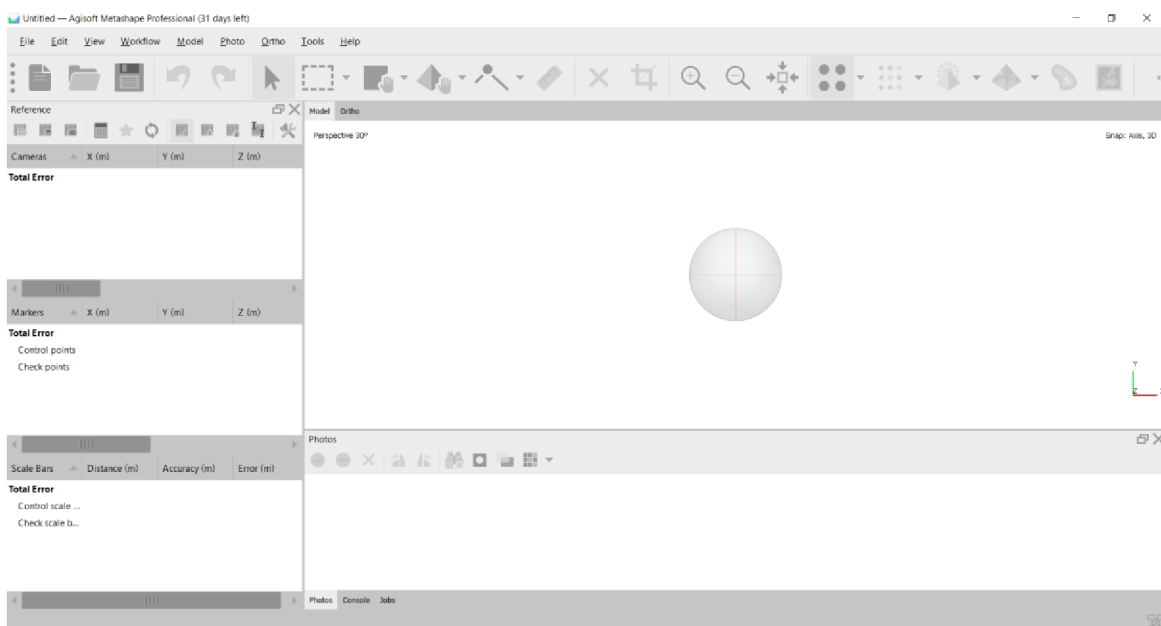


Figure 10: Agisoft Metashape Working Window

The output 3D model can be exported to various formats (OBJ,3DS, PLY, PDF) for further editing and rendering.

The Agisoft Metashape Professional Trial License was used in reconstruction of the 3D model. The working window of Agisoft is depicted above.

2.2 MESHROOM

Meshroom is a free open source Photogrammetric Software based on Alice-Vision framework. The Alice-Vision is Computer Vision framework which provides 3D Reconstruction and Camera Tracking Algorithms. This project is a collaboration between academics and industry to provide best Photogrammetric Technology for public.

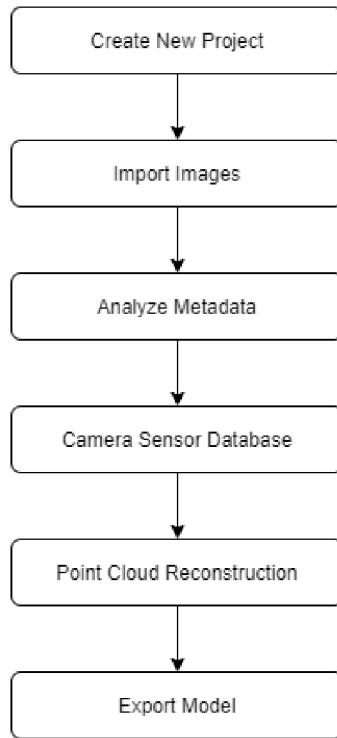


Figure 11: Meshroom workflow

Meshroom has a unique need for uploading the pictures where it requires the images metadata to be known beforehand to process the photos and generate a 3D reconstructed model. This sometimes makes it difficult for the users to upload the images from any format of the cameras. This feature has these shortcomings due to the data it requires for each individual images. The Meshroom uses the metadata embedded in the file to check the Focal length and other parameters for 3D Model build-up.

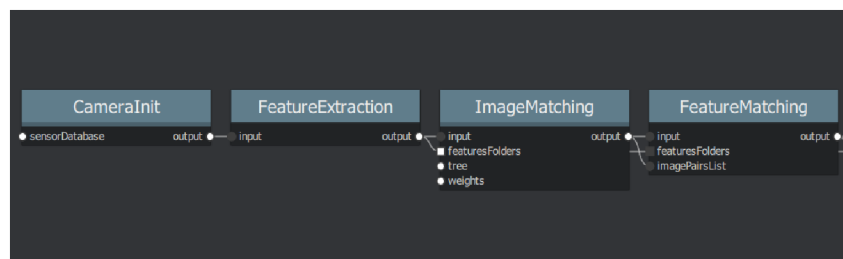


Figure 12: Work Flow 1

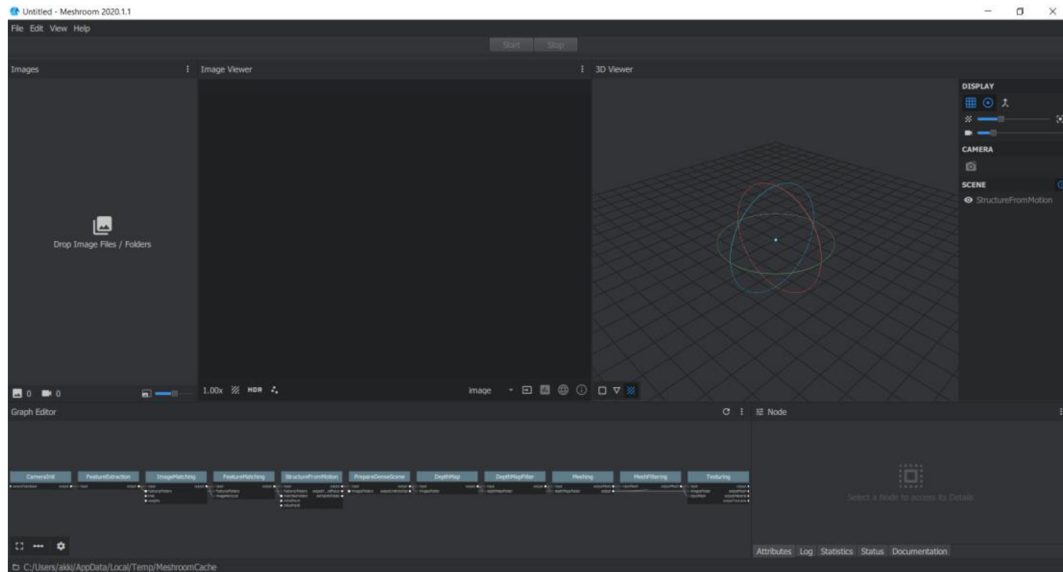


Figure 13: Meshroom Working Pane

This software has two types of reconstruction of the point cloud.

1. SfM: Structure-from-Motion (sparse reconstruction)
2. MVS: MultiView-Stereo (dense construction)

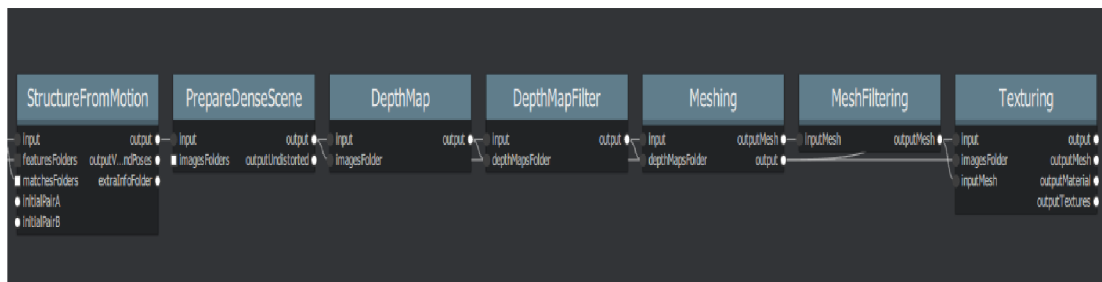


Figure 14: Work Flow 2

In the Meshroom software the images are uploaded irrespective of the minimum number of images. Then press Start button in the software. The reconstruction of the physical object takes place. The unique feature is displayed under the working window of the Meshroom software, where the user can see the background progress of each process taking place in the software. The Meshroom creates a point cloud at the end of its reconstruction. The user can visualize the reconstruction either as Solid model or Wireframe model or as a textured model. We can visualize each processing step during its process. Under the Meshing right-click and open the folder containing the .obj file is the output from this Software. For processing into *.stl file format the *.obj file needs to be imported into a free software called MeshLab. The MeshLab can export into preferred formats for further processing.

2.3 AUTODESK RECAP PHOTO

It is a 3D scanning software to create 3D models from imported images. It delivers a point cloud or mesh in support of BIM process. In this Application the Educational License was used for the creation of the model.

The Autodesk ReCap Photo software is used for the Photogrammetry. Initially the captured images are uploaded into the software. It requires a minimum of 20 images to obtain a 3D model. After the upload the no other changes the user can make in the model everything is done by the software itself.

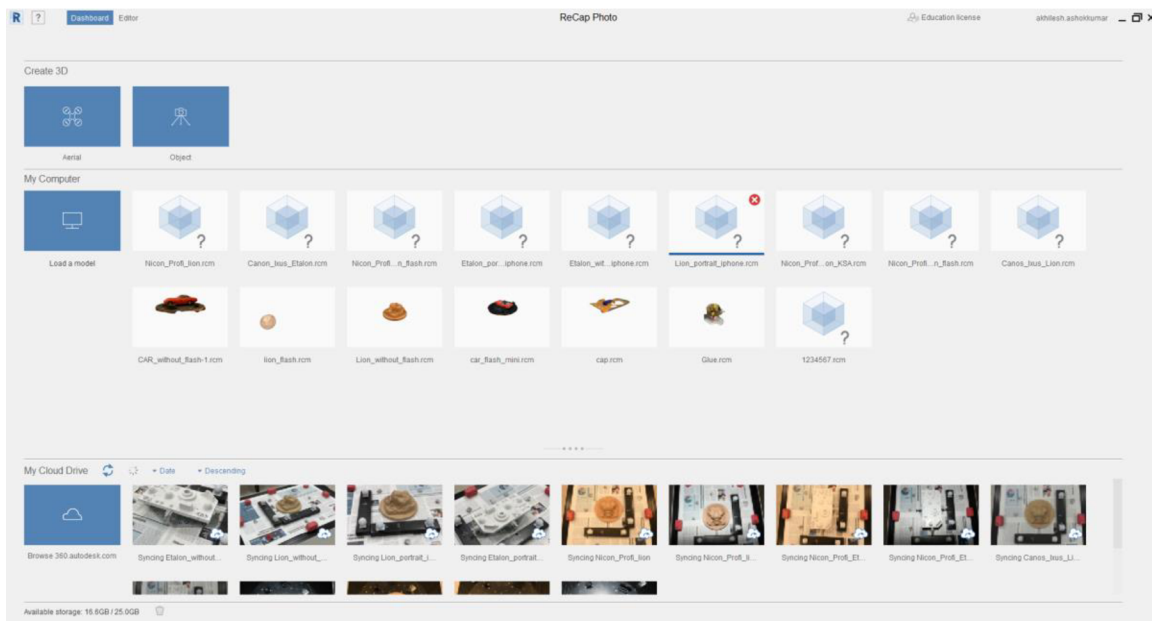


Figure 15: Working window of Autodesk Recap Photo

The images are uploaded into cloud the 3D reconstruction of the captured image is generated from the cloud server. The time for generating a model is based upon the number of images being uploaded in the application, the quality of the images also it has kind of priority for each and every model which needs 3D model generation.

The user interface is simple for any user as it just requires to upload a minimum of 20 photos and the software reconstructs the given 3D model with the images present in it. The educational license was utilised in this research for the 3D Reconstruction.

The output of the 3D model can be exported into formats such as *.stl, *.obj, *.ply, *.pts.

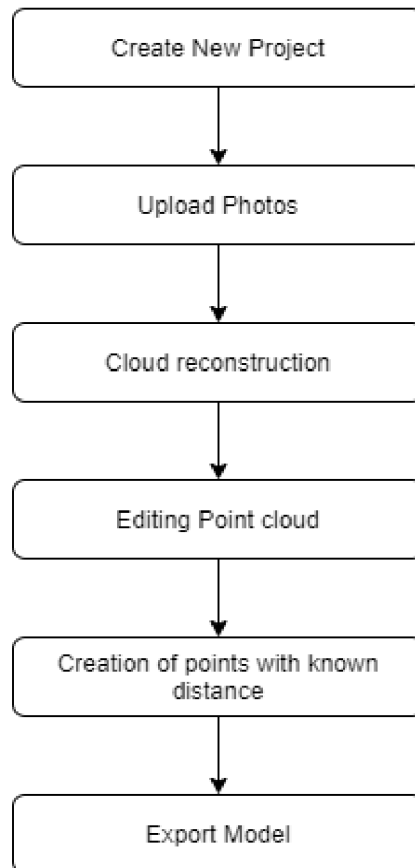


Figure 16: Autodesk Recap Photo Workflow

2.4 VISUAL SFM

VisualSfM is an academic open source software solution which can be used in Linux, Windows and MacOS which is developed by Changchang Wu.

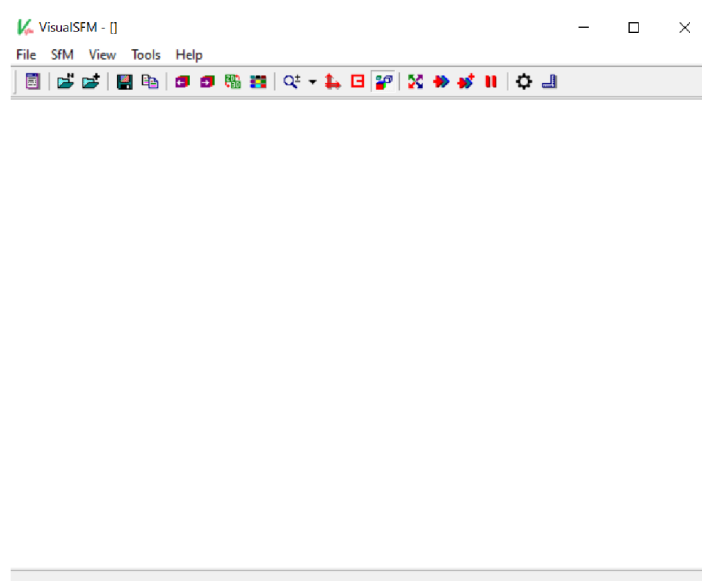


Figure 17: Visual SFM GUI

This software does not need any camera information as input. VisualSfM does not create a complete reconstruction, but it basically provides a point cloud that needs post-processing. The workflow starts with Adding images / importing multiple image files (step 1). It detects the images and determines all the parameters to obtain the photos. It finds all the matches in the image (step2). Matches found in the previous step are later transformed into points in 3D space (step 3). A dense reconstruction of point cloud can be achieved through PMVS/CMVS tool (step 4).

