Evaluation of Low-Cost 3D Scanner Hardware for Clothing Industry

Michael Danner[1][a], Elena Alida Brake[1][b], Christian Decker[1][c], Matthias Rätsch[1][d], Yordan Kyosev[2][e] and Katerina Rose[1][f]

[1]*Reutlingen Research Institute, Reutlingen University, Alteburgstraße 150, Reutlingen, Germany*

[2]*Institute of Textile Machinery and High-Performance Material Technology, Chair of Development and Assembly of Textile Products, Technische Universität Dresden, Dresden, Germany*

{*michael.danner, elena.brake, christian.decker, matthias.raetsch, katerina.rose*}*@reutlingen-university.de,*

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Abstract: In recent years, the demand for accurate and efficient 3D body scanning technologies has increased, driven by the growing interest in personalised textile development and health care. This position paper presents the implementation of a novel 3D body scanner that integrates multiple RGB cameras and image stitching techniques to generate detailed point clouds and 3D mesh models. Our system significantly enhances the scanning process, achieving higher resolution and fidelity while reducing the cost, time and effort required for data acquisition and processing. Furthermore, we evaluate the potential use cases and applications of our 3D body scanner, focusing on the textile technology and health sectors. In textile development, the 3D scanner contributes to bespoke clothing production, allowing designers to construct made-to-measure garments, thus minimising waste and enhancing customer satisfaction through fitting clothing. In mental health care, the 3D body scanner can be employed as a tool for body image analysis, providing valuable insights into the psychological and emotional aspects of self-perception. By exploring the synergy between the 3D body scanner and these fields, we aim to foster interdisciplinary collaborations that drive advancements in personalisation, sustainability, and well-being.

1 INTRODUCTION

3D body scanning technology has gained significant attention in recent years, revolutionising various industries by providing a means for accurate, non-invasive, and efficient body measurements. The ability to capture detailed, three-dimensional data of the human body in mere seconds has paved the way for countless applications, ranging from healthcare and fitness to the textile industry and performance diagnostics in sports and entertainment (Schlich et al., 2010).

Traditionally, measuring the human body has been a time-consuming and error-prone process involving manual measurements and subjective evaluations. The advent of 3D body scanning has not only streamlined this process but also enhanced the precision and consistency of the data collected. By employing techniques such as structured light, laser triangulation, or photogrammetry, 3D body scanners can create accurate digital representations of the human form, capturing intricate contours and dimensions (Daanen and Psikuta, 2018).

The versatility of 3D body scanning has allowed for its implementation in various sectors. In healthcare, it can facilitate diagnoses, monitor progress, and assist in rehabilitation. In fitness, it provides valuable insights into body composition and tracking physical changes, for example, in the analysis and diagnosis of high-performance athletes. The textile industry benefits from made-to-measure clothing pattern construction and improved sizing systems, while the entertainment sector can utilise the technology for character modelling, virtual reality, and motion capture animations capturing (Rozmus et al., 2021).

As we continue to explore the capabilities of 3D body scanning technology, it is crucial to foster dialogue and collaboration among researchers, practi-

[a] https://orcid.org/0000-0002-8652-6905
[b] https://orcid.org/0009-0004-7828-6501
[c] https://orcid.org/0009-0003-6030-5498
[d] https://orcid.org/0000-0002-8254-8293
[e] https://orcid.org/0000-0003-3376-1423
[f] https://orcid.org/0000-0003-4294-9700

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tioners, and industry stakeholders to address challenges, share advancements, and ultimately unlock the full potential of this transformative technology. This paper presents both the design and construction of the built 3D scanner's hard- and software as well as the post-processing of the collected data to a 3D avatar representation of the individual, termed as a 'scanatar'. It also includes validation of the scanner's output by comparison with existing 3D scans and an evaluation of the scanner's accuracy and precision against a defined list of requirements.

2 RELATED WORK

2.1 Low-Cost 3D Scanner

In the area of low-cost 3D scanning, (Iwayama, 2019) presented a novel system that uses the Raspberry Pi Zero W for full-body 3D scanning. Specifically designed for the production of avatars in VRM format, this system demonstrates the potential of affordable hardware for creating detailed 3D models. Iwayama's approach offers valuable insights into our work, particularly in terms of cost-effective hardware usage.

