UNIVERSITY OF ZAGREB
FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING

MASTER THESIS No. 70

DIGITAL PHOTOGRAMMETRY APPLIED TO ANTHROPOMETRY

Goran Jaković

Zagreb, February 2024

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MASTER THESIS ASSIGNMENT No. 70

Student:	**Goran Jaković (0036502140)**
Study:	Electrical Engineering and Information Technology
Profile:	Electronic and Computer Engineering
Mentor:	assoc. prof. Tomislav Petković

Title: **Digital Photogrammetry Applied to Anthropometry**

Description:

Anthropometry is the measurement of the dimensions of the human body. One possibility for performing such measurements is digital photography and the subsequent reconstruction of the three-dimensional world from captured photos, which is a classic photogrammetric procedure. The thesis shall contain a brief description of the current state of the art in the application of digital photogrammetry to anthropometry. A description of a classic process of photogrammetric processing in computer vision will be given using an open system such as AliceVision as a practical example. Investigation into how photogrammetry can be used for 3D reconstruction of the human body will be performed, and a recording protocol that ensures sufficient quality of 3D reconstruction will be proposed. The proposed protocol of photogrammetric recording shall be quantitatively evaluated through comparison with the data obtained by other measurement procedures that can be carried out in the laboratory (e.g. tailor's meter, structured light 3D scanner or ToF camera).

Submission date: 09 February 2024

SVEUČILIŠTE U ZAGREBU
FAKULTET ELEKTROTEHNIKE I RAČUNARSTVA

Zagreb, 2. listopada 2023.

DIPLOMSKI ZADATAK br. 70

Pristupnik:	**Goran Jaković (0036502140)**
Studij:	Elektrotehnika i informacijska tehnologija
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Mentor:	izv. prof. dr. sc. Tomislav Petković

Zadatak: **Primjena digitalne fotogrametrije u antropometriji**

Opis zadatka:

Antropometrija je mjerenje dimenzija ljudskog tijela. Jedna mogućnost za provedbu takvih mjerenja jest digitalno fotografiranje i rekonstrukcija trodimenzionalnog svijeta iz snimljenih fotografija što je klasični fotogrametrijski postupak. U diplomskom radu potrebno je ukratko opisati trenutno stanje tehnike u primjeni digitalne fotogrametrije u antropometriji. Također je potrebno opisati klasični postupak fotogrametrijske obrade u računalnom vidu na primjeru nekog otvorenog sustava kao što je AliceVision. Zatim je potrebno istražiti kako se fotogrametrija može koristiti za 3D rekonstrukciju ljudskog tijela te je potrebno predložiti protokol snimanja koji osigurava dostatnu kvalitetu 3D rekonstrukcije. Predloženi protokol fotogrametrijskog snimanja je potrebno kvantitativno evaluirati kroz usporedbu s podacima dobivenim nekim drugim postupkom mjerenja kojeg je moguće provesti u fakultetskom laboratoriju (npr. krojački metar, 3D skener koji koristi strukturirano svjetlo, ToF kamera).

Rok za predaju rada: 9. veljače 2024.

I would like to express my deepest gratitude to everyone involved in this master thesis, with special appreciation extended to my mentor, prof. dr. sc. Tomislav Petković. Additionally, I would like to thank my parents and grandparents for their unconditional love and support.

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1 Introduction

The idea of obtaining information about an object without physical contact is not a novel notion, therefore we can say that the roots of photogrammetry extend alongside the historical evolution of photography. Photogrammetry is a branch of engineering that deals with obtaining reliable information about the properties of surfaces and objects without physical measurement, achieved through the capture of images, recording of electromagnetic radiation, and subsequent interpretation of the collected information. The applications of photogrammetry are extensive, ranging from disciplines like topography, archaeology, and geology to practical domains such as quality control, engineering, aerial surveillance, and medicine [1]. Due to the diverse range of applications, various methods have been developed for capturing information from the surface of objects, which are then processed using various software packages. The focus of this work will be on the application of photogrammetry in anthropometry. Anthropometry can be defined as the science of measuring the body. In anthropometry, lengths, widths, and surfaces are used for the numerical description of body parts and the overall body shape [2]. Anthropometric measurements have long been used to study physical variations in the human body and have many applications, leading to the need for the development of non-contact measurements.

2 State of the Art

In recent years, the field of 3D scanning in anthropometry has significantly developed, mostly due to the development of available technologies and an increased demand for precise 3D models in the clothing, medical, fitness, movie and gaming industries [3] [4] [5] [6]. For photogrammetric 3D reconstruction, most of the commercially available solutions come in the form of chambers with numerous cameras that can capture the person from various angles [7] [8]. The main advantage of these kinds of scanning chambers is that the image capturing for 3D reconstruction is instantaneous, which means reduced likelihood of subject movement and improved scan quality. The biggest downside is the cost of these types of chambers, as they typically consist of 70 to 150 cameras and lighting equipment mounted at specific angles around the subject being 3D scanned. Another significant drawback is the spatial requirement as these chambers tend to take up a lot of space due to the necessary setup. Alternatively, photogrammetric 3D reconstruction can be achieved using only one camera to capture multiple images of the subjects [9], which is the method employed in this master's thesis. Utilizing a single camera significantly reduces the cost of photogrammetric 3D scanning, while still producing models suitable for various purposes. The post-processing time for the resulting 3D model can vary significantly, depending on its intended usage. AI and machine learning are also being implemented for processing of 3D models [6]. The current state of the art in photogrammetric 3D body scanning focuses on synchronizing all cameras in the booth, coupled with optimal lighting, to ensure maximum quality in terms of texture resolution and color depth while minimizing space requirements and maximizing portability. Some other methods for scanning bodies include those that utilize RGB-D, time-of-flight cameras, structured-light 3D scanners, and stereo vision.

3 Digital Photogrammetry Applied to Anthropometry

As a part of this master's thesis, research was conducted to explore how single-camera photogrammetry can be used for 3D reconstruction of the human body. The outcome is a proposed recording protocol that ensures a sufficient quality of 3D reconstruction for extracting body measurements. Since only one camera is utilized the image acquisition will not be instantaneous. As image acquisition is not instantaneous, the resulting 3D model's quality may not match that of the state-of-the-art image capturing booths. However, that is not the primary objective. The goal of the proposed protocol is to minimize the time required for image acquisition while attaining the highest possible 3D reconstruction quality, ensuring a sufficient quality of the 3D model for extracting the accurate body measurements. The protocol is divided into three parts: preparation, capturing, and processing.

3.1 Preparation

The subject should wear colorful or textured clothes and avoid black clothing to enable the photogrammetry software to better extract features from the photos. For the best quality of reconstruction, the manual operating mode is used, utilizing manual auto-focus and without the use of integrated flash. The use of the integrated flash is not recommended because it lengthens the time of image capturing due to the charging time of the capacitor used by the built-in flash. Recording can take place either indoors or outdoors. However, for outdoor recording, it should be conducted on a clear, sunny day to ensure optimal lighting. Regardless of the place of recording, it should be spacious, minimally 5x5 meters. On the floor, markings should be made to indicate both the position where the subject will be standing and the locations from which the images will be captured. If the recording is to be performed indoors, additional lighting equipment should be used. To extract measurements after obtaining a 3D model, a reference object with well-known and defined dimensions is needed in the scene. This allows the utilization of a measurement tool within the software used for viewing the reconstructed model, such as MeshLab [10] or Blender [11]. The internal measurement unit of the software used is correlated with real-world measurements, making it straightforward to convert into standard measuring units (SI). With this kind of setup, capturing of around 20 images was achieved in under 2 minutes, and the resulting 3D model was suitable for extracting body measurements.

3.2 Acquisition

To ensure successful image acquisition, the subject should remain as still as possible. Focusing on a specific point can help the subject maintain steadiness. Images should be captured equidistantly around the subject, with uniform angular increments. It is recommended that the person taking the images captures one at each step along the marked circle. Additionally, to distinguish between pictures from different sessions, taking a dummy photo at the beginning and end of each session is advisable. The images of the subject should be taken with the subject being in either A, I or T-poses. In the context of this study, the A-pose refers to the subject standing with their arms positioned at 30-45 degrees from their body. I-pose is when the subject has their arms placed next to body. T-pose is when the subject has his arms spread 90 degrees from the body.