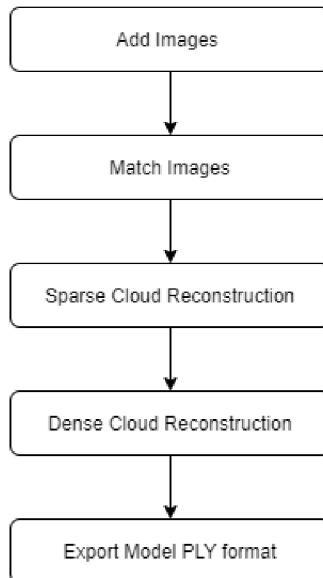


Figure 18: Visual SFM Workflow

The output file format is *.nvm format which gets saved automatically after the completion of Reconstruction. The experimentation using this Software was not possible due to some technical issues in the Software itself. The input formats of image file are in formats such as *.jpg, *.pgm , *.ppm . The images are loaded with the option Open+ multi images (step 1), where all the images are loaded into the VisualSfM. This software automatically detects the camera parameters automatically without any input from the users for the focal length, pixel size and camera manufacturer details.

The above details are also called as metadata which needs to be inputted in the image files for some photogrammetry software. After the loading of the images the next process is detect each features in each image and match them which is called as Compute Matches (step 2), for this feature the software has two algorithms in place which are called as Scale Invariant Feature Transform(SIFM) and SIFTGPU (a GPU variant of SIFT).

The next step involves creation of point cloud where the 3D reconstruction of the image begins by click the Sparse Reconstruction (step 3). A Dense reconstruction can also be created by click CMVS tool in Menu where the software prompts for a saving location of *.nvm file (step 4). The output file format of VisualSFM is *.nvm now export this to MeshLab and create *.stl file.

2.5 COLMAP

COLMAP is a Structure from Motion (SfM) and Multi-View Stereo (MVS) software which supports GUI Interface. The software was developed by Johannes L. Schoenberger[19] and is licensed under BSD license(Source:[20], visited: 11Dec.2020).

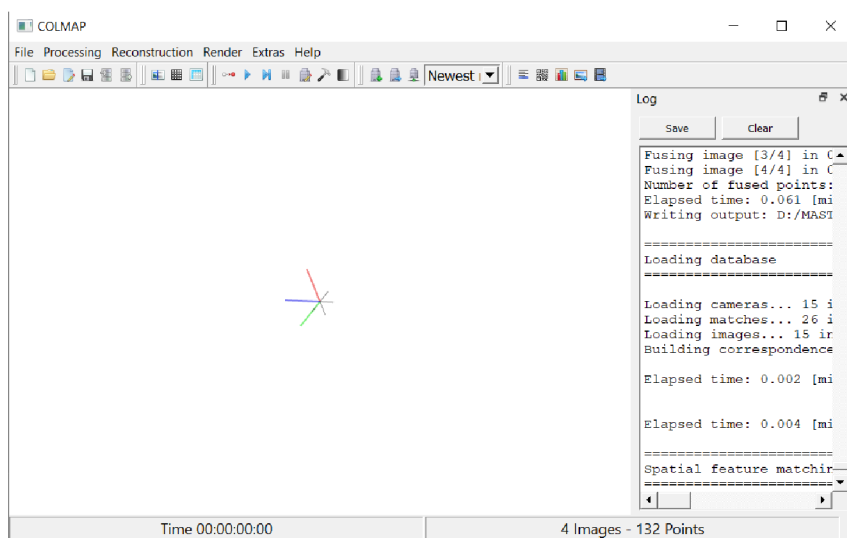


Figure 19: COLMAP GUI

COLMAP offers a single click Automatic Reconstruction of 3D Model. This has some trade-offs in comparing with step-by-step process of creation of 3D model in the software. COLMAP produces the 3D view while displaying cameras being included to the scene while it simultaneously creates a sparse point cloud. After this stage the point cloud can be exported.

The models can be exported in formats such as *.nvm, *.out, *.ply file format. Although the GUI looks to be so basic the reconstruction process by user is simpler than other open-source software. Generally, its output is imported into the MeshLab for further process. The first step involves opening *.bat file of the COLMAP software, which in turn opens the GUI of the COLMAP. The product user must specify the location of the project it needs to be saved (step 1), the image location where the photos are extracted (step 2), the next process involves feature extraction from the image set where once again the path way is created (step 3), after this tab

follows the feature matching (step 4), which is basically comparing the images which the obtained to create the given 3D model. Beginning of the reconstruction is generated by clicking Automatic Reconstruction (step 5). The final step is Meshing (step 6). The output can have exported into *.obj, *.ply, & *.wrl formats.

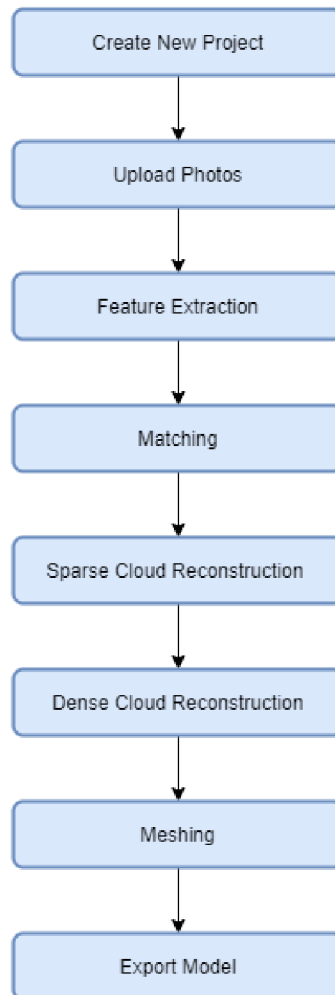


Figure 20: COLMAP workflow

2.6 REGARD 3D

The final photogrammetric software which is going to be compared is the Regard3D software which another free and open source structure from motion program that supports multiple platforms such as (Windows, Mac-OS, Linux). It has a simple and easy GUI. It has two output file format *.obj or *.mtl file format. At first new project has to be created in the Regard 3D software (step 1). Next the folder containing the Picture set has to be imported into the software (step 2), Computing the matches for the image set uploaded (step 3), Triangulation of point cloud (step 4), Generating dense point cloud (step 5), Exporting into MeshLab for exporting it into *.stl format.

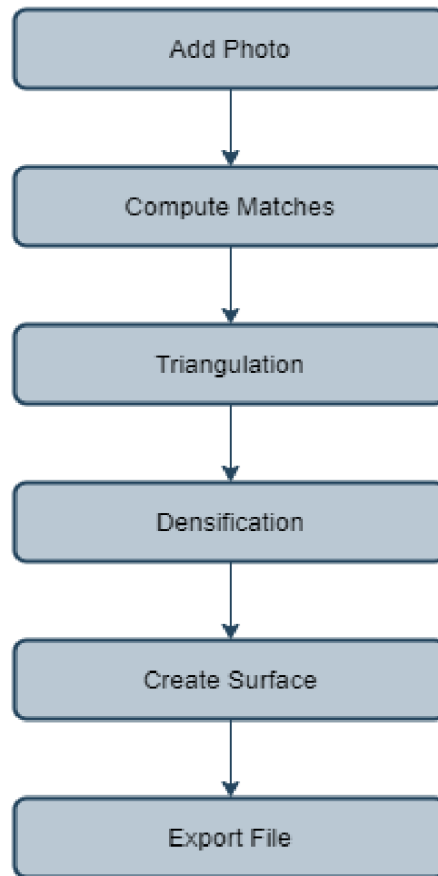


Figure 21: Regard 3D Workflow

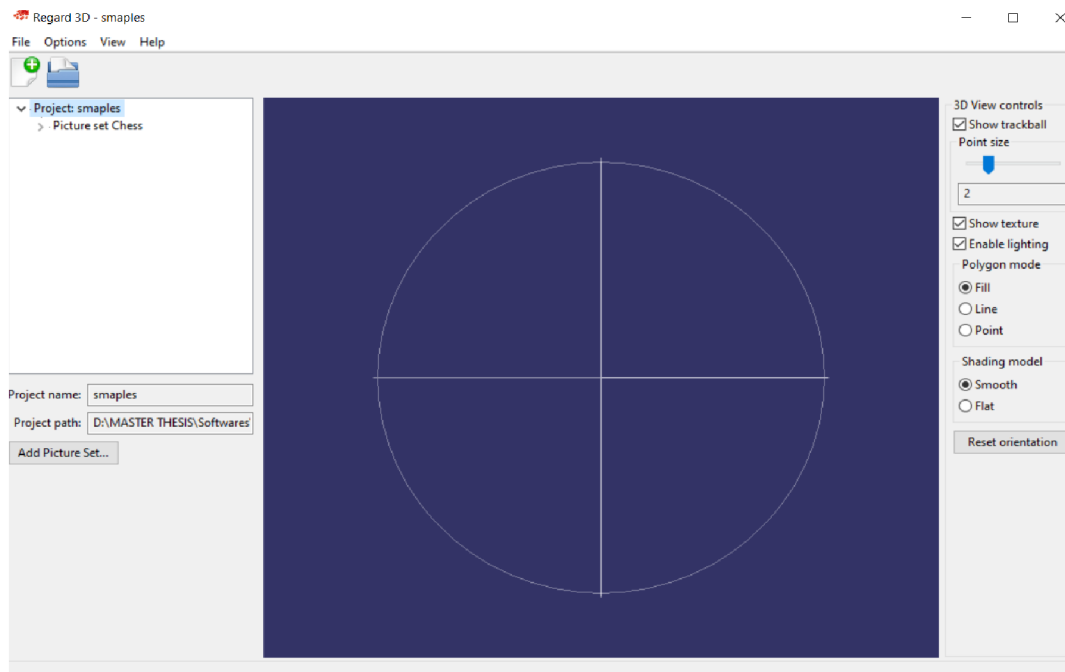


Figure 22: Regard 3D Working window

3. CREATION OF 3D MODEL

For the creation of 3D models using alternative software also with three different type of camera sensors some aspects need to be explained beforehand.

Materials taken initially:

1. Geometric Shapes
2. ATOS Triple Scan
3. Professional Sensor & Mobile Sensor
4. GOM Inspect
5. Image Dataset

3.1 Geometric Shapes

In order to evaluate the performance of the Photogrammetry two physical objects are taken into consideration. One object taken into consideration is a lion statue *Figure 23: Lion Statute*. The features are little complex.



Figure 23: Lion Statute

The Measurement Etalon in was designed in accordance to the basic shapes present in common engineering parts. For example, it has cylinders, holes, spheres, grooves, ribs. The external shape is easier to scan when it comes to scanning of inner parts of the etalon.



Figure 24: Real Model of Etalon before spray paint coating

3.2 ATOS Triple Scan

ATOS system is an optical scanning measurement system which is based upon Photogrammetry, Optical Triangulation and Fringe Projection Method.

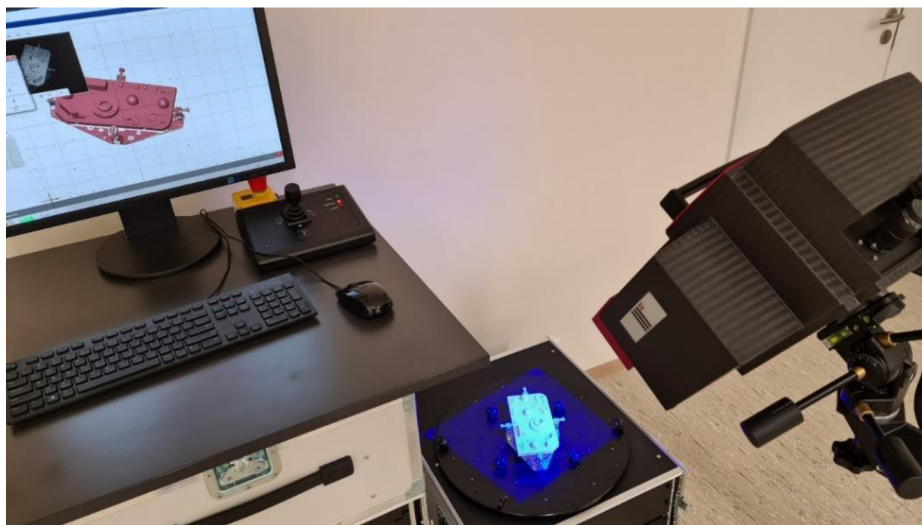


Figure 25: Optical Scanning of the Etalon using ATOS Triple Scan

The system uses Triple Scan principle in which it operates its projection unit. During scanning of the object precise fringe pattern are projected onto the surface of the object which needs to be measured and those are capture by the two cameras and the projector unit. The 3D surface points are calculated from the intersections measured. The Projector Unit uses Blue Light Technology. The sensor works as such involving the narrowband blue light interfering the ambient light which can be filtered during image acquisition stage.[21][22]

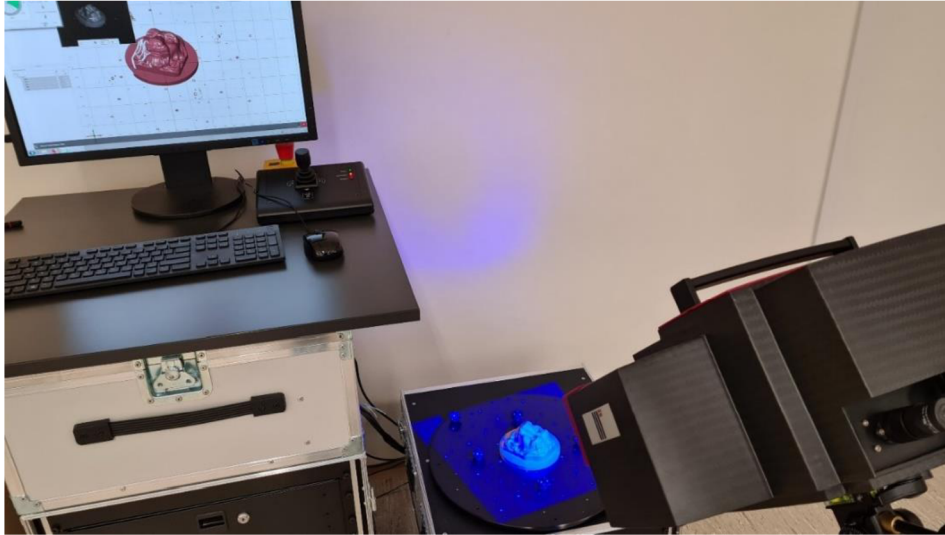


Figure 26: Optical Scanning of Lion statue using ATOS Triple Scan

The models were coated with a special coating since the shining surfaces are difficult to be scanned under the optical scanner. The spray used can be seen in Figure 27.