Garsthagen presented a low-cost, open-source, multi-camera, whole-body 3D scanner. It was used in a wide range of applications and proved its versatility and effectiveness (Garsthagen, 2014).

The research of Zeraatkar and Khalili (Zeraatkar and Khalili, 2020) details the creation of a cost-effective and speedy human 3D scanner, highlighting its design, construction process, and potential applications in diverse fields, notably in areas where traditional high-cost technologies are less prevalent.

In the investigation of Kyosev and Siegmund (Kyosev and Siegmund, 2019) the Asus RGB-D camera was found to be accurate enough for the apparel industry, with a mesh size of 3-4 mm for scanning a human body. However, challenges were encountered due to optical systems and body motion, resulting in mesh discontinuities. An algorithm was developed to evaluate gaps in the clothing based on the generated meshes, but further research is required to overcome limitations and achieve full automation in measuring clothing gaps.

2.2 Scanner Operating Modes

The operational methodologies employed by low-cost 3D scanning devices can be classified into three primary techniques, namely Photogrammetry, Triangulation, and Structured Light:

- **Photogrammetry** is a cost-effective 3D scanning method that measures object distances using photos. It offers precise data and diverse uses. This technique captures multiple photos from various angles and employs software to reconstruct a 3D model. (Journalists.org, 2020; Vedantu, 2023) Photogrammetry is utilised in mapping, architecture, engineering, manufacturing, quality control, forensics, and law enforcement. Schenk's (Schenk, 2005) introduction covers photogrammetry's principles, applications, advancements, challenges, limitations, and potential solutions.
- **Triangulation** is another technique used in 3D scanning. It involves projecting a laser point or line onto an object and then using a camera positioned at a known distance from the laser source to capture the location of the laser on the object. The distance to the object is then calculated using the principles of triangulation(França et al., 2005).
- **Structured** light projects a known pixel pattern onto an object, allowing vision systems to calculate depth and surface information. It is commonly used in applications like facial recognition and body scanning. (Rocchini et al., 2001)

2.3 Areas of Application

The utilisation of 3D scanners is widespread, with a multitude of forms and designs available, ranging from mobile to stationary. The applications of 3D scanners are equally diverse, with a broad range of areas in which they are employed. In various industries and industrial manufacturing, 3D scanners are utilised to measure, digitise, and analyse the forms and dimensions of construction parts, components, or other objects.

In the realm of art and culture, 3D scans are employed to digitise art and cultural objects or reconstruct them using the acquired data. This is done for archiving and conservation purposes, as well as to create virtual exhibitions or enable research without the need for a physical object on site. However, portable hand-held scanners are typically used for this purpose, as a high level of accuracy is of utmost importance (Akca et al., 2007).

In architecture and construction, the use of 3D scanners is also common practice to create 3D models of the object and premises. This is mainly used for precise and fast surveying for planning and visualisation in the building industry. In addition, in the field of mapping and surveying, terrain, infrastructure and environments can also be recorded to a certain extent (Sepasgozar et al., 2016).

In healthcare, 3D scanners are used for more precise detection of body parts or organs for the diagnosis and treatment of diseases for medical imaging (Hitomi et al., 2015). Likewise in the medical field, 3D scanners are also used in forensics, where they can be used to document crime scenes and capture exact 3D models of evidence (Haleem and Javaid, 2019).

In the application area of gaming and entertainment, 3D scanning technology is used to create digital 3D models of real objects or people and integrate them into virtual worlds or for motion capturing (Yahav et al., 2007).

In the textile industry, 3D scanners are used in the design and development of clothing as well as furniture, accessories and seats in the automotive industry. On the one hand, physical objects can be scanned and digitised so that the dimensions and shapes can be used in design and prototyping software, such as the dimensions of a scanned human body. On the other hand, objects such as car seats, furniture or even worn clothing can be scanned so the 2D patterns can be flattened from the 3D scans. (D'Apuzzo, 2007) Furthermore, body scanners can be used in this area of application to record dynamic body dimensions, such as the length of the back, which changes when a person bends forward (Chi and Kennon, 2006). 3D scans are also used to record the influence of clothing on the body, such as changes in the shape of the human soft tissue caused by compressive clothing or the lifting of the breast by wearing a bra (Brake et al., 2022).