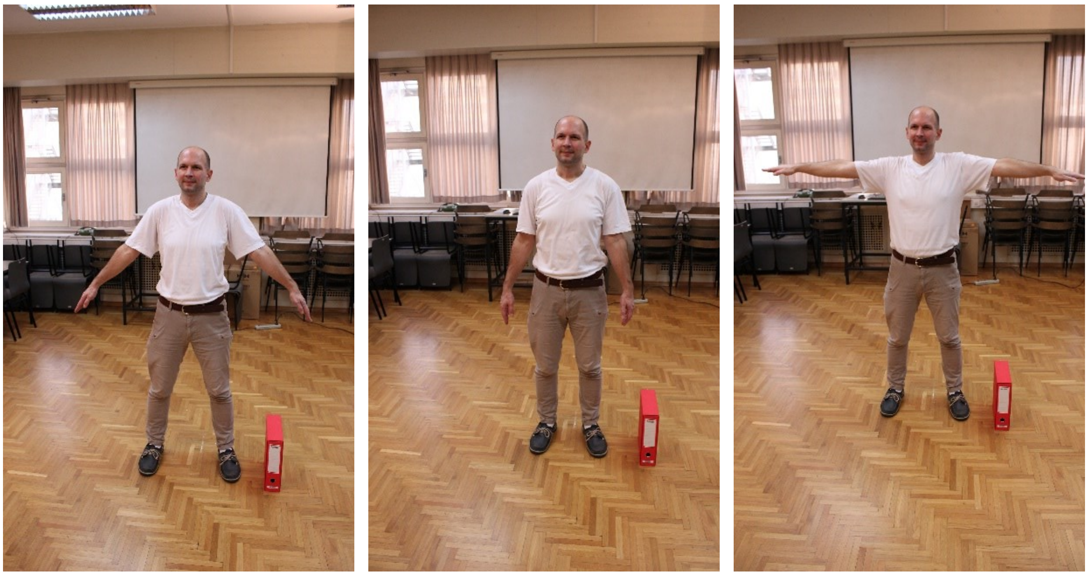


Figure 1 - Subject standing in A, I and T-poses respectively

3.3 Processing in AliceVision

Before the images are processed, a visual inspection for blurry images is recommended. The process of extracting a 3D model from the recorded images was achieved by employing AliceVision [12]. Meshroom [13] is an open-source software which utilizes its underlying 3D computer vision framework AliceVision. It provides a node-based environment for executing various computer vision tasks. Each node in the system represents a specific task, functioning as a tool implemented in AliceVision. These nodes are then organized into pipelines. The nodes in Meshroom serve as logical steps within the directed graph, which are initiated each time when there are changes in inputs or parameters, or when the graph undergoes modifications. While AliceVision offers preconfigured pipelines, users have the flexibility to change them as desired and save their configurations as the new default pipeline. Users can add or remove nodes in the pipeline and connect multiple nodes to the output of a stage. While it is interesting to explore the various possibilities that the changes in the pipeline enable, the default pipeline provides a good understanding of how photogrammetric processing in computer vision is done. On its example, the general pipeline of photogrammetric software can be explained. The AliceVision photogrammetry pipeline comprises the following steps: camera initialization, feature extraction, image matching, feature matching, Structure-from-Motion, depth mapping (including preparation, mapping, and filtering), meshing, mesh filtering, and texturing. The pipeline graph is provided in the Figure 2.

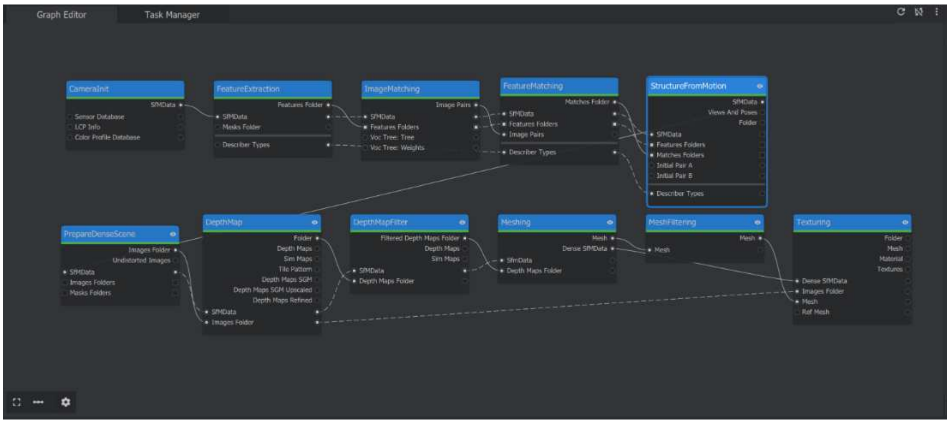


Figure 2 – Graph of the photogrammetry pipeline used in AliceVision [12]

The suggested protocol is provided in form of an acquisition checklist in Table 1.

Protocol Checklist	
Preparation	Subject(s): wearing bright colored or textured clothing focused on a single point to ensure maximum steadiness barefoot (if wearing shoes adjust the measured height)
	Equipment: Camera: all automatic features turned OFF, especially automatic flash and focus are turned OFF Lighting setup: if the image acquisition process is indoors place lighting in such way to ensure uniform and bright lighting Calibration object: a box of known dimensions is positioned next to the subject
	Environment/Room: Dimensions: ensure enough space for image acquisition (min. 5x5m) Floor markings: make markings on the floor where the subject is standing and a circle around the subject where images are taken
Acquisition	Subject should remain as still as possible in the A-pose
	Images should be captured equidistantly around the subject, following the markings
	Dummy images should be taken between sessions
Processing	Visual image check for blurry images
	AliceVision processing

Table 1 - Acquisition Checklist

For the purposes of this master's thesis, two incandescent light bulb reflectors were used, placed in the opposite sides of the room, pointed towards the white-colored ceiling, to ensure optimal lighting. To record the images, a DSLR Cannon DS126271 camera with Cannon EFS 18-55mm lens was utilized.

3.3.1 Camera Initialization

The main data extracted in this node are camera intrinsics and viewpoints. The lens name and camera maker are used to match the lens correction profile database. Furthermore, you have the option to choose the color processing method for RAW data, and adjust various ID parameters as needed. Additional information is provided in the image below.

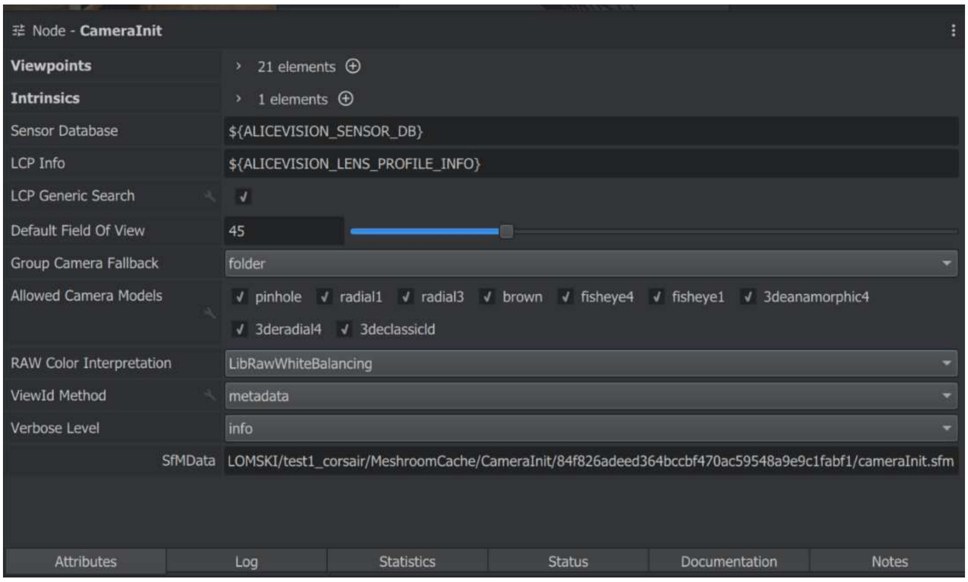


Figure 3 - Detailed description of Camera initialization node

3.3.2 Feature Extraction

The goal of this step is to detect a group of distinctive points in every image that are invariant to scale, rotation in 2D and 3D and several other properties such as lighting. AliceVision implements both natural feature extractors (SIFT, and AKAZE) and marker-based features (CCTag, April-Tag) [13]. Once those features are extracted, they can be used to determine the relative pose of the camera in space, and to initiate the scene. In the Advanced Attributes section of this node, “Force CPU Extraction” was unchecked to utilize the GPU for faster feature extraction. All node settings are shown in the image below.