Figure 27: Laser Scanning Spray

3.3 Camera Sensors used in this study

Nowadays several camera sensors are available for the user from portable to large camera. The research wanted to focus on three different aspects so a Digital camera, a compact camera and a mobile phone camera were taken into this study and evaluated in basis of how this performs when it is fed into the photogrammetry software. Table 2 represents the camera specifications of the three camera used in this work.



Figure 28: Cameras used in this study

Table 2: Camera Specifications

Camera Specifications	Nikon D500	Canon IXUS 220 HS	iPhone 12 Pro
Manufacturer	Nikon	Canon	Apple
Pixel Size	4.2 μm	1.54 μm	1.4 μm
Focal Length	24 mm	7 mm	4 mm
Sensor Size	23.5 mm x 15.7 mm	6.17 x 4.55 mm	7.01 x 5.79 mm
Sensor Type	CMOS	BSI-CMOS	-
Resolution	5568x3712	2816x1880	4032x3024
Aperture	<i>f/8</i>	<i>f/4</i>	<i>f/1.6</i>
Shutter Speed	ISO-1000	ISO-800	ISO-32
Image Format	JPEG	JPEG	HEIC/JPEG

The image parameters and all the camera settings done in this study using the automatic settings available from the manufacturer no modifications were done in the camera to perform capturing of the images.

3.4 Pre-Processing of Generated models using GOM Inspect

The models generated from the ATOS Triple Scan and the Photogrammetry Software needs to be pre-processed in order to utilise it for 3D Printing or other evaluation. So the steps or procedure involved in processing of the models are explained below.

3.4.1 Clean-up of models

Only the model subjected to evaluation not the other areas are considered to comparison.

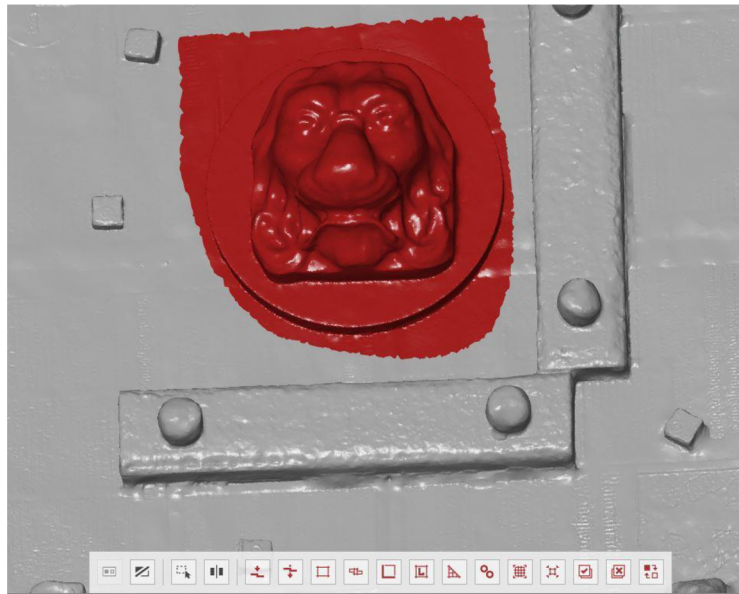


Figure 29: Selection of model and clean-up

For the assessment only the model is focussed for consideration not the others are needed. From Figure 29 we infer that the lion model is only the main intent for this study. So after the calculation of spheres and finding out the Scaling factor using the option “Select through feature” in GOM Inspect we select only the area of interest and click on “Invert Selection” and press “Ctrl+Delete” the delete other surfaces. Now with option “Select Along line” clear the boundary edges to define the outline of Lion model clearly and further steps are followed in the next paragraphs.

3.4.2 Creation of Spheres

The models generated from the Photogrammetry software are in improper scaling so in order to correct certain steps are followed to scale up the given model.

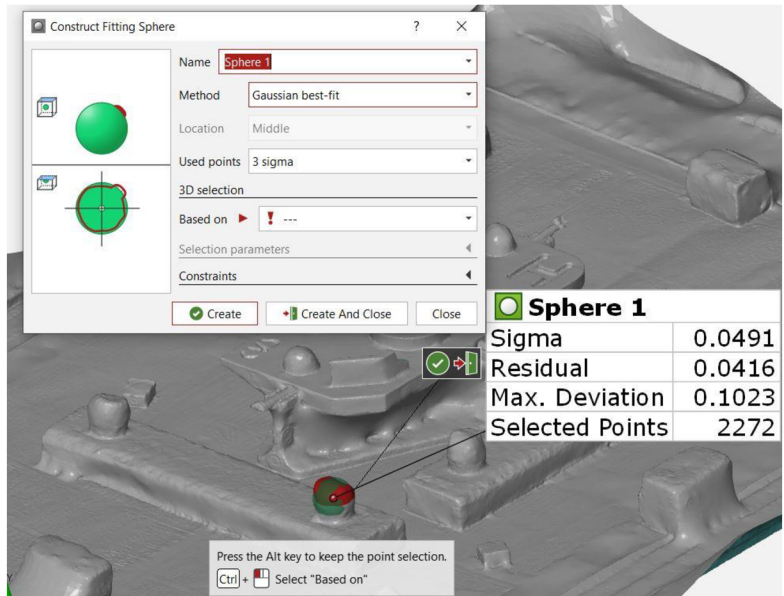


Figure 30: Creation of spheres using Gaussian best fit method

In order to find the correct scaling factor for each generated 3D model a different approach was executed to determine the model size. Initially a sphere is constructed to fit exactly to reprise it in the model. The method used was “Gaussian best-fit” for the construction of the sphere. Totally 4 spheres were created and the distance between sphere 1 and sphere 2 also similarly sphere 3 and sphere 4 were measured and noted from the model.

3.4.3 Calculation of Distance between the spheres

Initially two rods named as “Rod-1” and “Rod-3” were taken with their center-center sphere distance calculated. The actual distance of Rod-1 is 160.28mm and Rod-3 is 160.49mm. For each model generated from Photogrammetry software there will be a different value between the spheres respectively.

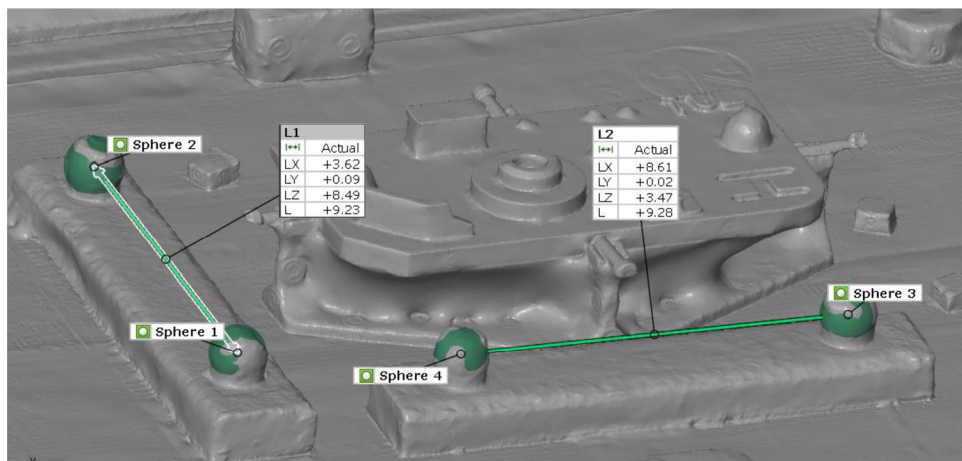


Figure 31: Distance between spheres generated from Photogrammetry model

The Figure 31 depicts the actual value from the 3D model the ratio between the real distance and the distance from the model is taken as the Scaling factor. The measured value of L1 is 9.073mm and L3 is 9.115mm and while dividing it with the Rod-1 and Rod-3 distance the factor found to be averaging around 17.63642. The Scaling factor utilisation is further explained in oncoming paragraphs. This procedure greatly helps in scaling up the model as accurate as possible. But prone to some deviations as the photogrammetry software does not allow any modifications based on this issue.

3.4.4 Mesh editing

The generated models from each software is mostly with some errors or with improper model generating so it is a must to some pre-processing to obtain a complete model.

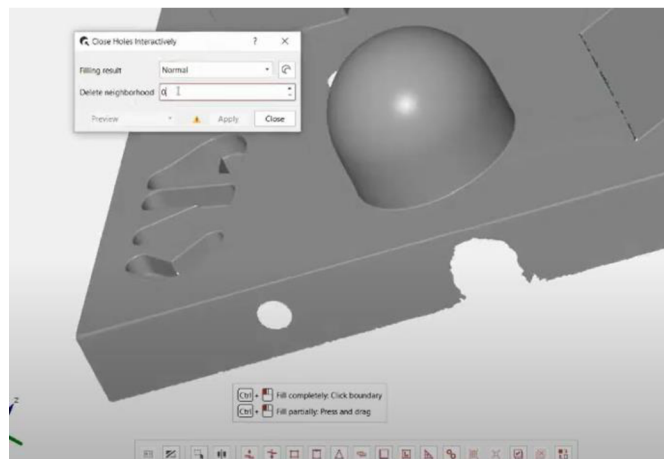


Figure 32: Closing of holes in ATOS model of Etalon

This mesh editing was mainly utilised in creating the nominal model which is created from the output of ATOS Scanner. The main features used in the GOM software was closing holes and smooth mesh. Some features involved in mesh editing are visualized in Figure 33.

- **Close holes:** This is one of the main feature present in the GOM Inspect Software were all the incomplete models generated can be filled by the use of this feature. Complete closure might sometimes result in bad model generation but this only can be used to some extent where only some regions needs to be closed whereas closing very large holes is a time consuming process. Also it cannot be processed all the time due to heavy processing done to the computer hardware.
- **Smooth mesh:** The other important feature involved is the smooth mesh feature were all the irregular surfaces in the mesh are removed using this option present. This feature was used to refine the ATOS Triple Scan model alone, since it was used as a nominal

model for comparative analysis for the other Photogrammetry models. The other models were not modified by external factors because the study is for checking its performance of each software.

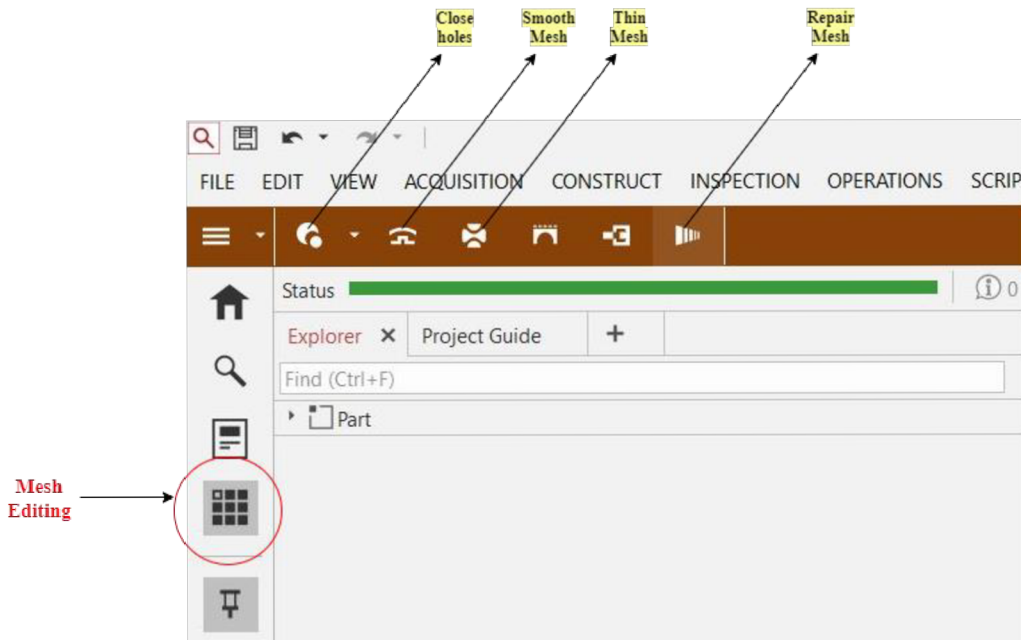


Figure 33: Mesh Editing feature in GOM Inspect

3.4.5 Scaling

The models generated have different scaling these needs to be changed to proper scaling in order to compare each and every model real time.

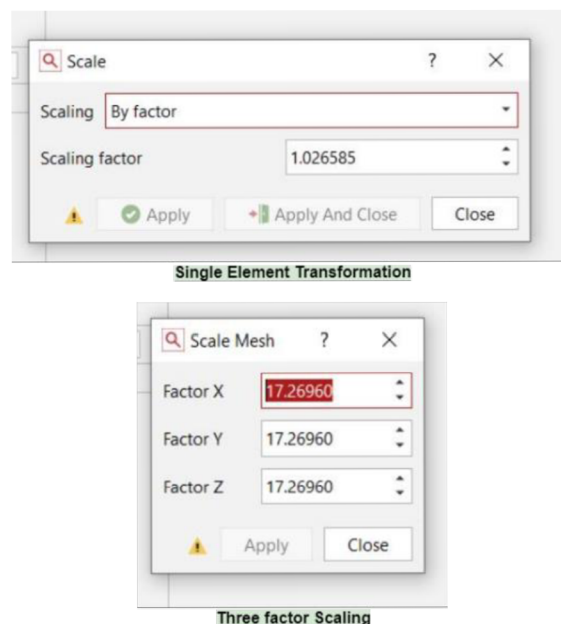


Figure 34: Two types of Scaling in GOM software

4.RECONSTRUCTION USING PHOTOGRAMMETRY

SOFTWARE

From the previous mentioned six software only four were used for the comparison. Due to some complications arose in the user experience and quality of model obtained. The comparison was brought to be two licensed(paid) photogrammetry software vs two open-source photogrammetry software.

4.1 Image Dataset

As mentioned in the beginning of this study three camera sensors are used in the reconstructing the two models. Before capturing the models certain procedure needs to be followed in order to precisely generate the reconstruction model.

4.1.1 Dataset of Etalon

The Figure 35 is captured using the Professional Camera Nikon D500 with Auto settings 40 images were captured and inputted into respective photogrammetry software.