2.4 Textile Application

The use of 3D scanning technology extends to the areas of development and prototyping in clothing technology. By scanning a physical object, developers can capture a digital model and use it in CAD systems, which can be modified and optimised before production. This approach not only saves time and resources but also allows for greater creativity and experimentation in the design process. Besides scanning garments to flatten a 2D pattern from the 3D object, 3D scanners are mainly used to scan people and objects to be measured. Capturing measurements and dimensions via scanning allows for an error-free method and also for fit checks in CAD to be done digitally on the avatar or object (Špelic, 2020).

In addition, 3D scanners can serve as a valuable tool for the restoration and conservation of historic textiles and artefacts. By creating a digital replica through scanning, experts can examine and analyse the object without damaging the original. This technology also enables the production of replicas for educational and exhibition purposes of historical textiles (Żyła et al., 2021).

The use of 3D scanning technology in the textile industry has led to significant improvements in quality control. This technology is able to detect even the most minor flaws or inconsistencies in textile products, ensuring that the final product meets the highest quality standards with a great fit. This benefits not only the consumer but also the manufacturer, as less waste is produced and the efficiency of the production process is improved (Jhanji, 2018).

2.5 Contribution

Our goal is to democratise access to 3D scanning for broad user groups who do not have financial resources for a commercial system or who do not have the know-how to design hardware and software for a scanner device by themselves. This is achieved by reducing the complexity, mainly through the use of standards and adherence to best practices that work in the environments of those user groups.

The full-body 3D scanner was built using commercial off-the-shelf (COTS) cameras and computing hardware. The software then allows different parts to act like a single device. This paper presents the design and construction process and the performance of the built 3D scanner but with only 48 cameras. It also includes validation and evaluation of the scanner's accuracy and precision against a defined list of requirements. The main problem addressed in this study is the need for a cost-effective yet accurate 3D scanner that can be used in the field of apparel engineering by researchers who are not software experts.

Figure 1 shows our installation of the 3D scanner. It consists of 48 Raspberry Pi 4 model B (RPi, 2023a) computers mounted in a frame around a 2m x 2m ground plate. Each Raspberry Pi connects to an 8 Megapixel camera module v2.1 (RPi, 2023b). The subject stands in the middle of the ground plate, and all surrounding cameras capture pictures simultaneously. These pictures are downloaded by a user for post-processing, stitching all single pictures together to create a 3D image.

The scanning software project is open source and available on Github[1].

2.6 Definition of Requirements

From the previous definitions of the areas of application and possible options for using the scanner, it is important to precisely define the requirements to be met by the scanner in order to use it in these specific cases.

[1] https://github.com/cdeck3r/3DScanner

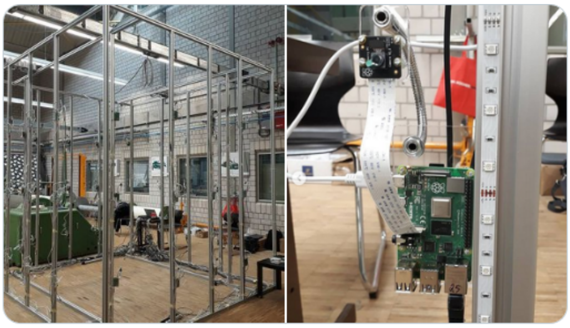

Figure 1: 3D Scanner installation.

- Capturing body measurements: The scanner must be able to capture precise measurements of body dimensions such as lengths, girths and circumferences (Bartol et al., 2021). This is important to construct and produce customised garments.
- Capture of body forms: The scanner should also be able to capture the whole individual body shapes and proportions of each scanned individual, including special physical characteristics such as asymmetries. This is important to ensure a correct fit, taking into account individual physical conditions (Ashdown et al., 2004).
- Speed: The scanner should capture data as quickly as possible in under 1 second and be efficient to save time and optimise workflow.
- Accuracy: The scanner should be highly accurate to ensure that the captured data is reliable and allows for precise measurement of the body. The maximum deviation of the scan from the real dimensions of the body should be within 5mm (Špelic, 2020).
- Compatibility: The scanner should be compatible with various software and hardware systems to ensure smooth integration into existing workflows.

The above requirements were identified through an analysis of the specific needs and challenges of the apparel industry (Kyosev and Siegmund, 2019; Istook and Hwang, 2001; Nayak et al., 2015). They serve as the basis for the design and construction of a 3D scanner for this application area. The following section describes in detail the process of planning and constructing the scanner in terms of hardware and the developed software.

