Inspection and evaluation of 3D model reconstruction from 3D scans in virtual reality

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Abstract

3D model reconstruction from scans is a standard problem of computer graphics with a wide range of solutions. When performing a complete 3D reconstruction, it is important to evaluate the quality of the resulting model. In the case of the available ground truth model, the evaluation process is quite straightforward. We can quantitatively compare the geometry of the reconstructed model and ground truth model, their topology or structure. Without the ground truth model, the situation is much more complicated. Several solutions based on various approaches have been recently proposed. The research suggests that many investigated methods can be used to evaluate the quality of 3D models, however, with different levels of relevancy. In the presented work, we addressed this problem by proposing a new evaluation method based on virtual reality (VR) involving multiple users. This technology brings generally accepted benefits of immersive interaction and enhanced model presentation. Using VR reduces the time needed for verification, validation and evaluation of the reconstructed model. Taking advantage of VR, this approach opens the way for qualitative evaluation applicable in a wide range of domains, especially if the ground truth model is not available.

Keywords: 3D model, Model reconstruction, Evaluation, Virtual reality, Scan

1 Introduction

3D laser scanning is a standard means to capture spatial data, that are subsequently used to create a unified spatial 3D model of object targets [28]. 3D models are important in many computer graphics fields using augmented and virtual reality [20].

In general, the model reconstruction process can be divided into two phases. In order to have the complete 3D model of the target object, the scans captured from different locations must be registered into a unified coordinate system. It is because the coordinates of the points in scans are relative to their own coordinate system. This problem can be phrased in terms of finding a coordinate system transformation. Figure 1 demonstrates two misaligned scans obtained from different positions.

How to register point clouds accurately and quickly is generating considerable interest of researchers at present [11]. The most used method is the Iterative Closest Points (ICP) algorithm provided by Besl [6]. More details on this will be given in the next section. This phase includes also other support operations like noise filtering, geometric correction, outliers removal etc [20].

Figure 1: Two misaligned scans.

Generally speaking, a 3D laser scanner provides data as a point cloud, which is not suitable to represent the object in the 3D scene. After successful registration, it is necessary to build polygon mesh representing the surface of the scanned object. Various approaches have been proposed to solve this issue, the most used method is the Poisson surface reconstruction proposed by Kazhdan et al. [13]. However, a detailed analysis of existing solutions is not the aim of this paper. In recent years there has been growing interest in 3D model reconstruction also for non-expert users [32]. Development in laser scanners in past decades made possible to scan with more accuracy. Consequently, resulting models are more accurate and more detailed [34].

When performing a complete 3D reconstruction, it is important to evaluate the quality of the resulting model. Evaluation approaches can be divided into two kinds:

- Quantitative evaluation
- Qualitative evaluation

First, the quantitative evaluation is based on comparing numerical parameters of models, such as geometric accuracy, topological accuracy or structure [4]. Quantitative evaluation is particularly useful when a ground truth model is available. Second, the qualitative evaluation process is not so straightforward. Numerous approaches have been suggested to this topic. Qualitative evaluation can be considered in each case, especially if the ground truth model is not available. This aspect will be dealt with in more detail in Section 2. The research suggests that many investigated methods can be used to evaluate the quality of 3D models, however, with different levels of relevancy.

Intricate domains of evaluation can benefit from the use of virtual reality (VR). This technology can help to decrease the time needed for verification, validation and evaluation of reconstructed model [1]. Also brings generally accepted benefits of immersive interaction and enhanced model presentation. The immersive environment allows the user of VR to interact with the 3D model as in real life. It helps to overcome common problems such as misinterpretation or errors in the results [9]. This convenience is especially noticeable with the modern scanners, that generate point clouds consisting of millions or even billions of points [25].

The rest of this paper is organized as follows. The second section gives a brief overview of standardized methods for scans registration and surface reconstruction, explains characteristics of input data, that affect the quality of the resulting model and presents user incorporation. In the third section, we provide a review of evaluation approaches divided into two subsections describing quantitative and qualitative evaluation. Virtual reality in the context of 3D model evaluation is explained in the fourth section. We propose a new evaluation method in the next section. Section 6 mentions the main finding. Our conclusions are drawn in the final section with outlined plans for future work.

2 Background

As stated in Introduction, the 3D model reconstruction consists of several steps. When scans are obtained, they must be registered into a unified coordinate system. After successful registration, the following stage is surface reconstruction. For reasons of space, only the single most widely used method for each stage is considered in this section. The quality of the resulting model is strongly affected also by the quality of the input data. In order to improve the resulting quality, users can be incorporated in the process of model reconstruction.