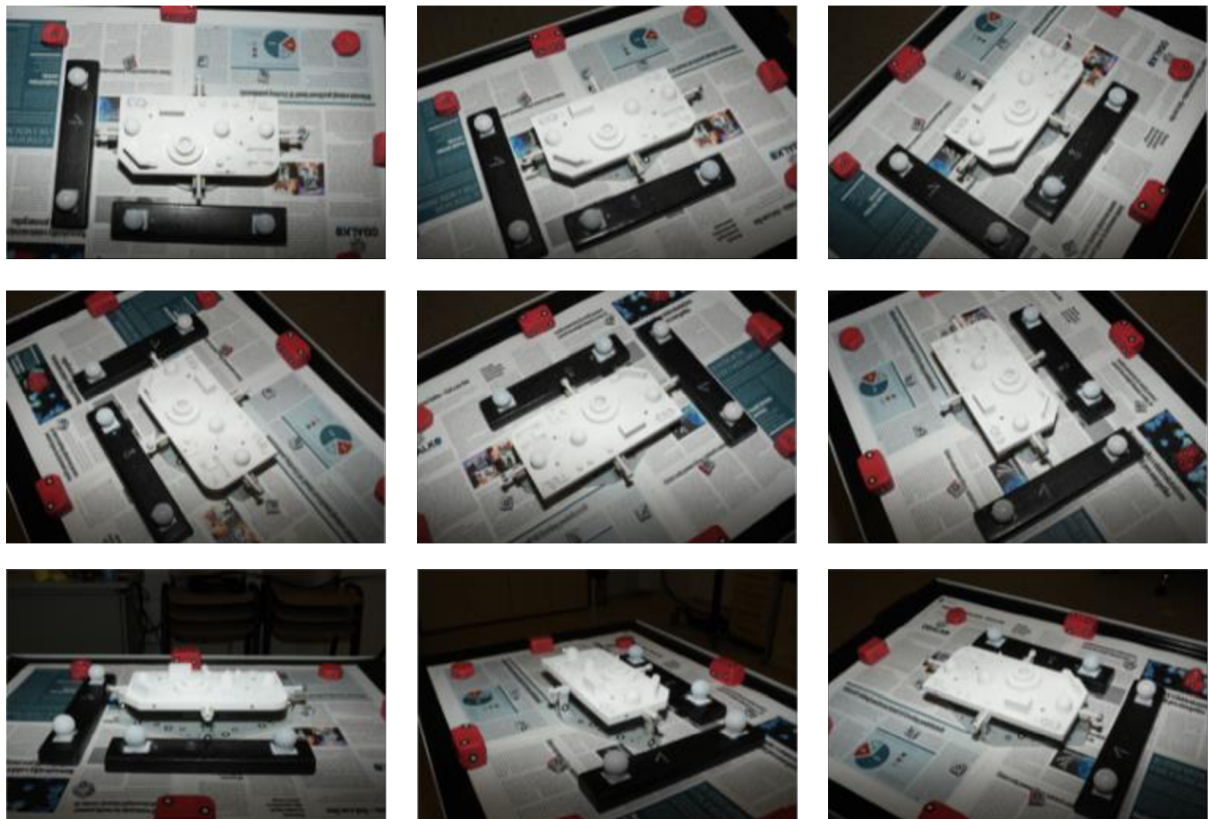


Figure 35: Dataset of Etalon with spray-paint

The image capture approach involved top-down approach by moving up and down the camera to cover entire body of the object.

Similarly, for the other two sensors (iPhone & Canon) separate images were captured with auto settings also with no compromise in the image quality for capturing the Etalon model.

The dataset of etalon has been captured from three camera sensors with two datasets from each camera. So in total of 6 image datasets from three cameras were computed in this study.

4.1.2 Dataset of Lion Statute

The same procedure was followed in capturing the Lion statue using three different camera sensors.

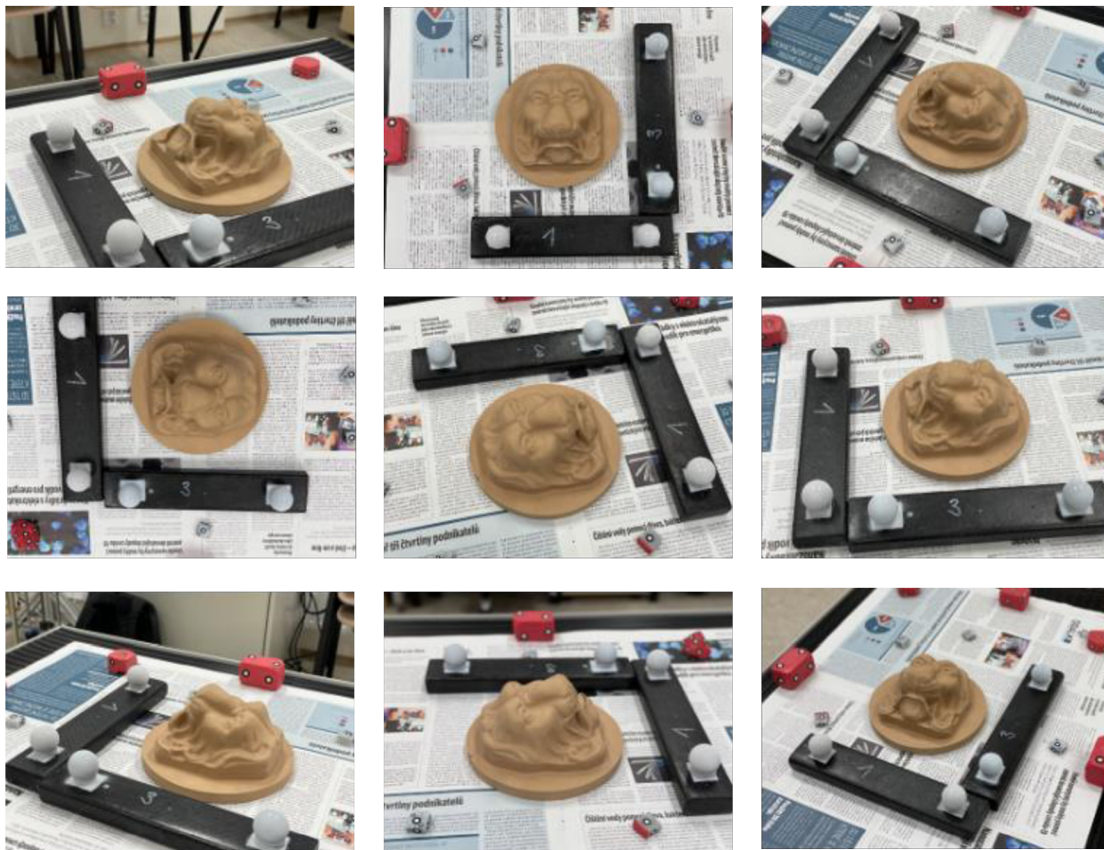


Figure 36: Camera Dataset of Lion statue

The Figure 36 of Lion model captured with the iPhone 12 pro camera sensor in Auto settings and about 47 images were captured and uploaded it into respective photogrammetry software. Also similar procedure followed to other camera sensors in the study.

The Lion statue image dataset too has 6 image datasets from the three camera sensors utilised in this study.

4.2 Outputs of 3D models from each photogrammetry software

The following data shows the model generation from each software and comparison with the three cameras Nikon, Canon, Apple utilised in this study for reconstruction. The first results of 3D model are from Etalon and followed by the Lion model. From the below generated models no modifications were done to any of the model in terms of externally refine the mesh.

The images from each sensor have two different datasets. So considering for model Etalon the sensor Nikon has two Image dataset similarly for Lion statute. The total dataset of images utilised in this study comes to 12 datasets. From the 12 datasets the models generated from the four photogrammetry software comes to 48 generated models.

Only the best models generated from 48 were chosen for further study in comparison for the Software and its evaluation. About 21 models were chosen from 48 models to compare the camera sensors with its software.

4.2.1 Agisoft

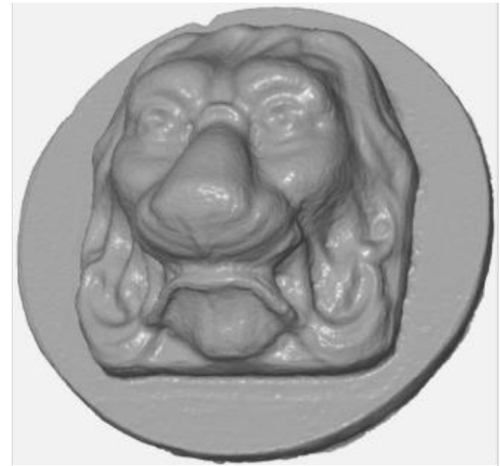
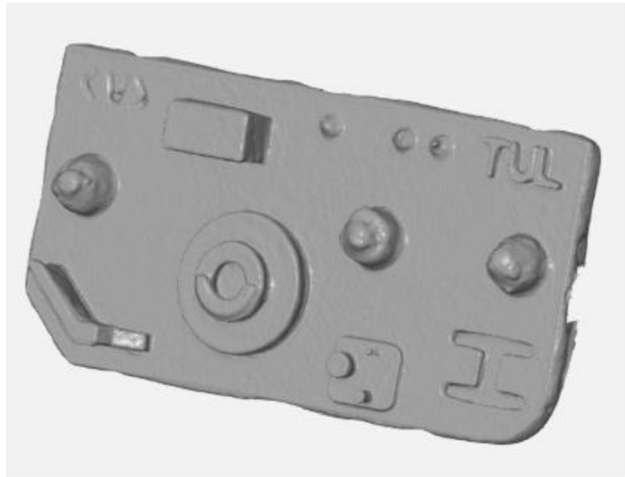
As we already stated about the working of the Agisoft software, the processing from in each camera sensor is mentioned along with the generated models from this Photogrammetry software.

The images format with .jpeg was uploaded into the Agisoft software. The software prompts for a Mesh quality range and it varies from Low to Ultra High mesh quality. For all the generated models High mesh quality setting was chosen in order to reduce the model generation time involved.

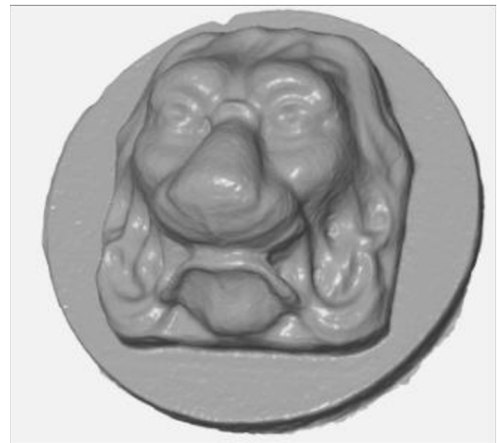
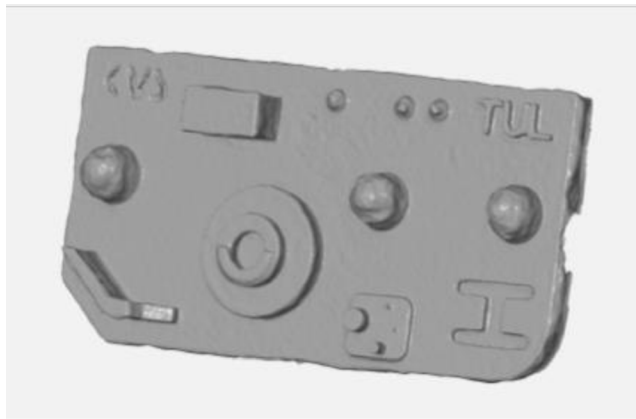
From the Figure 37 it depicts the model quality from each camera sensors. The details to be noted is how well the image quality is captured and the finer the details it can generated as a 3D model.

This clearly shows the quality of the images from the Canon IXUS 220HS not good with the mesh surfaces not smooth. Also the KVS logo from etalon in Canon were smudged very badly and the Lion statute center part could not be processed properly.

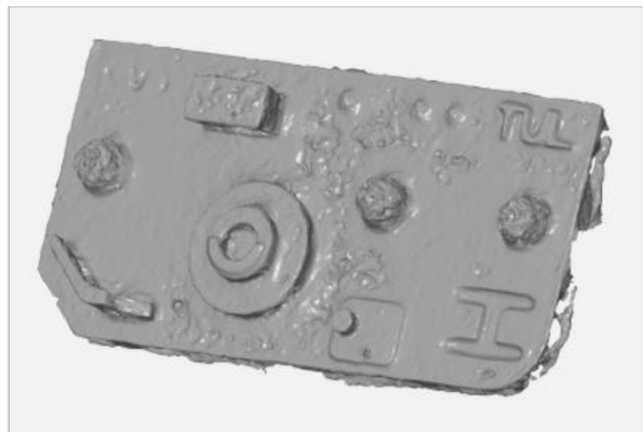
The model generated from iPhone 12 Pro had a good quality in the detail. Also the Nikon camera had good details captured.



Nikon D500 Camera



Apple iPhone 12 Pro Camera

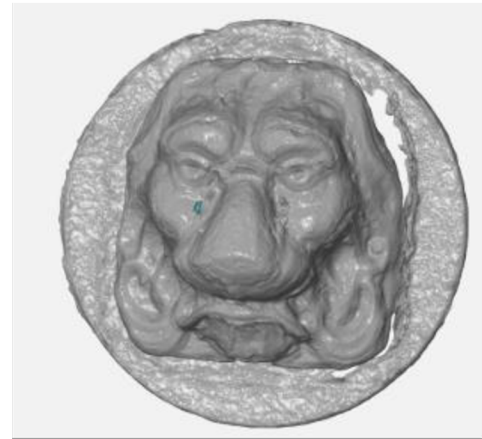
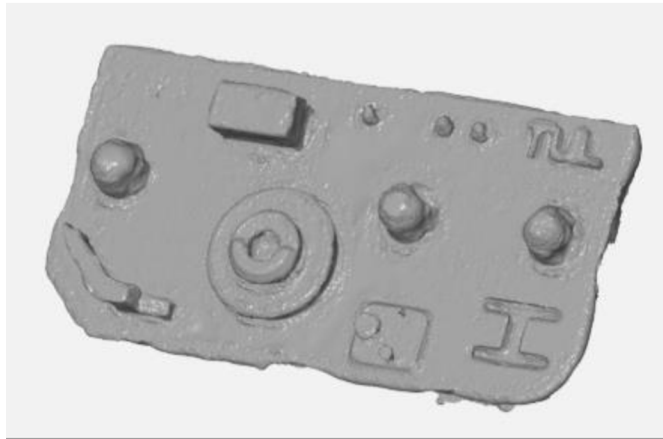


Canon IXUS 220 Camera

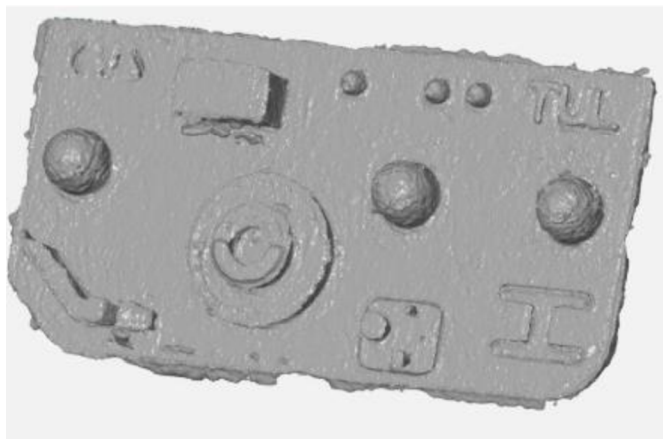
Figure 37: Models generated from Agisoft Software

4.2.2 COLMAP

The GUI of COLMAP is not as good when comparing the other three software used in this study. Although it is an Open-source software the time taken for generation of each model is on par with the paid software.



Nikon D500 Camera



Apple iPhone 12 Pro Camera

Figure 38: Models generated from COLMAP

The uploading of images is pretty simple as the images of .jpeg/.jpg are imported into the software and the model reconstruction dialog box appears. Here there the file location of the images needs to be specified next the location of the generated model where it needs to be saved also to be specified.