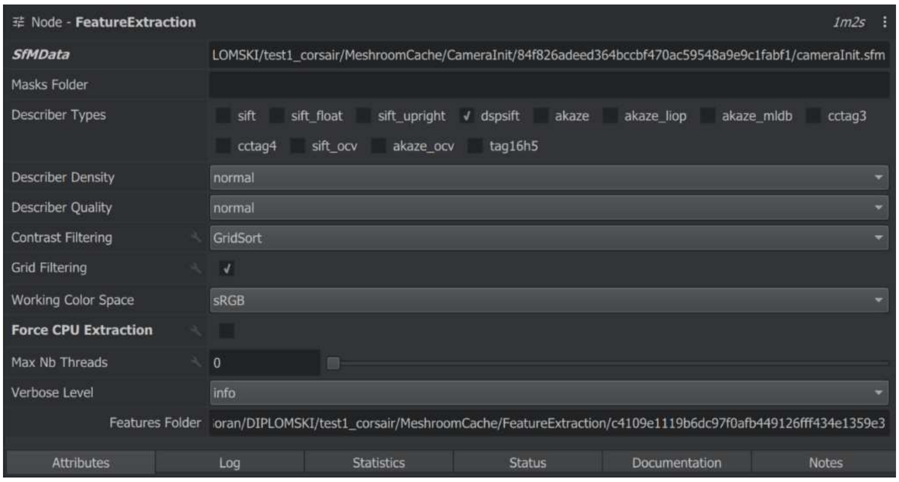


Figure 4 - Detailed description of Feature extraction node

3.3.3 Image Matching

The objective of this node is to find images that look at the same surfaces of the scene. The image needs to be simplified into a compact image descriptor that enables efficient calculation of distances between all image descriptors. One of the most common methods for generating image descriptors is the vocabulary tree approach. By transferring all descriptors of detected features into the tree, it performs classification by comparing descriptors with those at each node in the tree. Each feature ends up at a leaf, which can be stored using the index of the leaf in the tree. The image descriptor is then represented by leaf indexes. Comparing image descriptors in this way makes it possible to see if different images share the same content [14].

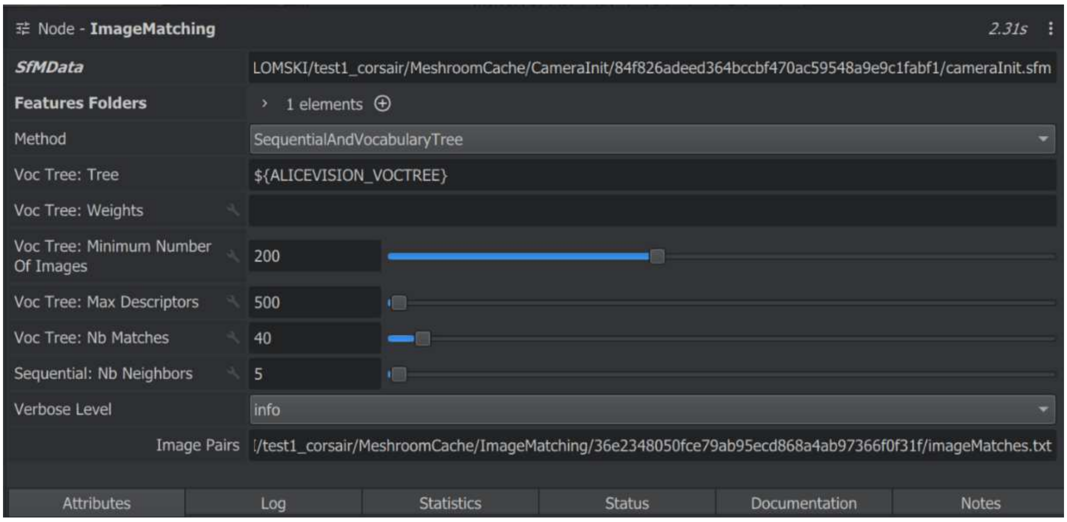


Figure 5 - Detailed description of Image matching node

3.3.4 Feature Matching

Feature matching involves finding similarities between features extracted in the Feature Extraction node across different images. The goal is to identify points or patterns in one image that correspond to the same points or patterns in another image. In this process relationships between images are established. Descriptors are employed to find the best fitting matches between images. Since this is an intensive step to use a brute force approach, algorithms like Approximate Nearest Neighbor and Cascade Hashing are utilized. Features positions are then used to make a geometric filtering using RANSAC (RANdom SAmple Consensus) outlier detection framework [12].

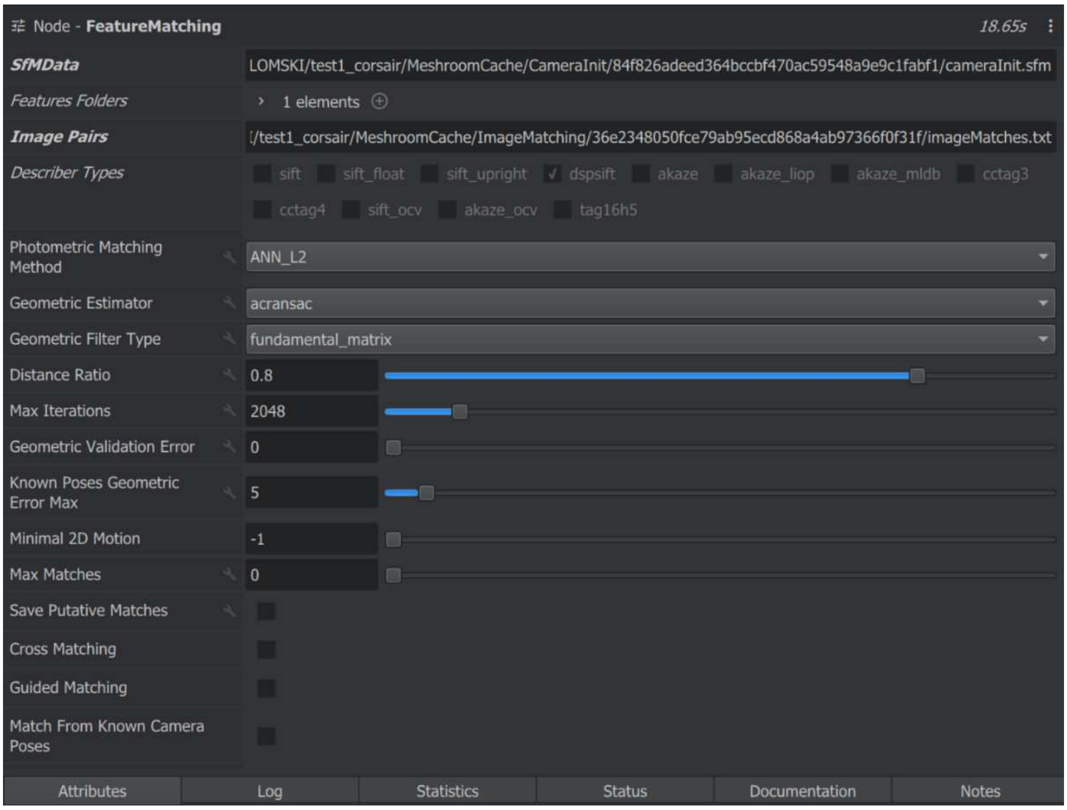


Figure 6 - Detailed description of Feature matching node

3.3.5 Structure from Motion

Structure from Motion (SfM) is a key component of the photogrammetry pipeline, as it merges the matched features into tracks that represent a point in space seen by different cameras. This means that a relationship between 2D images and points in 3D space is made in this step. These points are then used to solve the camera calibration and generate a 3D structure of the scene. AliceVision implements an incremental approach for computing the positions of points, which means that new cameras are incrementally added to the scene from an initial solution. The output of SfM node is statistical data about reprojection error, number of reconstructed 3D points, and number of tracks for each camera individually or globally, for the whole scene [13].