3 3D SCANNER SYSTEM DESIGN

While a similar hardware setup was found in a previous work (Iwayama, 2019), we aimed at a design to significantly lower the entry bar to set up and operate such a scanner. This is achieved by reducing the complexity, mainly through the use of standards and adherence to best practices that work in the environments of our user groups. We present and discuss the design of the 3D full-body scanner from three perspectives:

- Network, i.e., we describe the setup of the scanner's hardware components
- Structure, i.e., we report about the scanner's software components and protocols
- Behaviour, i.e., we illustrate how the cameras work together to take synchronised pictures from all angles around the subject

Finally, we briefly portray some relevant operational aspects to complement the design description.

3.1 Network Setup

Our main objective was to develop an easy setup that adheres to the best practices that work in the environments of our user groups. Figure 2 illustrates the network setup. All Raspberry Pi computers connect

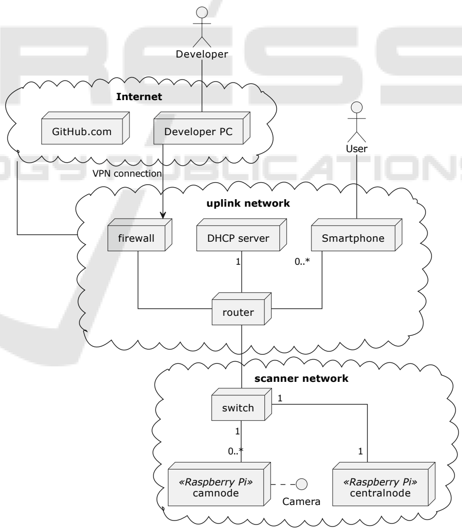

Figure 2: Scanner network setup.

to a switch and form a scanner network, which is connected to an uplink network via a router. The latter provides network services such as IP address assignment (via the DHCP server) to all Raspberry Pi computers. The user connects the smartphone with the uplink network, typically via WiFi, to access and control the scanner. A firewall shields the uplink network from the Internet and restricts access. The Internet hosts a code repository for software provision administered by a developer.

The uplink network is an infrastructure network with an Internet connection through a router. It is already available in the user's environment. Typical uplink networks are in-house university networks or even everybody's home networks. In the latter, standard home routers given to the user by their ISP provide all the functionality of the uplink network from our design. As a result, the only setup activity left to the user is to connect all Raspberry Pi computers to the switch and then plug it into the router of the uplink network.

From a network perspective, the scanner does not form a separate subnet but only consists of several networked camera devices operating in the same IP subnet as the uplink network. Therefore, from this perspective, camera devices do not differ from the user's smartphone. In the same way, a user connects a smartphone to the uplink network, and the user connects the scanner's camera devices. Consequently, additional network management activities such as IP assignment and routing are not required.

This is different from previous works, such as (Iwayama, 2019), where the camera devices are organised in a separate IP subnet to form a logical structure, which is then controlled by software. This adds to the complexity we want to avoid. In the following section, we describe our approach to creating a logical structure for networked devices.

3.2 Logical Structure

We must know all the networked cameras of the scanner to control them in an organised manner. Thus, we define a logical structure. First, we abstract the concrete hardware by naming the Raspberry Pi computers according to their functional roles. Thereby, we distinguish between two roles: camnode and centralnode. The camnode is a Raspberry Pi connected to a camera. The centralnode is a Raspberry Pi that controls all camnodes and provides a web-based GUI to the user via a web server. Figure 3 shows the UML diagram of the structure. Both nodes connect and exchange messages via the MQTT publish-subscribe protocol (OASIS, 2019), a well-known defacto standard from the Internet of Things (IoT) domain. Central to this concept is a broker that collects all messages and forwards them from publishers to subscribers. The MQTT broker is part of the centralnode. Each camnode connects to the broker via an MQTT client. The number of camnodes is not fixed. Zero to many camnodes could be connected to the broker.

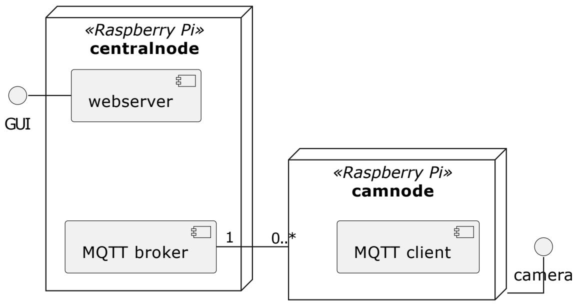

Figure 3: UML diagram of the abstract model for the scanner's system structure.