Finally, the mesh quality needs to be selected for model generation, here similar to Agisoft High settings was chosen to make the process quicker. But when choosing the Ultra high mesh settings COLMAP software did not produce any results for any of the images. After the model

generation process the model gets automatically saved in the given location as specified initially. The software saves the model in the name of “meshed-poisson.ply” format. The ‘.ply’ format can be opened in GOM Inspect software straightway.

Now considering the model generation from the sensors used. As specified initially two datasets from each sensor were utilised to generate the models. The images from iPhone performed really good the generating model when comparing Nikon and Canon. Although the surface of the model was very rough and finer details were harder to be generated in this software.

The model did not generate the images from Canon camera. The output did not even generate a proper model in order to be visualized in this study.

The Lion statute had good details captured from the iPhone sensor but the Etalon missed some of the details in the iPhone sensor. The surface texture was very rough in the Etalon model of iPhone sensor.

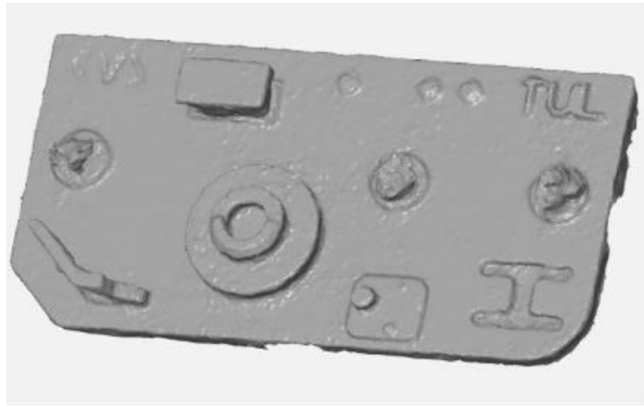
The Etalon model from Nikon camera has smooth surface texture but the KVS logo was failed to be recognised in the model so this itself is self-explanatory on how each sensor performs under this software.

4.2.3 Meshroom

The Meshroom is also an Open-source software but the user interface is far better compared to COLMAP. The processing is more complicated and requires some data specified before its model generation.

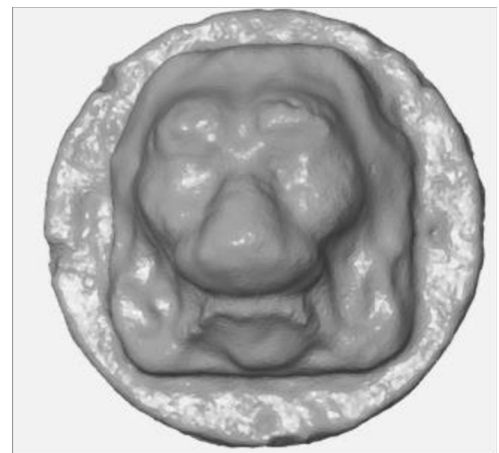
Each image has data known as Metadata which stores all the information of the image right from megapixel, sensor size etc. This photogrammetry software requires this metadata present beforehand to process the images for generating the model. The metadata can be viewed and edited using a software known as “AnalogExif”. Here the data is filled and then the images are uploaded into the Meshroom software for further processing.

The metadata is already present in Professional camera Nikon D500 so there were no further changes needed to be done for the images generated from this camera. But the Canon and iPhone camera images had some data need to be filled before further processing. There were no Mesh settings presented in this Software for pre-selection.



Nikon D500 Camera

Meshroom cannot process the images of this camera



Apple iPhone 12 Pro Camera



Canon IXUS 220 Camera

Figure 39: Models generated from Meshroom

The output from the Meshroom creates a separate for viewing as a 3D model and it needs to be accessed only under the Meshroom saved file folder. It saves in ‘mesh.obj’ file format where the ‘.obj’ file can be opened in the GOM Inspect software directly without any use of any external software.

From the above Figure 39 we can clearly see the quality of each generated model from the Meshroom software. The Etalon model generated from Nikon camera has a smooth texture but the KVS logo is far from visible. The spheres too are in bad shape to be processed correctly. The Lion statue also has a very rough surface created from the Photogrammetry software.

The next model generated is from the iPhone 12 Pro camera. The Etalon model was not processed in the Meshroom software due to unknown issues. The Lion model was generated from Meshroom had a very smooth texture but it resulted in a very smooth surface where the details of models too got smoothed out. The finer details were not clearly defined in the model.

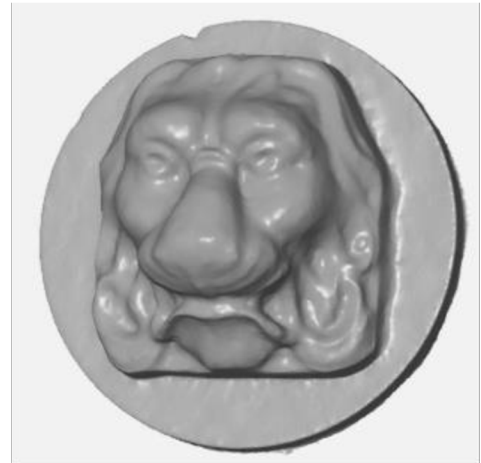
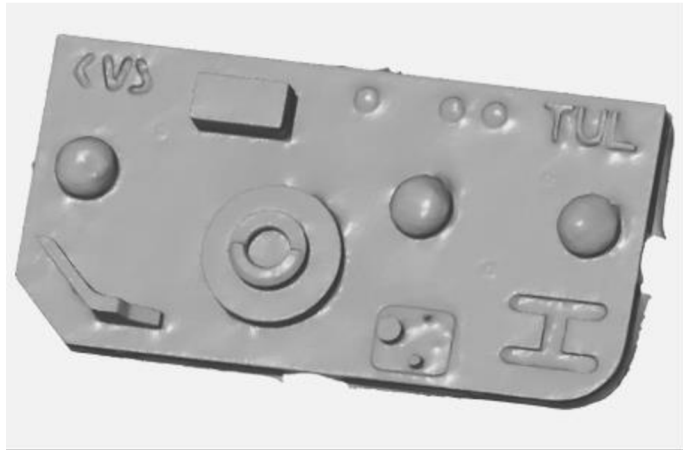
The model constructed from the images from Canon camera shows a poor quality generation. Initially the Lion statue shows a very bad processing of the model created were no details is captured and the surface is also very rough whereas the Etalon model could process the larger spheres but the “TUL” logo is far from recognition. The KVS logo cannot be seen and it is not generated in the software. The surface too is not smooth for the Etalon model present.

4.2.4 Autodesk Recap Photo

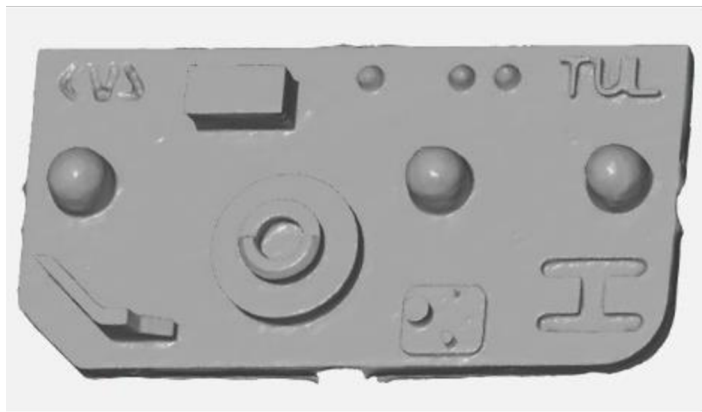
This software is a paid one where the GUI is very simple. From the user point-of-view only the image needs to be uploaded and the software uploads into the cloud server for processing the models. The time taken for model generation cannot be determined properly since all operation are done in the cloud server. This is a paid software but an Education license was utilised in this study for creation of 3D models. Only internet has to be function properly to download the model from the server present.

The model generated from all the camera sensors proved to generate the best results from Autodesk software. Some drawbacks or flaws are from the Canon camera sensor where smaller spheres did not generate properly in the model.

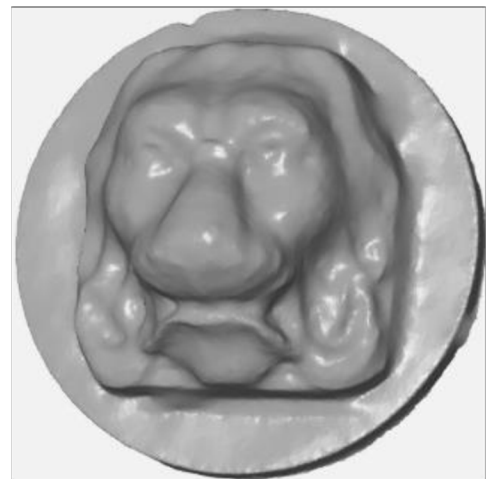
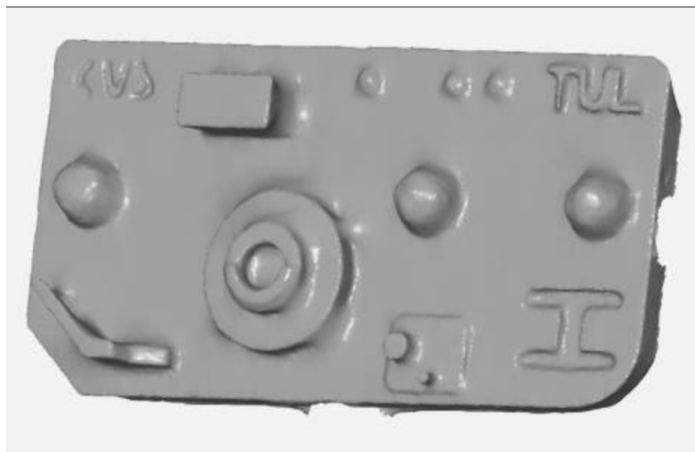
Both the iPhone and Nikon camera produced better results and finer details too had been captured from the images to the generated model.



Nikon D500 Camera




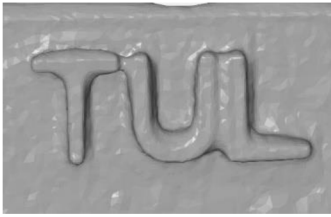
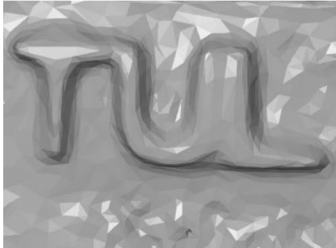

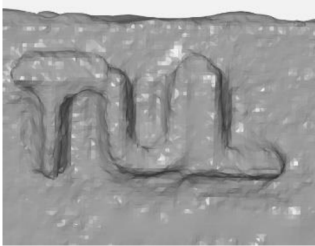
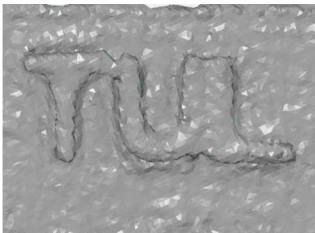
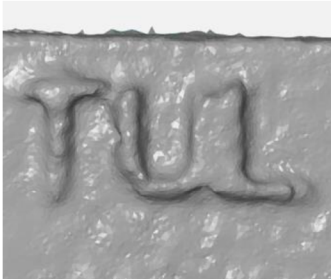
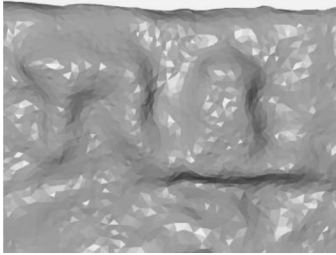
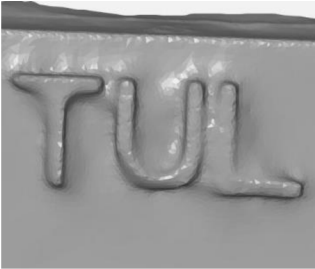

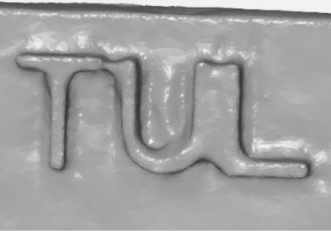
Apple iPhone 12 Pro Camera



Canon IXUS 220 Camera


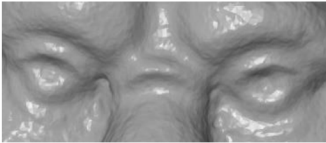
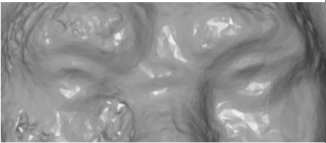
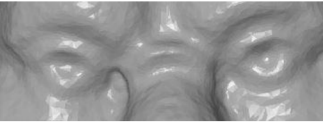
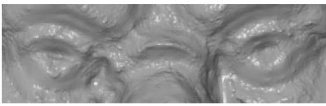
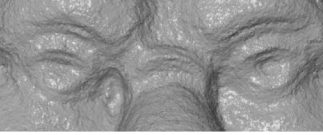
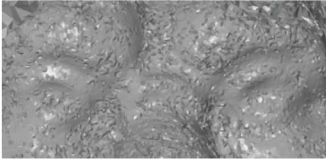
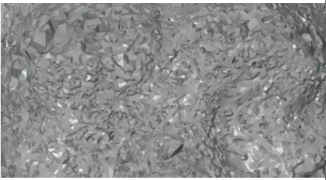
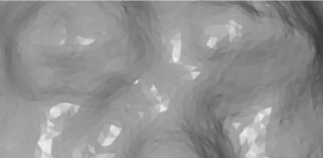



Figure 40: Models generated from Autodesk Recap Photo

Table 3: Closer look of inscription "TUL" in each Etalon model

Etalon Model Software used			
	Cameras used		
	Nikon	Canon	iPhone
Agisoft			
COLMAP		None	
Meshroom			None
Autodesk ReCap			

From viewing each model on the whole we cannot come to conclusion as a whole, so a closer look is needed for each model. Hence from the Table 3 we can see a differentiation of the “TUL” inscription from each photogrammetry generated model also the difference in each camera sensors. The Table 4 depicts the details in the eyes of the Lion statute generated from each software and the each camera sensors taken under this study.

Table 4: Lion Statue zoomed view of eyes for each model

Lion Model Software used			
	Cameras used		
	Nikon	Canon	iPhone
Agisoft			
COLMAP		None	
Meshroom			
Autodesk ReCap			

In Table 3 & Table 4 at the Top the model from ATOS III Scanner is placed in order to visualize the quality the optical scanner generates when compared to Photogrammetry.

From the generated models we can come to conclusion like the model generation is purely based upon the image quality of the processed model but that's not the case. The quality of the model processed generally depends upon how the software performs under these condition and how quickly it produces results for some of its applications. The models generated from each software has some flaws present when taken into comparison but the best model created using these camera sensors was from the Autodesk Recap Photo were all the models generated had better quality of details from the reconstructed models. So the visual analysis results the best performing software is from the Autodesk Recap Photo. The next in line is the Agisoft which is also a paid software but in terms of cost it less compared to Autodesk. Both the Meshroom and COLMAP are in same level some aspects are better in one software than the other for instance the GUI is better in Meshroom than COLMAP but the processing time is faster in COLMAP than Meshroom. A Table below gives some clarity about the visual comparison of the four software.