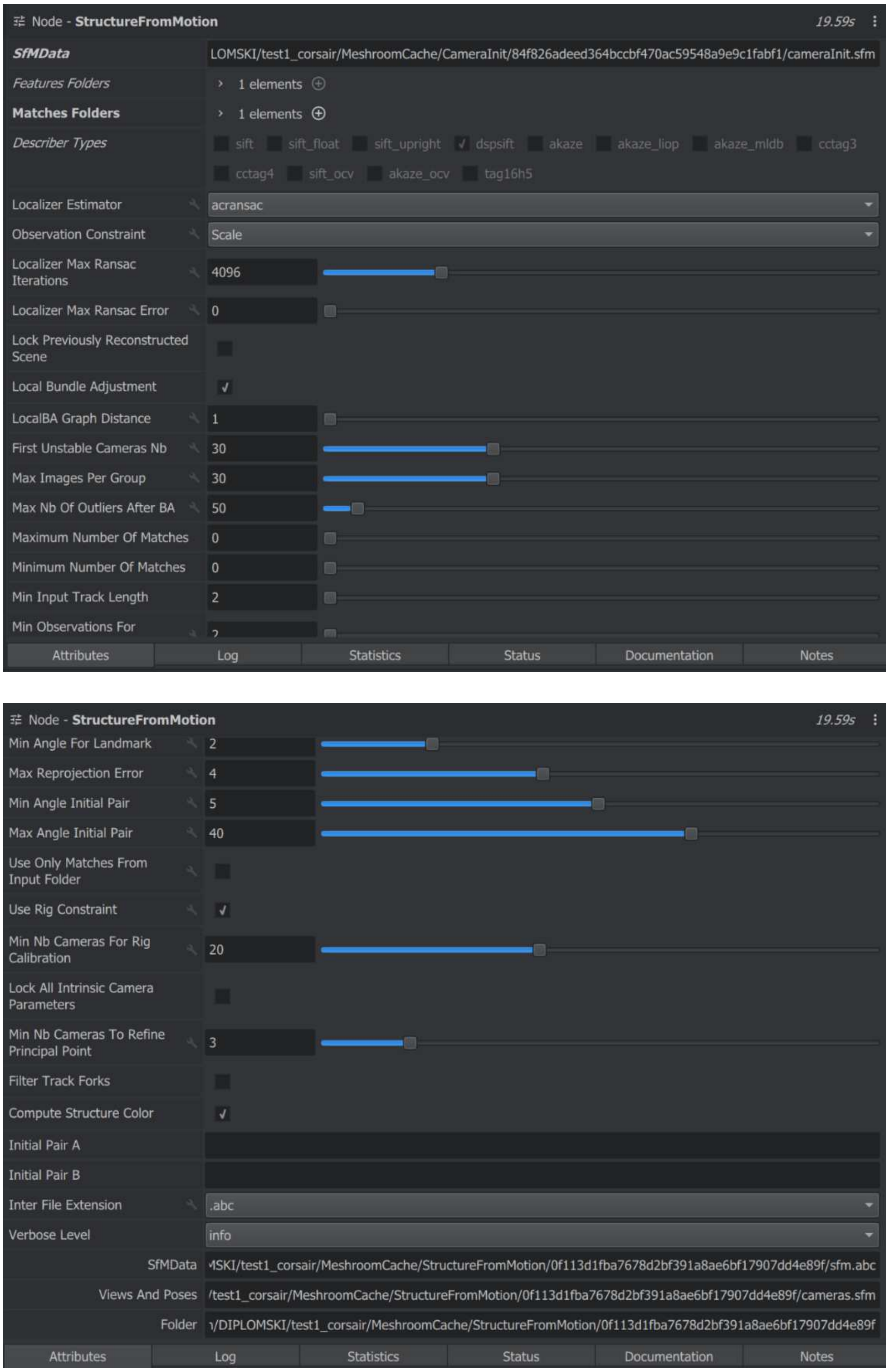


Figure 7 – Detailed description of Structure from motion node

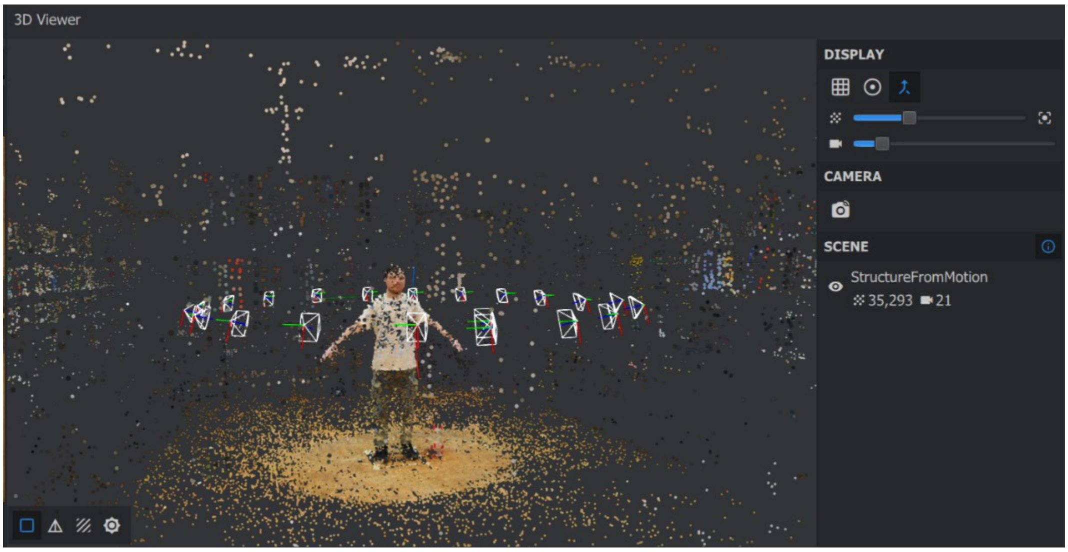


Figure 8 – Dense 3D point map generated after Structure from motion node

3.3.6 Depth Map Estimation

This step aims to assign a depth value estimation to each input pixel. The area that is to be estimated needs to be seen by at least two cameras that have been validated by SfM. Some of the methods used for retrieving depth values are Block Matching, Semi-Global Matching (SGM), and ADCensus. AliceVision implements the SGM method. For each image, a number of closest images are selected based on the intersection of the optical axis with the pixels of the selected neighboring cameras. Similarity between them is estimated using the Zero-Mean Normalized Cross-Correlation (ZNCC), after which a denoising filter is applied. Depth maps computed for each image can be visually represented using a colormap in both the 2D and 3D viewer. This visualization allows for a qualitative assessment of the depth map's quality when projected onto the reconstructed scene [13].

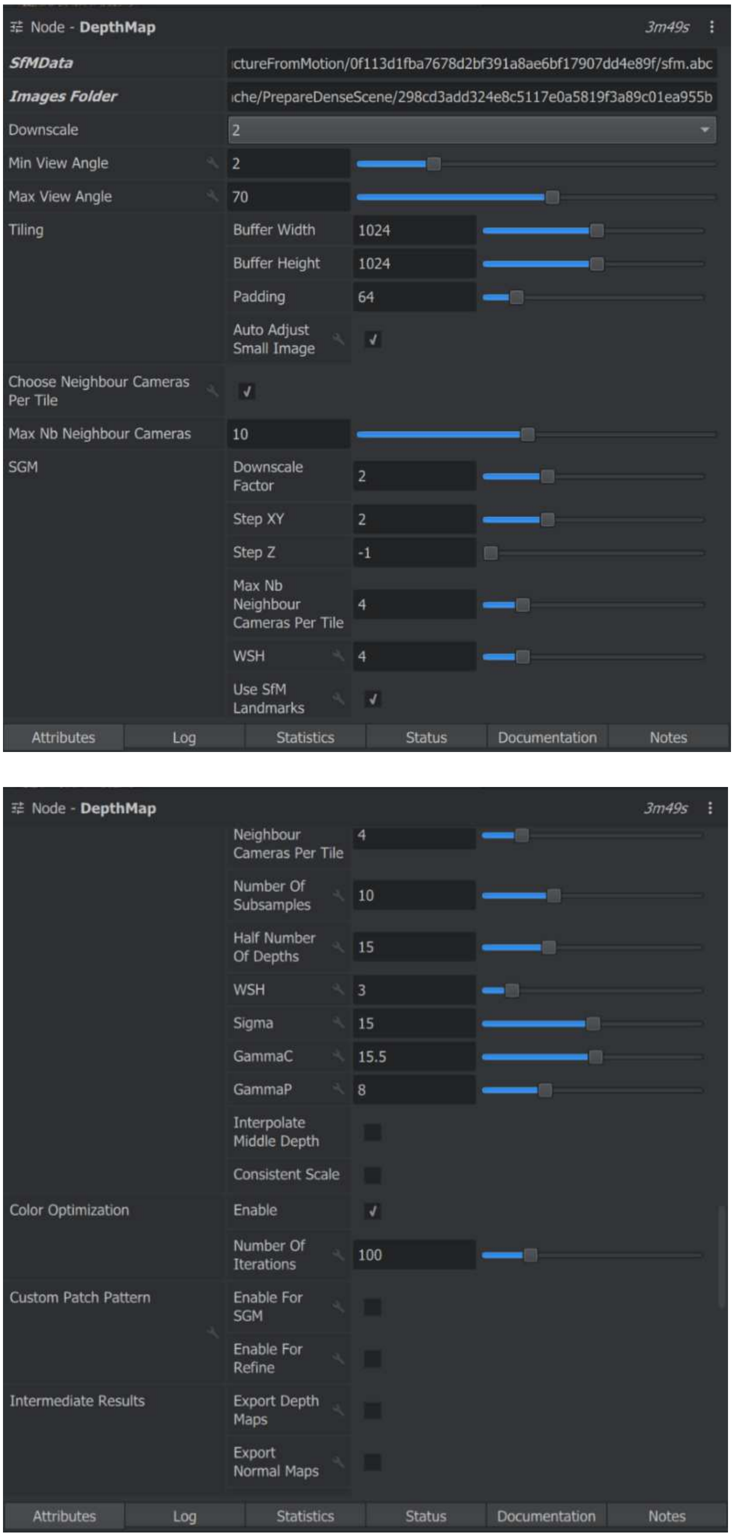
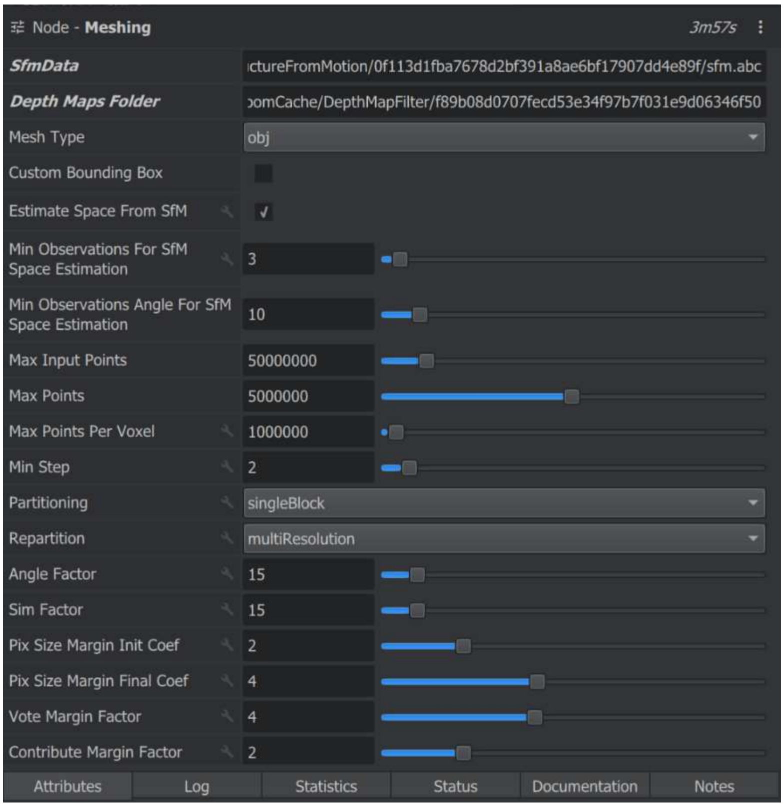