The MQTT broker utilises hierarchically organised message topics. The figure 4 shows an example of a tree-like topic hierarchy. In this ex-

```
scanner/
scanner/button
scanner/camnode1/button
scanner/camnode1/image
scanner/camnode2/button
scanner/camnode2/image
...
```

Figure 4: Example of a MQTT topic hierarchy.

ample, the `scanner` topic serves as the root and subsumes the camnodes as subtopics, for example, `scanner/camnode1`. Below each camnode topic are other topics, such as pushing the camera button or providing the captured image. The `scanner/button` topic represents the function of pushing all the camera buttons simultaneously.

Topics can have two purposes: to publish a message to a topic and to subscribe to a topic. The first purpose corresponds to sending a message, and the second is to receive a message. All message exchange interactions run through the broker, maintaining the current state of all the nodes. This tree-like structure serves in two ways: first, as an organisational structure for collecting and naming all known scanner hardware components, and second, as an interface to communicate with the named components.

This approach enables loose coupling. It works like a marketplace - whoever is on the place, that is, connected to the broker, is part of the scanner and provides services, for example, pushing a button or providing an image. If a camnode fails, the scanner still works as expected but takes one image less. This makes the scanner resilient to camnode failure. If a user installs more camnodes, the scanner seamlessly integrates their services. No separate software updates are required. This renders the scanner a web of many interacting cameras, and the structural system model enables them to behave like a single large device.

3.3 Software Behavior

Using the above structure, the scanner's behaviour is determined by a sequence of message exchanges via MQTT. The UML sequence diagram in Figure 5 illustrates this, which shows the interaction between a centralnode and all camnodes when capturing images. Initially, all camnodes subscribe to the topic

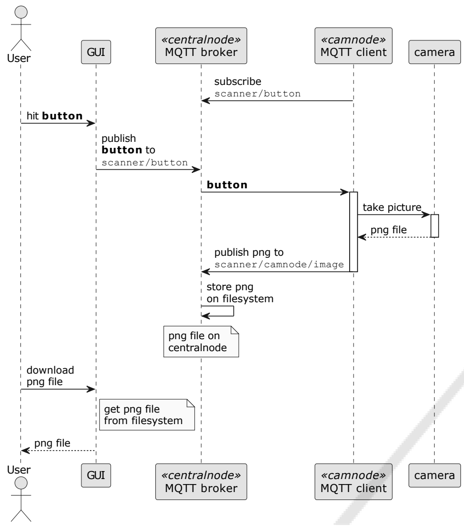

Figure 5: UML sequence diagram for taking pictures.

`scanner/button` on the central node's MQTT broker. In the web browser, the user hits the button on the web-based UI to take images from all camnodes. This command is published to the topic `scanner/button`. Because all camnodes are subscribed to this topic, they receive the button command synchronously. Each camnode then takes an image and publishes it to the broker under the topic `scanner/camnode/image`, where the camnode subtopic is enumerated to distinguish the images from each other. The broker receives all images and stores them as files in its file system. Finally, the user accesses all images via a web browser for download.

3.4 Operation

We briefly portray some relevant operational aspects to complement the design description.

3.4.1 Jitter

An important characteristic of a functional 3D scanner is the jitter in the image creation time. The larger the jitter, the longer the subject must stand still to avoid blurring of the reconstructed 3D image. All Raspberry Pi computers have synchronised system clocks. This allows us to compare the image creation times of all camnodes. We measured the jitter, that is, the range across all creation times, in several runs and found it always below 100ms.

3.4.2 Remote Maintenance and Update

Although the loosely coupled approach of the scanner design makes it resilient and extendable, assistance for maintenance or failure analysis by an external software expert may be required. In Figure 2, a software developer can access the scanner's Raspberry Pi computers remotely from the Internet via VPN and support these activities.

An important part of these activities is updating the software on the Raspberry Pi computers. The code was versioned in the Github repository, as shown in Figure 2. When a code update is requested, the Raspberry Pi reboots and updates its software from the repository when booting. This allows all Raspberry Pi computers to be updated simultaneously. Finally, after the update, the camnode device must reconnect to the central node MQTT broker to re-establish the logical structure.