An assessment was carried out to find some of the aspects in the Photogrammetry Software. The evaluation of the various parameters reveals a variety of results ranging from bad (-) and average (*) and good (+).[23]

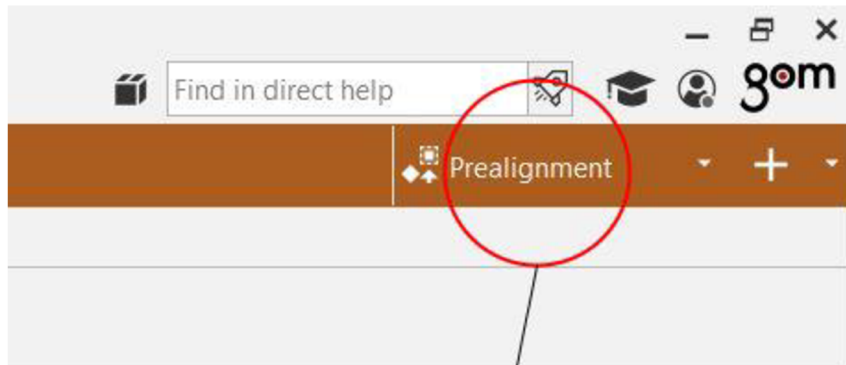
Table 5: Evaluation of Photogrammetry Software based on Visual Inspection of Models

Typical Evaluation	Software Used			
	Agisoft	COLMAP	Meshroom	Autodesk Recap Photo
GUI	+	*	*	+
Usability	*	-	*	+
Tutorials	+	-	*	+
Texture Quality	+	-	-	+
Processing Time (depends on user)	+	*	-	*
License	Price	Open-source	Open-source	Price

5.RESULTS

5.1 Deviation in actual model with respect to CAD model using GOM Inspect Software

With the GOM Inspect software the meshed model and CAD nominal which is the model generated from the ATOS is taken for comparison using the option pre-alignment Figure 41.



Alignment of Meshed model along with the nominal CAD model

Figure 41: Pre-Alignment feature in GOM Inspect

From the pre-alignment feature the model generated from Laser Scanner is taken as nominal model and the option from Figure 41 says about the pre-alignment selection where the meshed model is aligned with the nominal CAD model and the deviation from the CAD model is calculated. This feature utilises Global-best fit method to determine the surface deviation model from CAD model to the Meshed model.

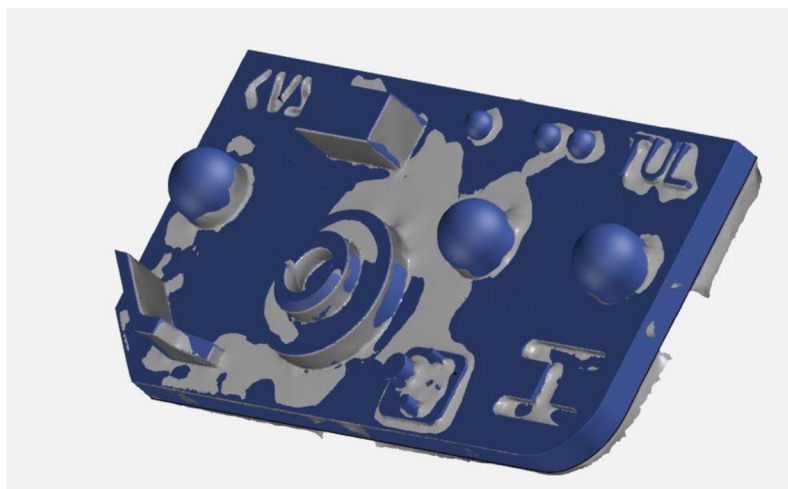


Figure 42: Pre-alignment between CAD model and meshed model

From the Figure 42 we can visualize that CAD model is in Blue colour and Grey colour is the meshed model. So the deviation calculation is done for the both the models generated from the Photogrammetry software. The similar procedure was followed to detect the deviation for the Lion model the set of values are explained further in detail below.

The Photogrammetry models generated from four software for Lion model and Etalon model are compared with the CAD nominal model and the deviation is computed in the Table 6 & Table 7.

Table 6: Alignment using GOM Software with nominal model from Etalon

ETALON deviation(mm)	Agisoft	COLMAP	Meshroom	Autodesk ReCap Photo
Nikon	0.1236	0.1938	0.0808	0.3515
Canon	0.308	None	0.2922	0.6531
iPhone	0.3753	0.1502	None	0.2543

Under Table 6 the minimum deviation from the CAD model of Etalon to Meshed model the value of 0.0808 mm is from the Meshroom Software. The highest deviation is from Canon model which arrives to 0.6531 mm generated from Autodesk ReCap Photo.

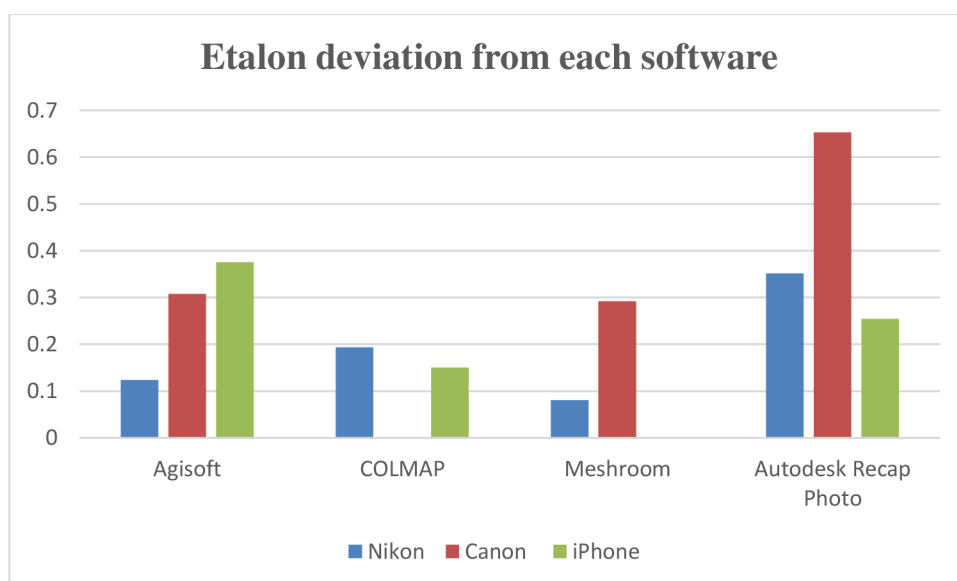


Figure 43: Graphical data representing the deviation from each software from Etalon

A total average of which software has a minimum deviation from the three camera sensors cannot be specified since some models of the Etalon were not generated to arrive at a result for minimum deviation in Etalon. From Figure 43 its visible that COLMAP has the least possible deviation overall and highest overall deviation is from Autodesk ReCap Photo.

Table 7:Alignment using GOM Software with nominal model from Lion Statute

Lion Statute deviation(mm)	Agisoft	COLMAP	Meshroom	Autodesk Recap Photo
Nikon	0.1769	0.2495	0.261	0.2014
Canon	0.528	None	0.3828	0.5043
iPhone	0.2307	0.149	0.4774	0.3015

Under Table 7 the minimum deviation from the CAD model of Lion Statute to Meshed model the value of 0.149mm from COLMAP software of iPhone camera. Considering the overall performance of the models with respect to the minimum deviations Agisoft and COLMAP looks to provide satisfactory results in terms of evaluation.

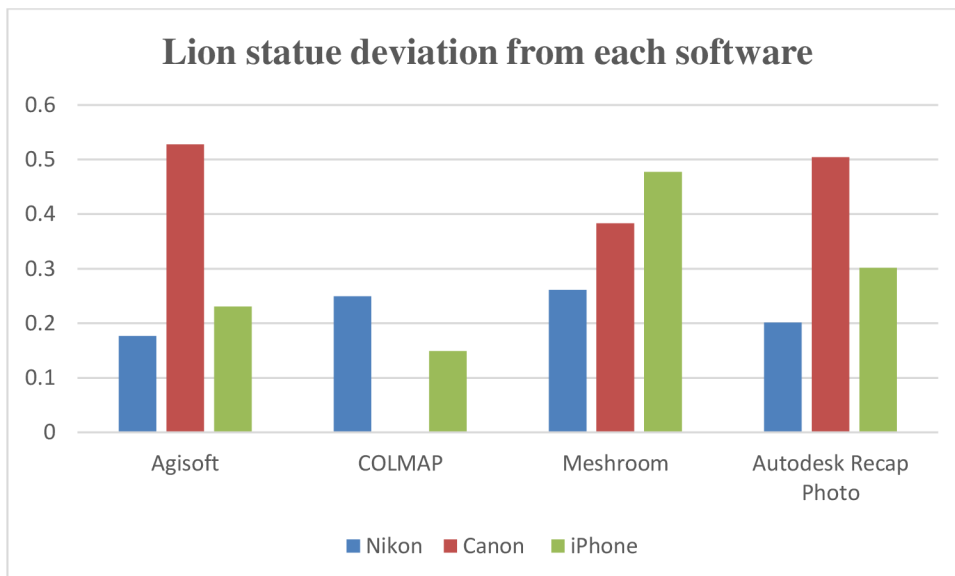


Figure 44: Graphical data representing the deviation from each software from Lion statue

Figure 44 depicts the deviation calculated from GOM Inspect software with a lack of one model from COLMAP the deviation is lower when comparing other software. The overall highest deviation is from Autodesk ReCap Photo. The highest deviation was from the Canon camera from all the photogrammetry software.

Table 8: Values of Sigma, Max & Min deviations from Etalon model

Etalon Model	All values are in mm			
Nikon	Sigma	Range	Min Deviation	Max Deviation
Agisoft	0.89	8.01	-4.3	3.71
COLMAP	0.99	10.85	-5.16	5.69
Meshroom	1.34	11.68	-6.08	5.6
Autodesk ReCap Photo	1.02	11.75	-6.49	5.26
Canon	Sigma	Range	Min Deviation	Max Deviation
Agisoft	1.48	8.88	-4.35	4.53
COLMAP	none	none	none	none
Meshroom	1.8	13.99	-9.84	4.15
Autodesk ReCap Photo	1.36	10.89	-6.5	4.39
iPhone	Sigma	Range	Min Deviation	Max Deviation
Agisoft	0.88	6.4	-2.54	3.86
COLMAP	0.73	14.49	-5.41	9.08
Meshroom	none	none	none	none
Autodesk ReCap Photo	0.66	6.67	-1.45	5.22

The values from Table 8 represents few of the deviations calculated through colour map of deviations from the nominal model and meshed model from Etalon. The sigma from Table 8 denotes the average deviation of the meshed model across the surfaces. As for the deviation is concerned the generated models are in bad reconstruction. The GOM Inspect could handle the deviations close to 1mm perfectly since the deviations are more than 10mm in some places the software finds it hard to compute it perfectly.

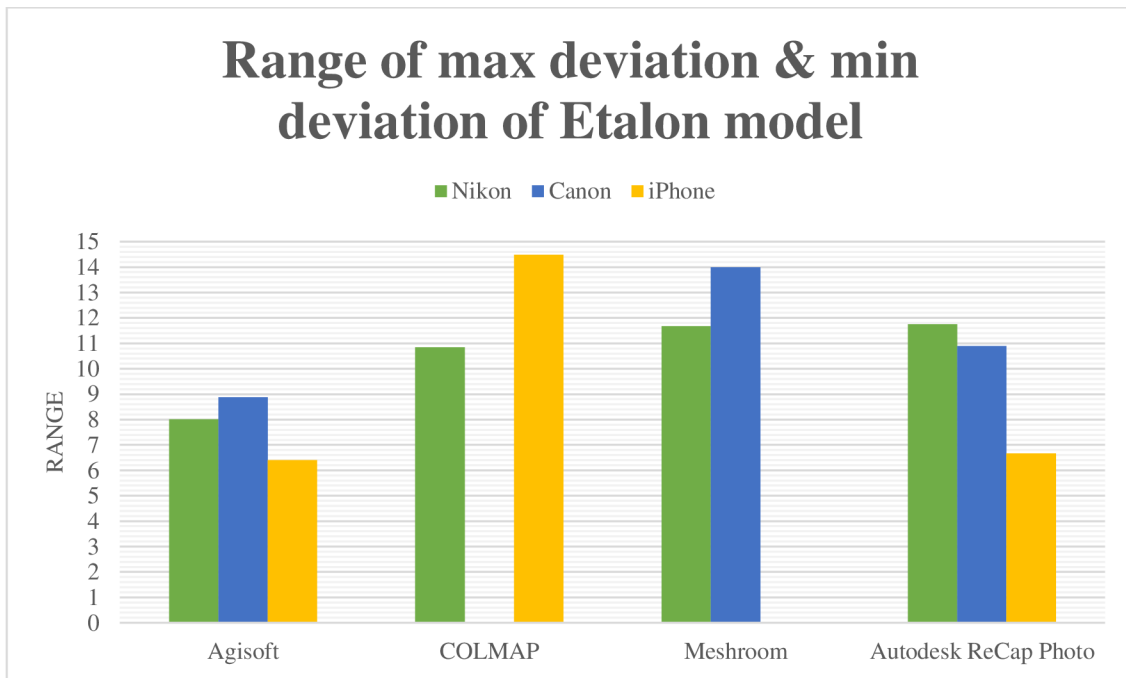


Figure 45: Range values from Etalon model

The above Figure 45 we can visualize that the lowest range is achieved in the software Agisoft and next is Autodesk ReCap Photo. As for the camera is concerned the iPhone camera performs better when compared to the other two cameras.