Figure 9 - Detailed description of Depth map estimation node

Figure 10 - Depth map estimation for one image in the scene

3.3.7 Meshing

In the meshing step, all depth maps generated in the previous steps are combined into a dense point cloud, from which a surface is then extracted. AliceVision uses an iterative KDTree approach to fuse the 3D points, reducing the point cloud to accommodate the available RAM. After the dense point cloud is created, 3D Delaunay triangulation [15] along with a voting strategy is used to create a space filled with tetrahedra. Finally, the mesh surface is extracted using graph cut max-flow [16], and filtering is applied to achieve surface smoothing [13].



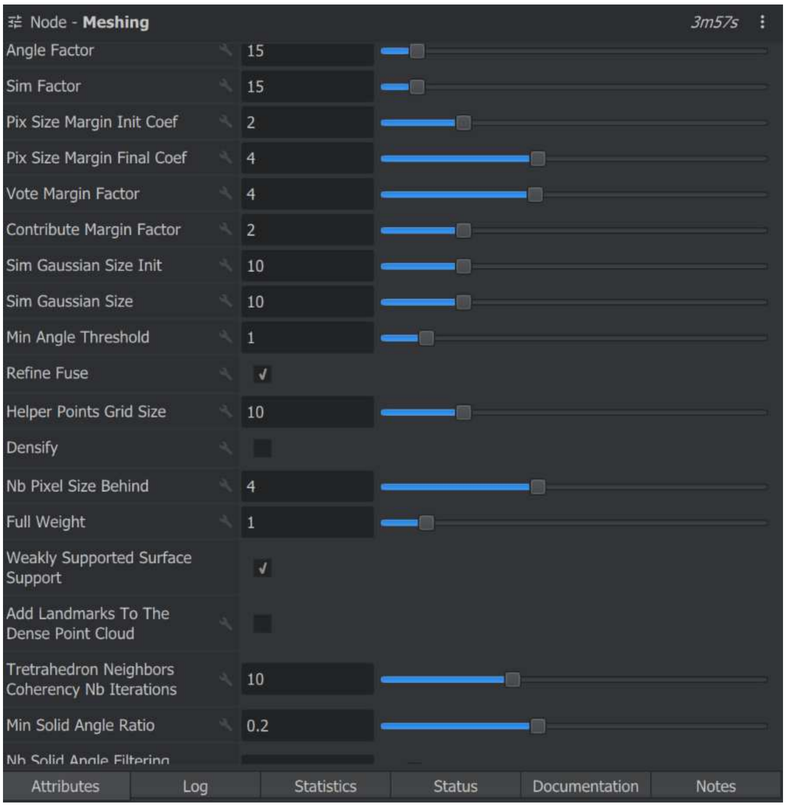


Figure 11 - Detailed description of Meshing node

3.3.8 Texturing

Texturing is the final phase of the pipeline, and its primary objective is to enhance the realism of the reconstructed 3D model by applying texture to the mesh. AliceVision uses views from different cameras to form the final texture that will be used. If there is no UV associated, a basic UV mapping approach to minimize the texture space is incorporated [17].

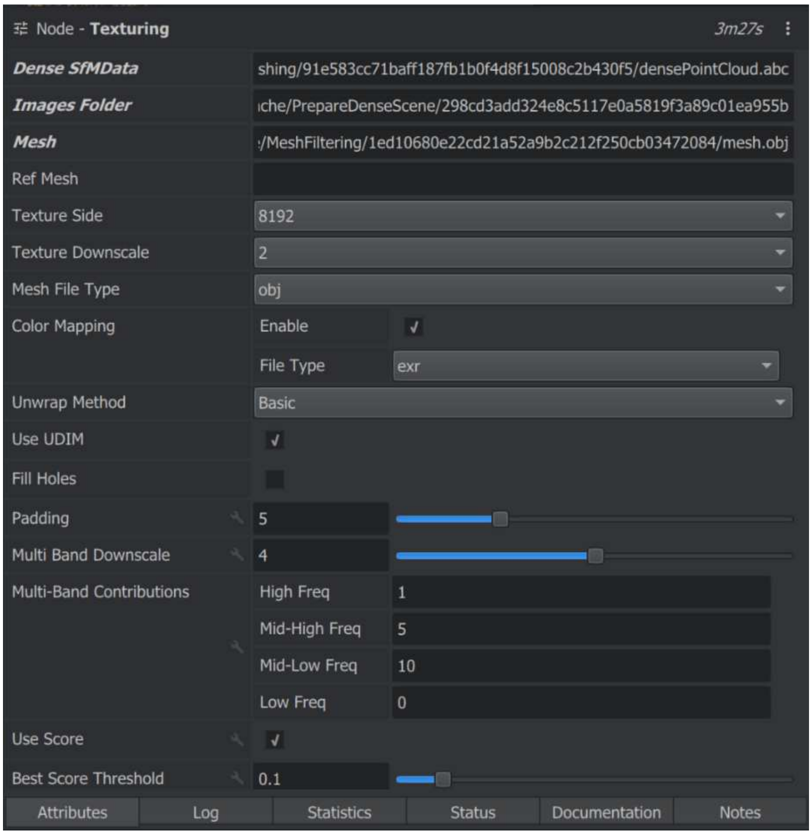


Figure 12 - Detailed description of Texturing node

4 Results and Discussion

In this chapter, the results will be presented through a photo gallery that includes images from the photoshoots and visuals of the reconstructed 3D models. Subsequently, a comparison of measurements obtained from the 3D models, as well as those measured with a measuring tape, will be provided in a table. Following that, measurement errors and the required number of images for reconstruction will be discussed. The measurements were extracted following the CAESAR anthropometry protocols [18]. The measurement chosen for comparison is body height. To ensure the highest possible accuracy of the results, attention should be paid to these few things:

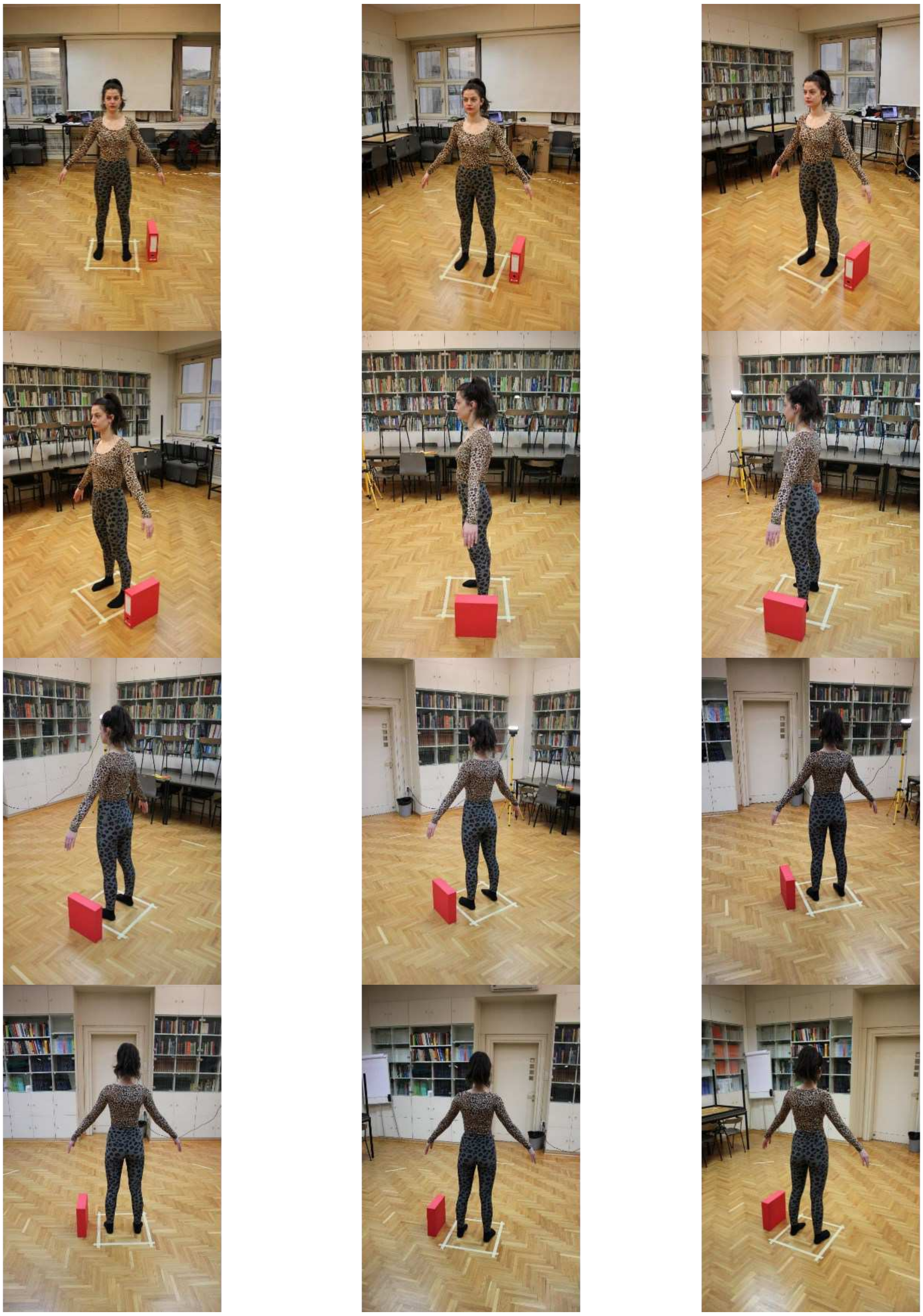
Firstly, spatial constraints play a crucial role in photogrammetry. Limited space can hinder the ability to capture comprehensive images of the subject.

Secondly, proper lighting is necessary to avoid distortions in measurements and reconstructed models. Shadows, reflections, and uneven illumination can affect accuracy. Overhead lighting may cause glare or obscure body features, while insufficient lighting can lead to underexposed images.

Furthermore, clothing worn by subjects significantly impacts measurement accuracy. Loose or bulky clothing can obscure body contours, affecting the precision of extracted dimensions. Ideally, subjects should wear brightly colored, textured, and tight clothes.

Finally, subjects' cooperation during the photo session is vital. Proper posture, relaxed limbs, and rests between sessions are needed to minimize errors introduced by movement or deviation from the desired pose.

As mentioned before, the equipment used for the purposes of this masters thesis is a single DSLR Cannon DS126271 camera equipped with a Cannon EFS 18-55mm lens and two incandescent light bulb reflectors to ensure proper lighting. In the Figure 13, we can see the images used for reconstructing a subject’s model. To maintain anonymity, we shall refer to her as Subject 1.



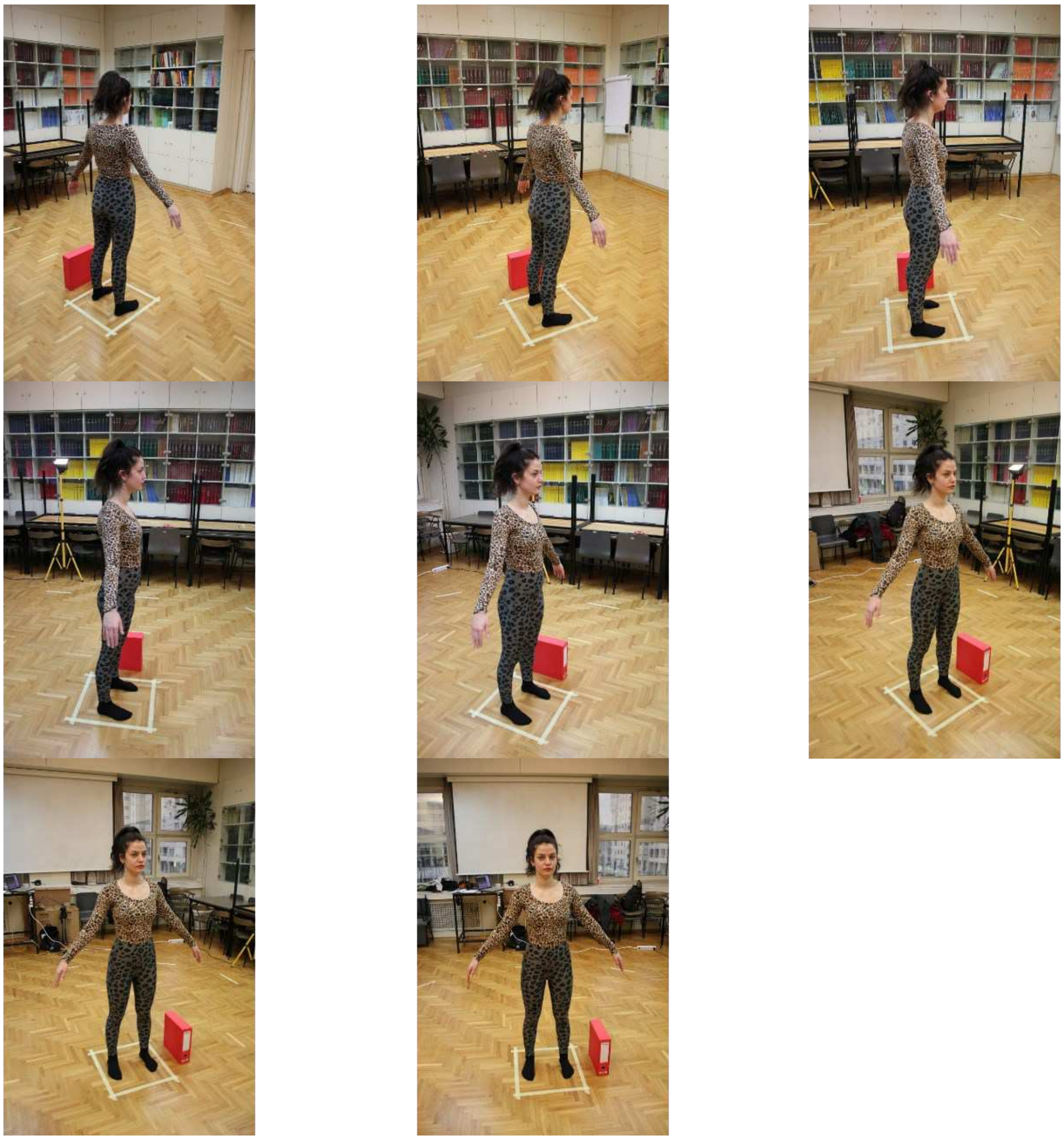
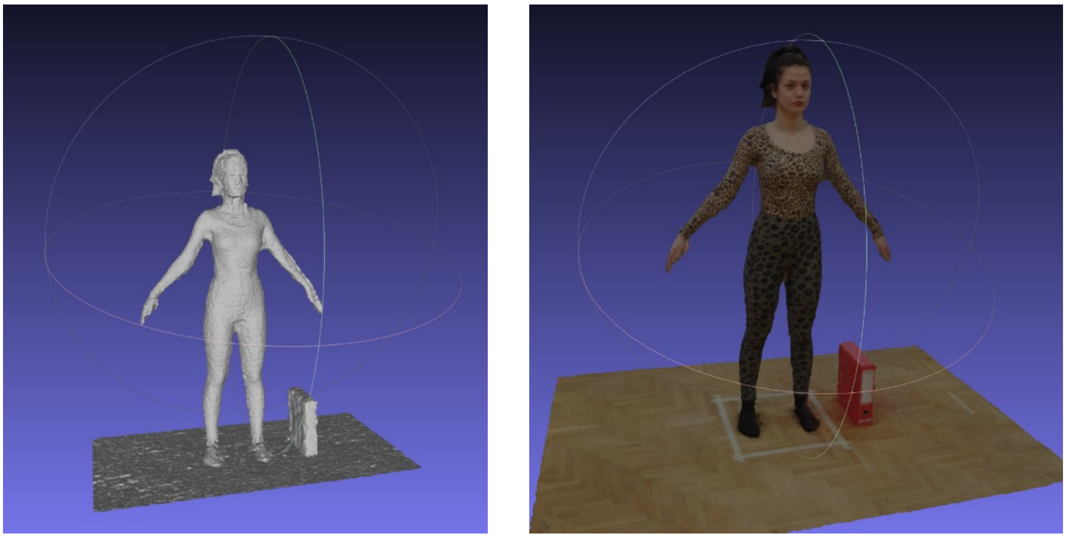