The code repository serves as a single source of truth. This allows the system to automatically check that all Raspberry Pi computers work with the same and the most recent software version. This prohibits intermittent behaviour in such a distributed system design caused by deviating software versions.

3.4.3 Single Point of Failure

Both centralnode and camnode are Raspberry Pi computers. The nodes' roles are not mutually exclusive, i.e., a Raspberry Pi may work in both roles, centralnode and camnode, at the same time. However, if there is only one Raspberry Pi with a centralnode role, it represents a single point of failure. When this device fails, the MQTT broker disappears and the scanner's logical structure dissolves. However, an MQTT broker can work in the failover mode, that is, if one broker fails, another redundant one on another Raspberry Pi takes over. This mitigates the problem of a single point of failure and does not require additional hardware or software.

3.4.4 Security Considerations

The Raspberry Pi computers are part of the uplink network and are therefore accessible to all devices in this network, as well as from the Internet. Therefore, we applied the following measures to secure them without limiting the functionality of the scanner to the user.

It is recommended and already often seen implemented practice to shield the uplink network from the

Internet using a firewall and restrict remote access using VPN. Even in home networks, firewalls are installed on the router provided by the user's ISP. Moreover, all password-based logins to the Raspberry Pi computers are disabled, and only cryptographic key-based logins are allowed. This secures the scanner from unintended and malicious access from the uplink network and the Internet. However, physical access to these devices may undermine these security measures.

4 3D IMAGE RECONSTRUCTION

Once the images were captured and downloaded from 3D scanner's centralnode, post-processing starts to reconstruct the 3D image.

4.1 Image Preprocessing

The preprocessing involves adjusting the images' brightness, contrast, and colour temperature. This is crucial to ensure that the images are neither too bright nor too dark, have sufficient contrast to distinguish between different objects and have a correct colour temperature that accurately represents the colours in the scene.

The second step involves adjusting the exposure of the images. This is important to ensure that all parts of the image are correctly exposed and that no areas are overexposed or underexposed.

The final step in the preprocessing pipeline is white balancing. This is necessary to ensure that the colours in the images are represented accurately. White balancing corrects the colours by removing any colour casts caused by the lighting conditions under which the images were taken.

For our experiments and to test our hardware and software architecture, we used in this attempt the free software Darktable, see figure 6 to apply these adjustments to multiple images. The preprocessing of images is a critical step in the photogrammetry workflow. By adjusting the brightness, contrast, colour temperature, and exposure and performing white balancing, we can significantly improve the quality of the input images and, consequently, the accuracy of the photogrammetric analysis. Darktable provides a comprehensive and user-friendly interface for performing these preprocessing steps.

4.2 Photogrammetry

This section outlines the post-processing steps and practical application of RealityCapture (Capturing Reality, 2023) in photogrammetry. The process involves the collection of 48 images, alignment of these images using AprilTag markers, model calculation, texture application and mesh colourisation. For this procedure, MATHLAB can also be considered, there are different solutions for stitching the images (MathWorks, ided). For this specific project, a total of 48 images were collected. The quality of these images significantly impacts the accuracy of the final 3D model, so it is essential to ensure that the images are high-resolution and cover the object of interest from multiple angles.

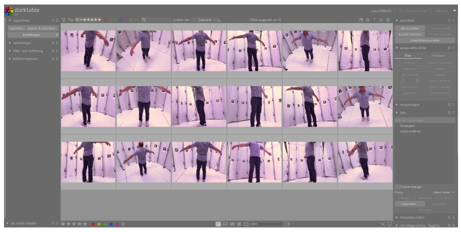

Figure 6: Preprocessing in Darktable.

The next step is to align the images. This is done using AprilTag markers, a type of fiducial marker system. These markers are placed in the scene before image collection, providing a common reference point across multiple images. For this work, 16 AprilTag markers were used to align the 48 images accurately.

After the images have been aligned, the next step is calculating the 3D model. This involves calibrating the cameras and markers in 3D space. The calculation uses the aligned images and the known positions of the AprilTag markers to calculate the 3D positions of the cameras and to generate a 3D model of the scene.