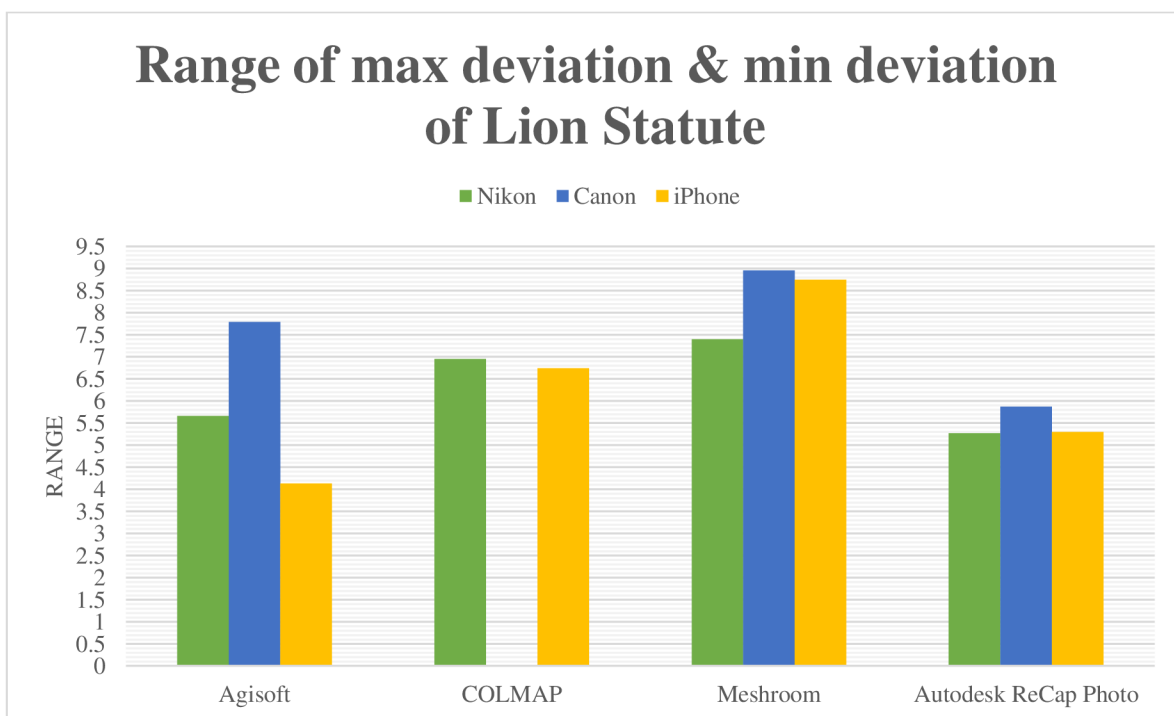


Figure 46: Range values from Lion statute

In Figure 46: Range values from Lion statute the lowest possible outcome of Range was achieved from the Agisoft software for iPhone camera and for overall comparison from all the sensors the Autodesk ReCap photo provided low average results than their counterparts.

Table 9: Values of Sigma, Max & Min deviations from Lion Statute

Lion Statute	All values are in mm			
Nikon	Sigma	Range	Min Deviation	Max Deviation
Agisoft	0.51	5.66	-1.38	4.28
COLMAP	0.8	6.95	-2.21	4.74
Meshroom	0.74	7.4	-4.64	2.76
Autodesk ReCap Photo	0.51	5.27	-1.58	3.69
Canon	Sigma	Range	Min Deviation	Max Deviation
Agisoft	0.93	7.79	-3.48	4.31
COLMAP	none	none	none	none
Meshroom	1.26	8.96	-4.88	4.08
Autodesk ReCap Photo	0.92	5.87	-2.17	3.7
iPhone	Sigma	Range	Min Deviation	Max Deviation
Agisoft	0.41	4.13	-1.24	2.89
COLMAP	0.36	6.74	-4.03	2.71
Meshroom	1.06	8.75	-4.01	4.74
Autodesk ReCap Photo	0.5	5.3	-1.05	4.25

The Table 9 values are from the Lion statute model from which the Photogrammetry software model were generated. As stated earlier each values denote the deviation present in the meshed model of each Photogrammetry software. Generally, the lower the value the better the software in terms of the accuracy of the reconstructed model. The models had some errors in terms of scaling, reconstruction and in-built errors in the mesh so some deviations cannot be computed since it is larger than the values considered.

5.2 Colour map of deviations with reference to the nominal CAD model

The next findings which can evaluate the quality of output delivered from each software is through colour map of deviations. With the use of GOM Inspect software using the option called Surface comparisons on CAD model the colour deviations are evaluated visually. Some aspects to be known before visualizing the colour map deviations are the range which is set between -2mm to +2mm. Various colouring used to display the range of results for the understanding Red colour is the extreme range where it denotes deviation is larger in the actual model with respect to the CAD model. Dark blue colour denotes the model deviates with reduction in the actual model in comparison with the nominal model.



Figure 47: Colour map of deviations of Autodesk ReCap Photo from Nikon Camera

Under Figure 48 the images from the Nikon D500 Camera with the model outputs produced from the previously generated image dataset as mentioned in the Chapter 4. From Figure 48 we can visualize that the Photogrammetry software from Autodesk Recap Photo reconstructs it with better colour deviations on all the surfaces in the Etalon model is very low. The one with poor results even on the flat surfaces are from COLMAP model of etalon where its value is 0.48mm.

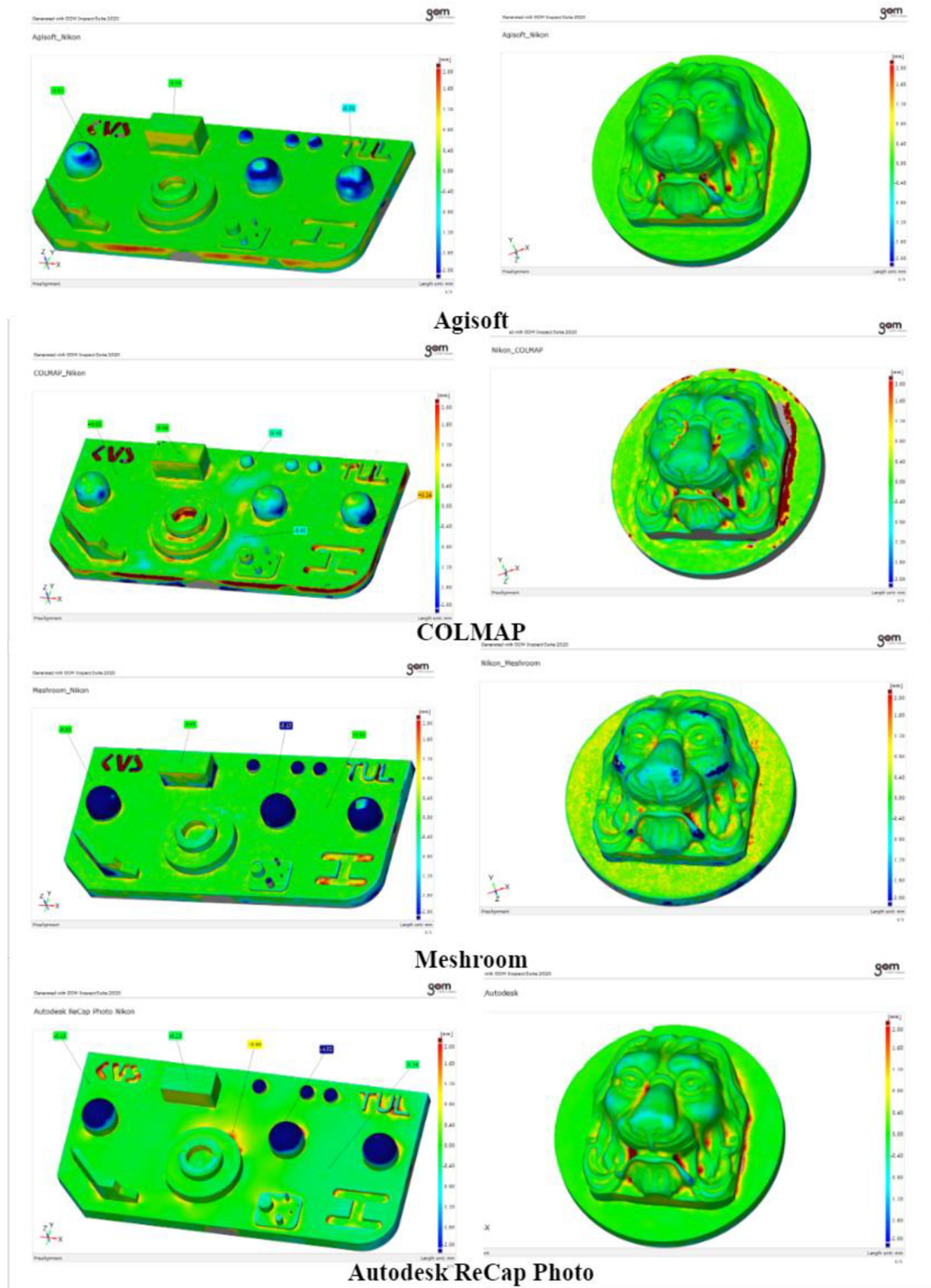


Figure 48: Colour Map of deviations from Nikon Camera

Under Figure 50 the images from the Canon IXUS Camera with the model outputs produced from the previously generated image dataset as mentioned in the Chapter 4. From the picture we can visualize that the Photogrammetry software from Autodesk Recap Photo reconstructs it with better colour deviations on all the surfaces in the Etalon model also the Lion statue from this software recreates better output. Average value from the flat surfaces of Etalon comes to +0.21mm which accounts for good result from the other software of same camera used in study.

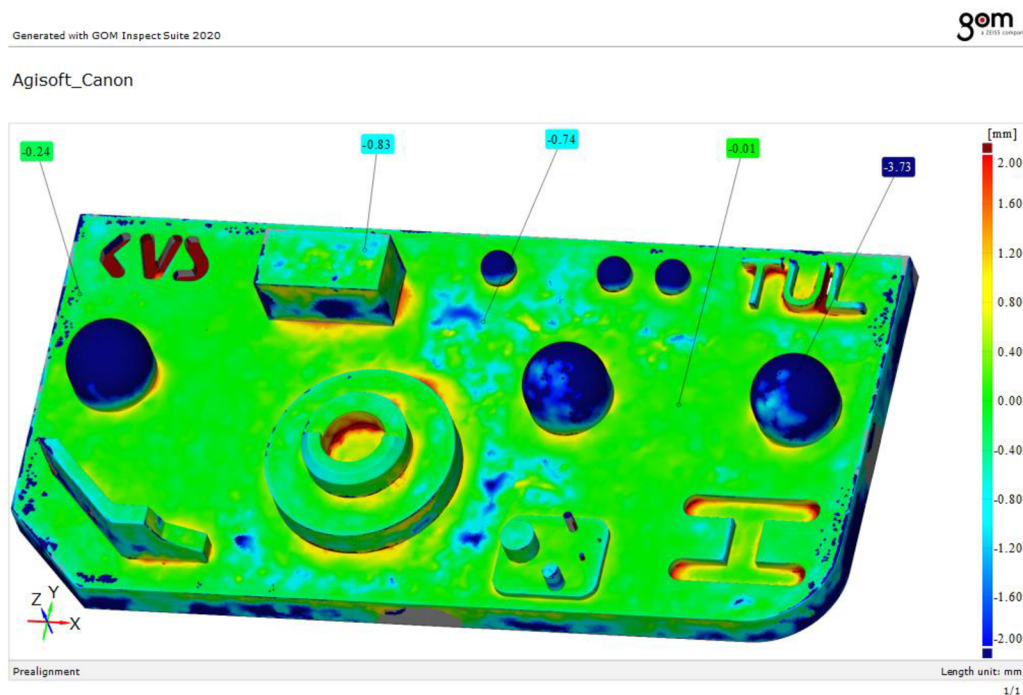
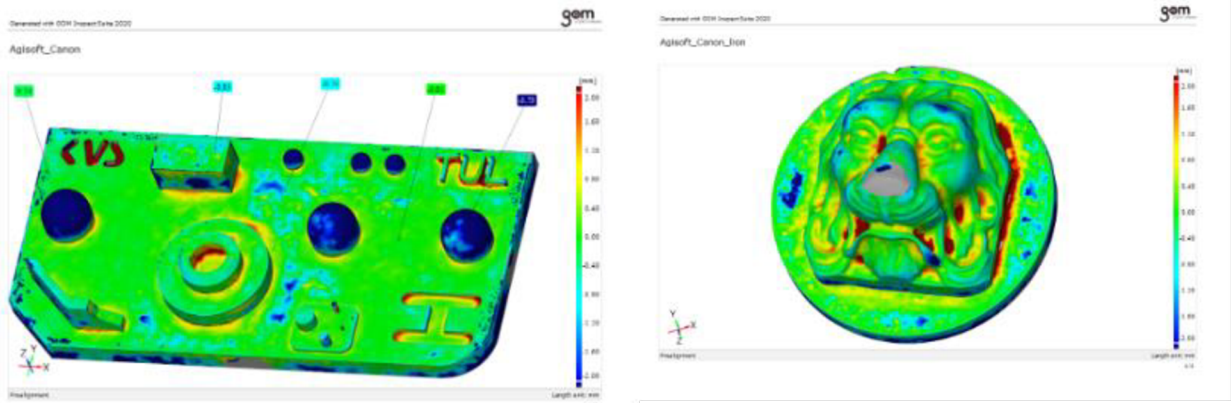


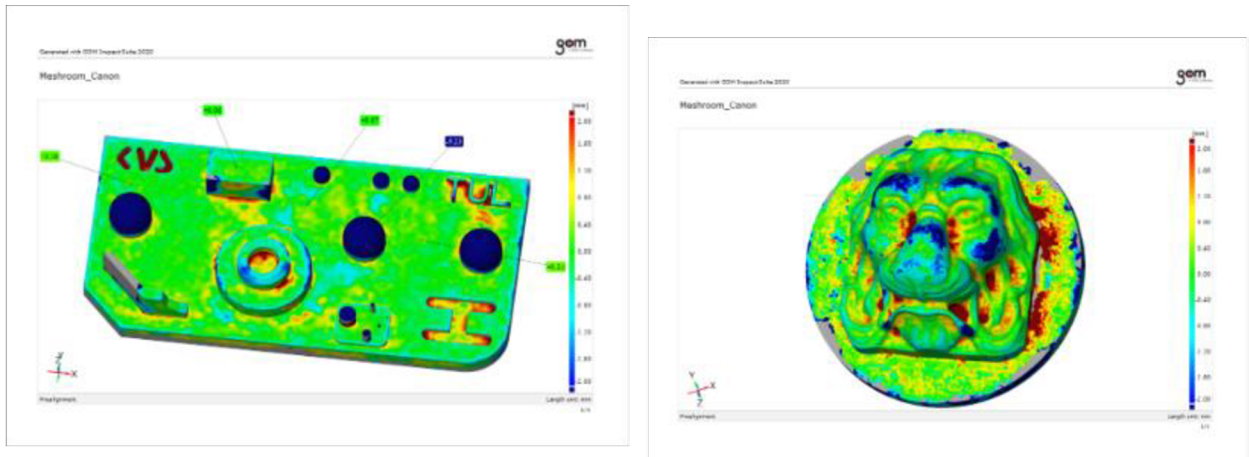
Figure 49: Colour map of deviations of Agisoft from Canon Camera

The one with no results are from the COLMAP software where the model could not be generated the reason could be the quality produced from Canon Camera is not in par with the camera sensors taken in this study. The Meshroom Software has even colour distribution all over the flat surfaces from the Etalon model and Lion statue has good results with some geometries missing. The Agisoft Software performed very poorly given the circumstances of a good photogrammetry software known predominantly. The Agisoft have the deviations very high on flat surfaces. The Lion model from Agisoft had some geometry missing at the center of the reconstructed model this considered to be a bad performance from the Agisoft software.