Figure 13 – Subject 1 image gallery

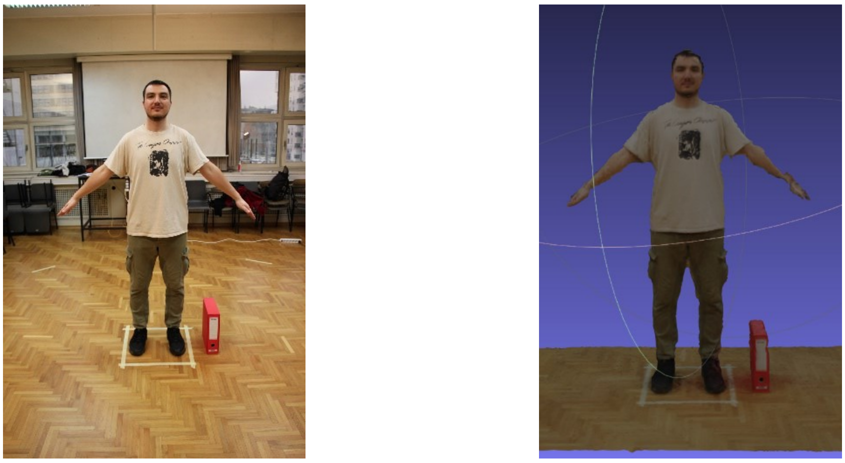
From these images the following 3D model was obtained:



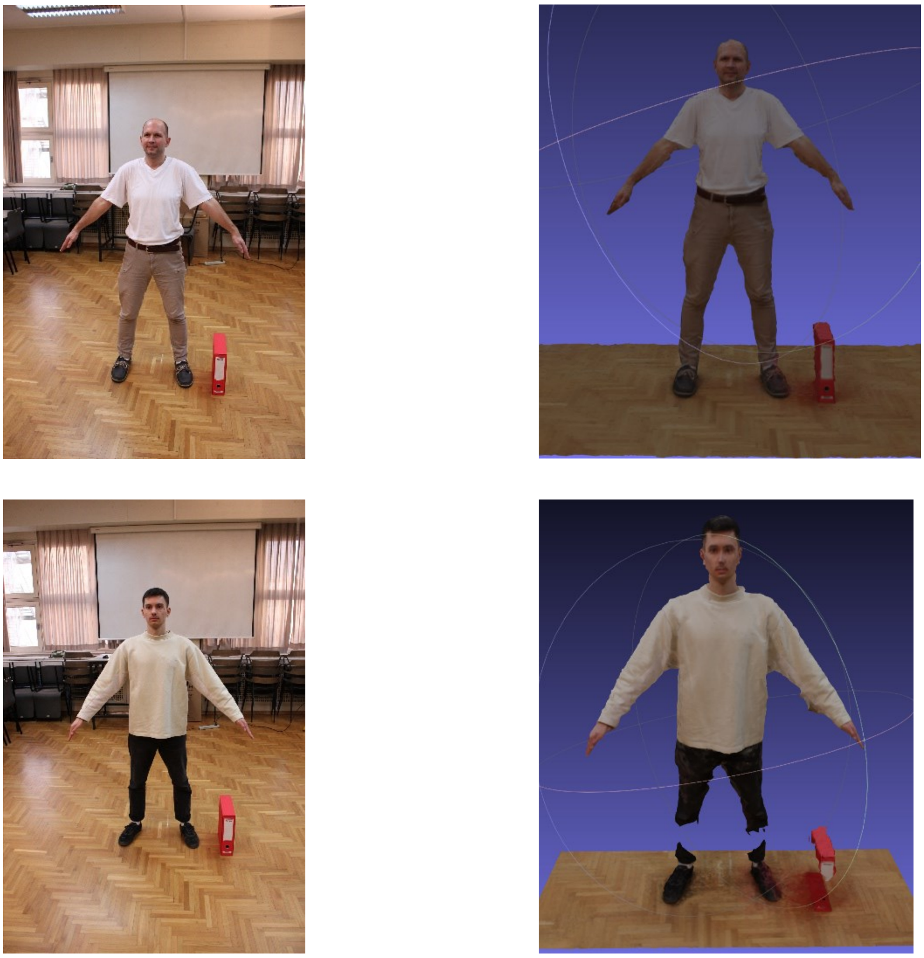
a) b)

Figure 14 – Subject 1 reconstructed 3D model: a) without texture; b) with texture

In the images below, Subjects 2, 3 and 4 are introduced, along with their respective 3D models.



a)

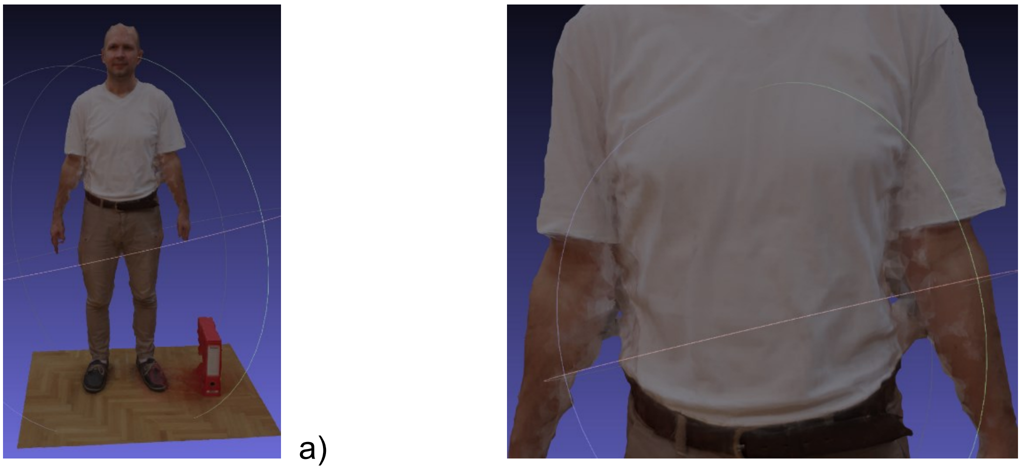


b)

c)

Figure 15 – a) Subject 2 and reconstructed 3D model; b) Subject 3 and reconstructed 3D model; c) Subject 4 and reconstructed 3D model

It can be observed that all the provided images and models depict subjects in A-pose, despite the reconstruction being conducted for both I and T poses, respectively. This is because the desired measurements are easiest to extract from the 3D models reconstructed from subjects in the A-pose. Measurements can also be extracted from I-pose; however, there is a larger volume of reconstruction-based artifacts present in the reconstructed models.



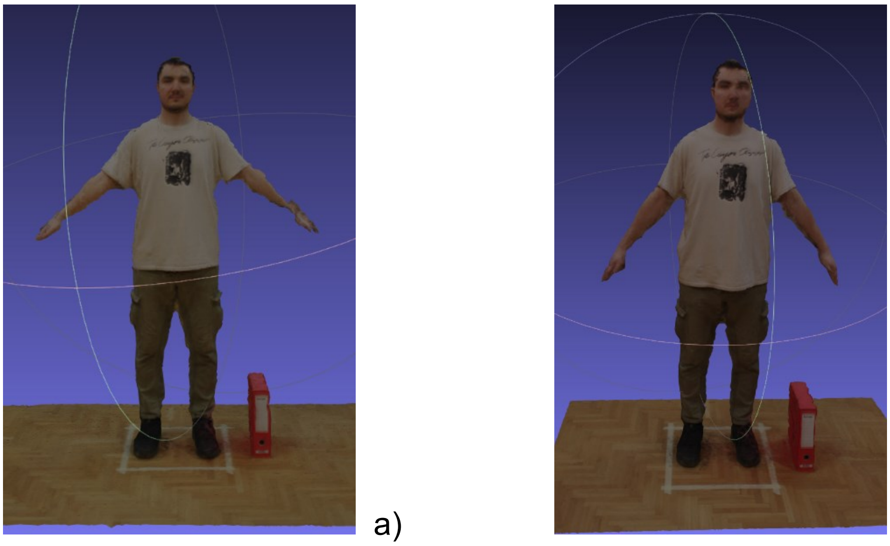
a) b)

Figure 16 – a) Subject 3 I-pose; b) a close-up of reconstruction-based artifacts

In the case of the T-pose, the primary challenge lies in achieving a well-reconstructed model where all the limbs are reconstructed in their entirety. This happens mainly because it is difficult for subjects to maintain the T-pose without moving throughout the duration of the image capturing process.