The final step in the process is applying texture to the 3D model and colourising the mesh. We use the colour information from the original images to generate a realistic texture for the 3D model and to colourise the mesh. This results in a final 3D model that accurately represents the colours and textures of the original scene.

5 EVALUATION

For the investigation of the generated 3D scans and their suitability for textile development, the scans of 3 different test persons were first visually examined since artefacts and rough inaccuracies were already visible at first glance.

As seen in Figure 7, especially in the area of the legs, the inaccuracies are the largest, so the calves are barely captured, and there are also erroneous connections between the legs.

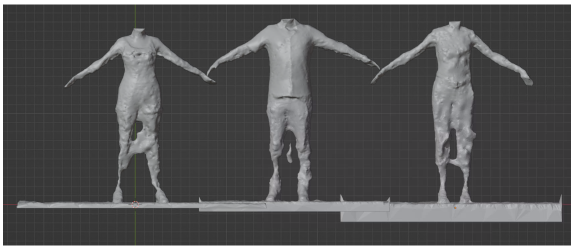

Figure 7: 3D Scans Evaluation.

The inaccuracies on the torso, on the other hand, are moderate. Still, when the scan is observed visually alone, it can already be seen that the accuracy and the mesh do not meet the previously defined requirements for 3D scans to be used for textile applications. Therefore, the generated 3D scans are not yet sufficient for measuring the body dimensions for comparison with the actual dimensions of the test persons.

6 RESULTS

In this section, we delve into an analytical discourse concerning the outcomes derived from the photogrammetric processes of our 3D scanner. Given that these constitute our inaugural 3D scans, the results are beneficial and exhibit a promising trajectory for future endeavours. For data security and privacy protection, we truncated the head from the data set.

However, it is noteworthy to mention that, as pointed out in the evaluation, minor complications were encountered in the representation of the legs. Potential resolutions for these issues could include incorporating additional AprilTag markers, which would provide more reference points for the alignment of images. Alternatively, an enhancement in the camera resolution could also contribute to rectifying these issues by capturing more detailed and higher-quality images.

Looking at the mesh of the scans, we see a very high amount of data. As shown in Figure 8, the mesh of test person 1 consists of 48.3K vertices, and the distance between them is about 0.5 cm.

7 CONCLUSION

In conclusion, this paper presents the design, operation, and validation of a low-cost 3D scanner system that utilises Raspberry Pi computers and MQTT protocol for image capture and processing. The scanner's software behaviour is determined by a sequence of message exchanges via MQTT, and the system is

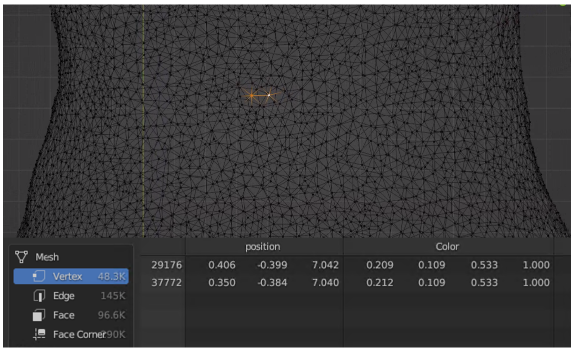

Figure 8: 3D Scan Mesh Vertex distance.

designed to be resilient and extendable, with provisions for remote maintenance and updates. The system's operation is characterised by low jitter in image creation time, and the potential for a single point of failure is mitigated by the failover mode of the MQTT broker. The paper also discusses the post-processing steps involved in 3D image reconstruction, including image preprocessing and photogrammetry.

The paper provides a consideration of the scanner's accuracy and precision and discusses the results derived from the photogrammetric processes. While the results are promising, minor complications were encountered in the representation of the legs, which could potentially be resolved by incorporating additional AprilTag markers or enhancing the camera resolution.

The previously defined requirements for the scanner used in the textile industry, such as speed and compatibility, were already met in the first attempt. The criteria that the scanner should capture body dimensions and shapes were also met, but not accurately enough for the intended use. The artefacts and inaccuracies already detected visually are too significant for the scans to be used for the generation of measurement tables or for the processing of patterns, but by optimising the image quality to improve the scan quality, the next step is to recheck the accuracy of the scans for measurement and dimension accuracy.

In future work, the system will be further optimised and expanded to improve its performance and versatility. The scanner represents a valuable tool for 3D image capture and reconstruction, with potential applications in a wide range of fields.

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