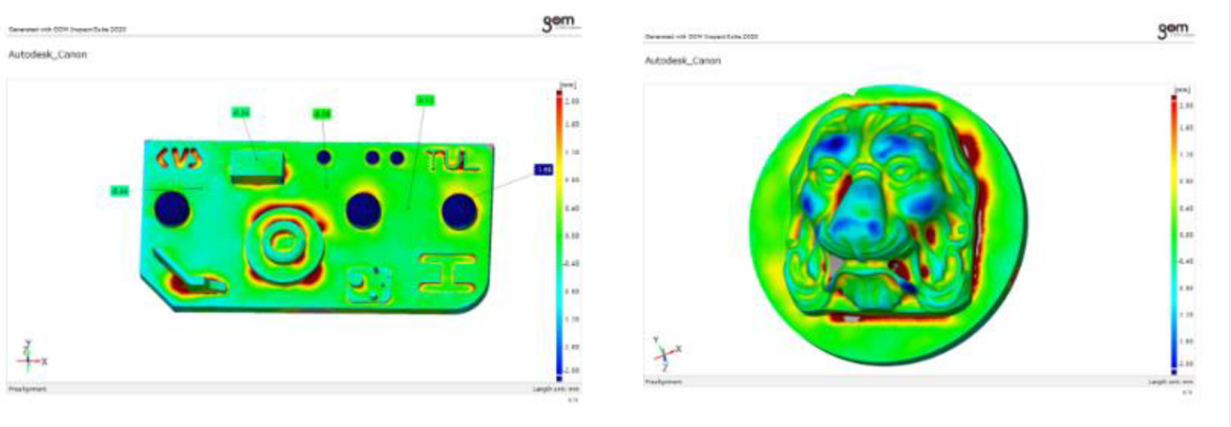


Agisoft

Surface comparisons could not be generated from COLMAP Software



Meshroom



Autodesk ReCap Photo

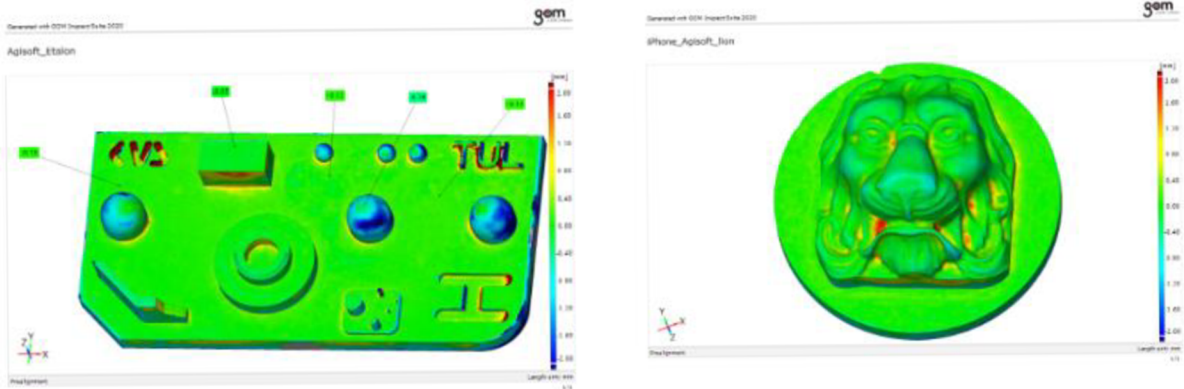
Figure 50: Colour map of deviations from Canon Camera

Under Figure 52 it is pretty easier to visualize almost all the models from the Etalon and Lion statue exhibit overall green on the flat surfaces. The model from Autodesk for the Etalon model has an overall average value under +0.05 mm. The good results were produced from the Autodesk Software. The COLMAP too performed good outputs with an average value in flat surface close to +0.15mm. Lion model from the COLMAP produced from iPhone was one of the best reconstructed with the deviations close to 0.25mm over the entire model. This is considered the best overall minimum deviations when compared to other Lion models generated from this study. The Meshroom could not reconstruct the Etalon model from the images of iPhone camera sensor. Also the Lion statue had bad results from the Meshroom software. Since the features from the Lion model is complex due to uneven surfaces the Meshroom had some difficulties in recreating the model with all the features intact. The blue colour patches from the Meshroom of the Lion model suggest some bad generation in some places of the geometry. 3D output from the Agisoft for the Etalon model produced results from the flat surfaces averaging +0.12mm. The Lion statue from the Agisoft had the surface deviations under the green colour overall.

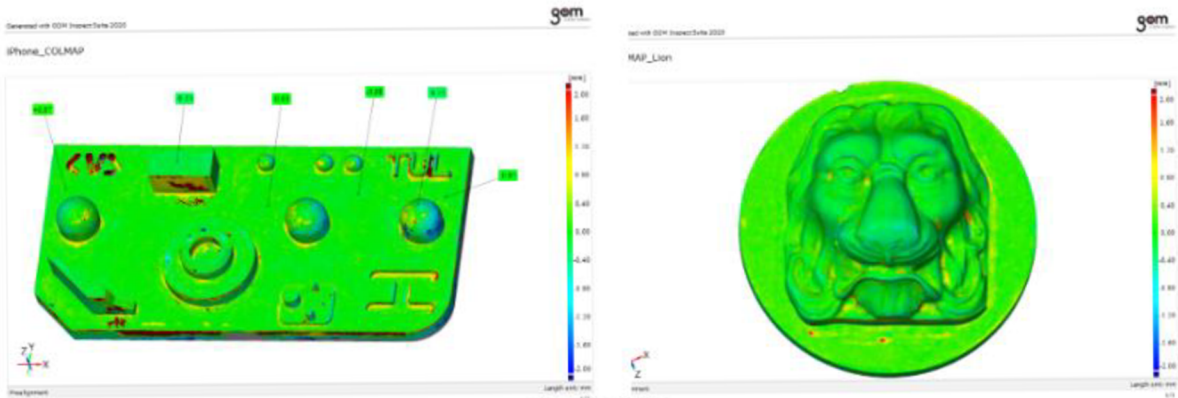


Figure 51: Colour map of deviations of COLMAP Software from iPhone camera

The reconstruction from the iPhone camera produced good results in comparison to the other images generated from the camera sensors. Apart from this the Etalon has several shapes present which can be taken into the study individually.

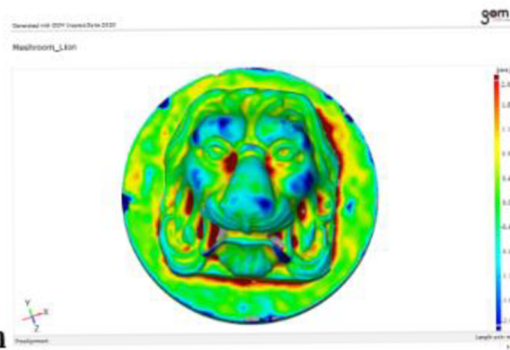


Agisoft

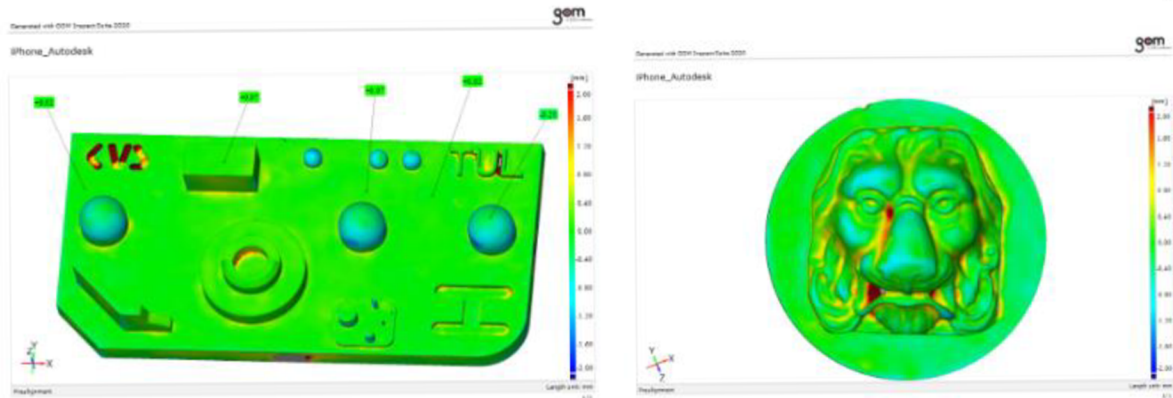


COLMAP

Meshroom did not process images from iPhone etalon model



Meshroom



Autodesk ReCap Photo

Figure 52: Colour map of deviations from iPhone camera

Since the study only reviews four software and experiments it for its daily use the geometry based characterization was not considered. For viewing purpose three spheres from the Etalon were considered for visualizing. Most of the Photogrammetry software has some erratic deviations when these 3 spheres were considered. No software can be pointed as the best from the reconstruction spheres due to the difference from each model and camera.

To consider evaluating the colour map of deviations all the generated models are compared so in this case Autodesk ReCap photo generated models from all the camera and the results were good in comparison to the others present. The next in line is the Agisoft Software but only on the basis of regenerating all the models and next is the COLMAP software which on par performs similar to that of the Agisoft software in some ways. The software which needs some improvement is the Meshroom software due to some difficulties in proper regeneration of the models from the camera sensors.

5.3 3D printing of stl models

From the Figure 53 for 3D printing one stl model of Lion statue from ATOS Triple Scan and four models from the output generated from Lion statue of the images of the iPhone camera were taken. The reason for taking the iPhone camera is due to the models of the Lion model were generated successfully with some minor changes done in the stl model such as closing of holes and smoothing of mesh. The models printed were printed on 1:1 scale.

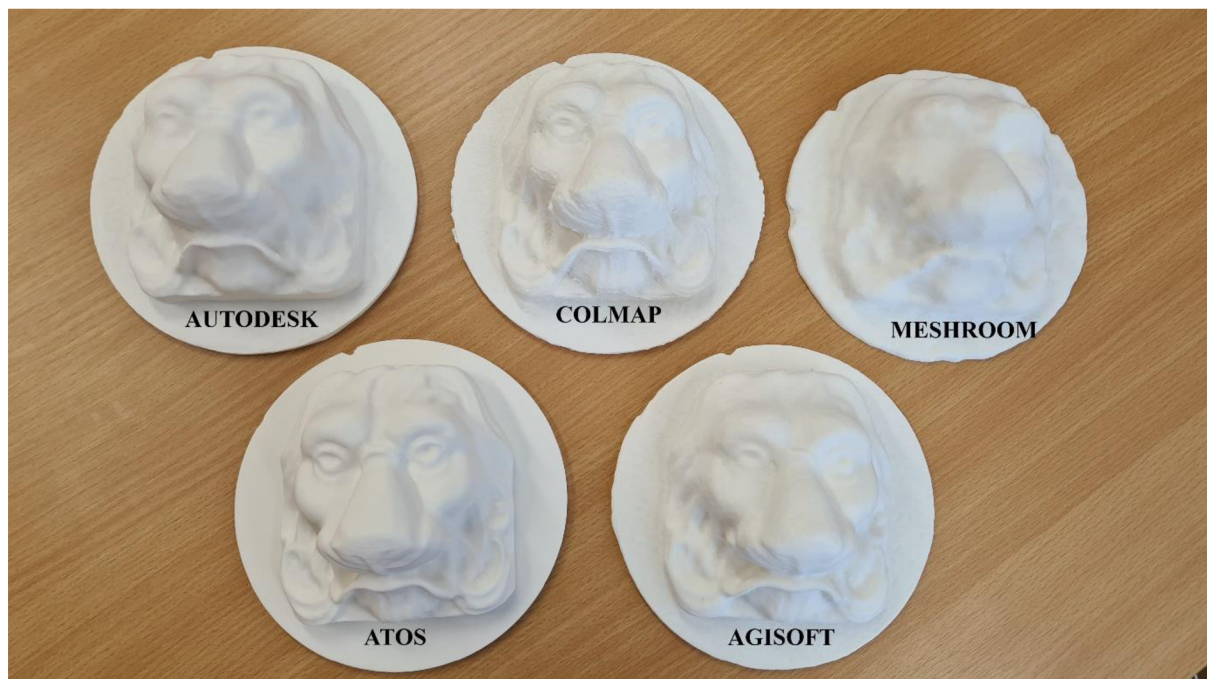


Figure 53: Printed 3D Models

6. CONCLUSION

The advancement in Computer technology paved way for 3D objects reconstruction. Many Photogrammetry software are available for general usage. The four software considered in this study Agisoft, Autodesk, COLMAP, Meshroom all are good in terms of user experience. The considered criteria are the paid and the Open-source nature of these software. The advent of mobile phone camera has changed the entire scope of the Photogrammetry on whole. The portable camera which can process several images at a given short period of time and also the internet access opened portals for communication, this improved the quality of these software. One of the parameters involved in the model generation is the image quality. For comparison with the quality of the images Canon camera were used along with Nikon and iPhone camera because comparatively the still camera of Canon has significant lower quality when set side by side with the other two cameras. There are studies which compares the algorithm involved in each photogrammetry software but this was not considered in this thesis.

The first evaluation is from the output generated from each software and from each camera. The model generated from the Autodesk ReCap Photo proved to have better results in terms of the model quality. The meshed models had an overall smooth surface from images from all the cameras. As stated earlier Canon camera had a poor quality in correlation with the other cameras taken in this study. To briefly summarize from the visuals Autodesk ReCap Photo with images from iPhone Camera performed better under this category. The next comparison is from Nikon camera which on par had good results. The Agisoft software too provided good results but not as good as Autodesk ReCap in terms of the texture quality visually. The COLMAP comes third in position since the model cannot be generated from the Canon camera. The Meshroom performed poorly by providing results not even visually pleasing.

The next evaluation is based upon the deviation of the meshed model with the nominal model created from the ATOS Triple Scan. The deviation is calculated from the feature Pre-alignment available in the GOM Inspect software. The results were tabulated separately for Etalon model and the Lion statute. From the results obtained the minimum deviation for Etalon was obtained from COLMAP software from the all the camera sensors. Similarly, the deviation from COLMAP was the lowest for the Lion statute. The highest deviation overall is from the Autodesk ReCap photo software and Agisoft too had similar result.

Colour map of deviations considered to be a proper way in assessing the photogrammetry models. The similar way in which the colour map visualizes on the basis of CAD model as its base view. As per the estimation of the colour map Autodesk ReCap photo has an overall deviation in the flat surface lower in comparison to the other software. As for the cameras iPhone camera had good result from the colour map of deviations.

The final valuation is from the output of the 3D printed models utilising Lion model from the iPhone camera. Models from the iPhone camera of Lion statue were only considered due to the overall mesh quality and the finer refinement in details of the reconstructed models. Autodesk and Agisoft models had the model created with the models as good as from the ATOS Triple Scan. For the model from the COLMAP, the details of Lion statue were good but the surface was very rough and whereas the Agisoft and Autodesk had smooth surfaces. Meshroom had no sort of details captured and reconstruction from this software turns out to be poor.

According to this study, in the perspective of Photogrammetry software the paid versions Agisoft and Autodesk works significantly better than the open-source software COLMAP and Meshroom. For consideration, COLMAP had level of details captured better in some models but the surface quality turned to be poor. Meshroom on the other hand needs some serious revamp in terms of software processing since most of the output from software were not good. When it comes to the cameras involved in the study, the iPhone 12 Pro camera sensor performs better than Nikon D500. When expressing about Canon IXUS 220 camera, it showed significantly poor performance than other two cameras.

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