Figure 17 – Subject 3 T-pose

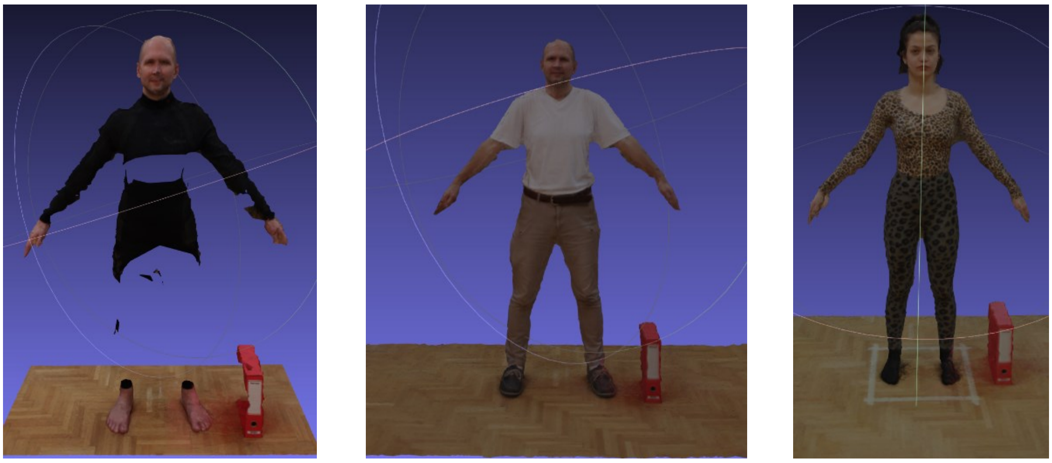
Furthermore, the difference between utilizing manual and auto modes during image capturing process should be discussed. While the full automatic mode can be utilized, better quality 3D models were achieved using the manual mode. In the images below we can observe the difference between models reconstructed using these different modes. When utilizing auto mode, the photogrammetry software may encounter difficulties in accurately forming depth maps, leading to misaligned texture mapping. As can be seen in image below, the subject's arms were reconstructed poorly due to movement during the capturing process. However, this still means that using manual mode is more accurate for reconstructing the 3D models.



a) b)

Figure 18 - a) reconstruction using photos taken with manual mode; b) reconstruction using photos taken with auto mode

As previously mentioned, the clothing worn by the subject significantly influences the quality of the reconstruction. The images below illustrate how darker-toned clothing can adversely affect the reconstruction quality. This is primarily due to the challenges photogrammetry software faces when extracting features from darker colors. Consequently, superior lighting equipment yields better results. Ideally, for the purposes of anthropometrical measuring, the subject should wear gym clothes that are tight, brightly colored, and textured.



a) b) c)

Figure 19 - a) Subject 3 wearing a neoprene diving suit; b) Subject 3 wearing casual outfit; c) Subject 1 wearing tight and textured clothes

Extracting measurements from 3D models is accomplished using free software such as MeshLab or Blender. In the image below, the measurement tool from MeshLab is shown being used to extract anthropometric measurements from the 3D model. AliceVision utilizes autocalibration, providing calibration parameters up to scale, which requires a known-sized object in the scene to establish scale.

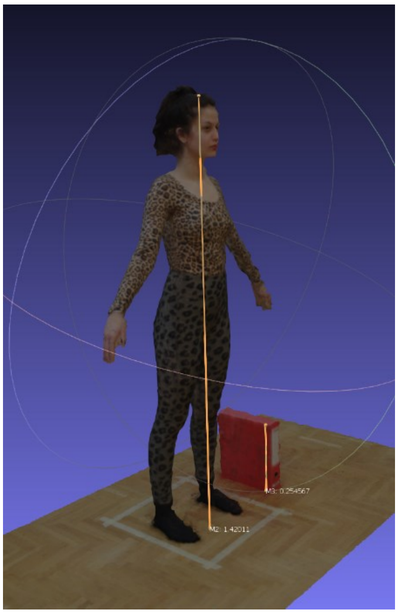


Figure 20 - Using measuring tool to extract anthropometric measurements

Subject	Height measured, x_{An}	Height estimated, x_{Bn}	$\lvert x_{An} - x_{Bn}\rvert$
1	169 cm	168.69 cm	3.1 mm
2	184 cm	184.67 cm	6.7 mm
3	182 cm	184.00 cm	20.0 mm
4	179 cm	181.43 cm	24.3 mm
		Average	13.5 mm

Table 2 – Height measurement and its absolute errors

The ANSUR study establishes the Allowable Error (AE), which sets the maximum Mean Absolute Error (MAE) that a measurement method can have. For height, the MAE is 10 mm [19]. The calculated error for height using single-camera photogrammetry is 13.5 mm, which exceeds the allowed limit. This discrepancy can be attributed to some subjects having their height measurements taken while wearing shoes, significantly influencing the results. Measurements were retaken, adjusted, and the results are presented in the table below.

Subject	Height measured, x_{An}	Height estimated, x_{Bn}	$\lvert x_{An} - x_{Bn}\rvert$
1	169 cm	168.69 cm	3.1 mm
2	184 cm	184.67 cm	6.7 mm
3	183 cm	184.00 cm	10.0 mm
4	181 cm	181.43 cm	4.3 mm
		Average	6.0 mm

Table 3 - Measurements compensated for shoe height and recalculated absolute errors

The new measurements reveal that the calculated absolute error (AE) is less than the mean absolute error (MAE), indicating that the proposed method is suitable for anthropometric measuring. The proposed protocol resulted in acceptable reconstruction quality using 20 images. The recommended minimum number of images for successful reconstruction is 15; below this threshold, reconstruction quality is significantly affected.

5 Conclusion

In this master's thesis the application of digital photogrammetry for extracting anthropometric measurements was explored and a recording protocol that ensures reliable 3D reconstruction for extracting body measurements was proposed.

By employing a DSLR camera and utilizing the open-source software AliceVision, 3D models were generated from photographs of subjects. The method demonstrated sufficiently accurate measurements for the height measurement, with the mean absolute error of 6.0 mm which is falling within the acceptable limit of 10.0 mm.

However, to ensure reliable results critical steps of the proposed data acquisition protocol are: (a) The spatial requirements needed for image acquisition should be taken care of. (b) Lighting should be uniform and bright. (c) Subjects should wear brightly colored, textured, and tight clothes. (d) Subjects should be given adequate time to rest between sessions, and the images should be captured in either the I or A-poses to minimize errors caused by movement.

Acknowledgement

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Abstract

Digital Photogrammetry Applied to Anthropometry

Goran Jaković

Anthropometry is the science of measuring human body dimensions and proportions, with many applications ranging from medicine and fashion to fitness. In this master thesis a study was conducted to explore how digital photogrammetry can be utilized to extract anthropometric measurements. The goal of the thesis is to define a reliable and quick data acquisition protocol which utilizes photogrammetry for anthropometric measurements, providing sufficiently accurate measurements of the human body. To achieve this, a DSLR camera was employed to capture photographs of several subjects. Then, AliceVision, an open-source photogrammetry software, was utilized to generate 3D models from these images, and selected measurements were extracted from the 3D models using a calibration object. Finally, obtained measurements were compared to those taken using a measuring tape. The mean absolute error of selected measurements is within the allowable error margin indicating that the proposed method can be used for anthropometric measurements.

Keywords: anthropometry ; photogrammetry ; computer vision

Sažetak

Primjena digitalne fotogrametrije u antropometriji

Goran Jaković

Antropometrija je znanost koja se bavi mjerenjem dimenzija i proporcija ljudskog tijela. Antropometrija ima mnoge primjene, uključujući one u medicini, modi i fitnesu. U okviru ovog diplomskog rada provedeno je istraživanje kako se digitalna fotogrametrija može iskoristiti za antropometrijska mjerenja. Cilj rada jest definirati pouzdan i brz postupak za dobivanje preciznih mjera ljudskog tijela koji koristi fotogrametriju. Korištena je DSLR kamera za snimanje fotografija više subjekata. Zatim su pomoću AliceVisiona, besplatnog softvera za fotogrametriju, generirani 3D modeli iz tih fotografija. Odabrana antropometrijska mjera je izmjerena iz 3D modela pomoću kalibracijskog objekta. Na kraju su dobivene izmjere uspoređene s onima dobivenima pomoću krojačkog metra. Prosječna apsolutna pogreška odabrane mjere nalazi se unutar dopuštene granice pogreške, što ukazuje da se predložena metoda može koristiti za antropometrijska mjerenja.

Ključne riječi: antropometrija ; fotogrametrija ; računalni vid

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