2.1 Scans registration

As was mentioned, the most used method for point cloud registration is Iterative Closest Points (ICP) [6]. To be brief, the transformation of two point sets is calculated thought distance between corresponding points of these points sets until it reaches the required precision. However, the standard ICP algorithm suffers from a number of problems [11]. The main pitfall is the selection of initial value, which affects the final registration results. If the selection is not correct, the ICP algorithm may tend to converge to the nearest local minimum of distance metric. To address the limitations of the algorithm, much work on the improved algorithms has been carried out [11]. An alternative method to this state-of-the-art algorithm, though less used, is Normal Distributions Transform (NDT) proposed by Biber et al. [7].

2.2 Surface reconstruction

After successful registration, it is necessary to build polygon mesh representing the surface of the object. We consider the Poisson surface reconstruction [13], as one of the most used methods. Input data for this method is a set of samples, each sample contains point and an inward-facing normal. The output is a watertight, triangulated approximation of the surface. The most important part is computing the indicator function from input samples. The first step is a derivation of the relationships between the gradient of defined indicator function and the integral of the surface normals. In the next step, already stated integral is approximated by a summing over oriented point samples. The indicator function is finally reconstructed from the gradient field as the Poisson problem [13]. Application of the original method can result in an over-smoothed surface, which is one of the major pitfalls. Several approaches have been proposed in order to solve this problem [14]. As was noted, various methods have been proposed beyond Poisson surface reconstruction. The most widely used approaches are the Ball-Pivoting Algorithm (BPA) [5] and Marching cubes [19].

2.3 Incorporating the user

Incorporating the user can be very beneficial, especially if we are dealing with challenging data (discussed later in 2.4) [4]. User incorporation can be integrated at any stage of 3D model reconstruction or evaluation. To begin with obtaining input point cloud, in the method proposed by Yan et al. [35], the user is interacting with the scanned object during scanning to achieve quality output. The method interactively updates actual reconstruction and modifies the scene. Accordingly, the user can expose the problematic parts of a given point cloud and optimize them.

During the phase of surface reconstruction, user's high-level knowledge can improve the quality of the resulting model. The approach suggested in [29] correct actual data through the detection of the topologically poor regions. Detected regions are displayed to the user to be resolved. The user combines constraints for interior or exterior on a 2D tablet. The reconstructed model is iteratively updated through other user interactions.

Beyond obtaining of the point cloud and surface reconstruction, it is also desirable to incorporate user in the quality evaluation stage. In several methods, the fundamental evaluation procedure is visual quality assessment estimated by the user [18]. A balance between useful feedback from users and the level of interaction is one of the most important characteristics in user incorporation.

2.4 The quality of input data

Besides algorithm for scans registration or surface reconstruction method, the quality of resulting 3D model reconstructed from scans is strongly affected by the quality of input data. These four characteristics are recognized as being the most commonly discussed [4]:

Sampling density In broad terms, sampling density is defined as the distribution of the points in point cloud sampling the surface. In most instances, sampling density is not spatially uniform.

Noise The term noise is generally understood to mean randomly situated points near the surface of the model. Noise can be produced due to sensor noise, model distance, orientation or surface properties.

Outliers Points that are distributed in the volume far from the real surface are defined as outliers. The density of outliers is lower than the density of points from the real surface. In point cloud processing, there are many methods aimed at their safe removal.

Missing data Missing data are one of the most important limitations for many reconstruction algorithms. Short sensor range, light absorption or geometric features of shape are the most common reasons for the emergence of areas without data.

Considerable attention must be paid because each separate method will produce point clouds containing a variety of characteristics and also imperfections. The abovementioned characteristics have a significant impact on the outcome.

3 Evaluation

As was mentioned in the Introduction, in many fields it is important to evaluate the quality of the 3D model. Methods of evaluation can be divided into two groups:

- Quantitative evaluation
- Qualitative evaluation

Research has tended to focus on the reconstruction process and results rather than evaluation approaches. Therefore, an overview of evaluation methods is explained in this section.

3.1 Quantitative evaluation

The main objective of the quantitative evaluation is to compare numerical characteristics of the reconstructed model to the ground truth model from which the scans were obtained [3]. There are three most used methods, namely geometric accuracy, topological accuracy and structure [4].

Geometric accuracy This is a common method based on direct geometry comparison of the reconstructed model to the ground truth model. The most used error metrics are Hausdorff distance [2], mean distance along with the errors in normals. However, it can be challenging to acquire data of the ground truth model from a physical shape. Direct comparison is inadequate when the reconstruction result consists of several levels of details or is reconstructed under an error tolerance [4].

Topological accuracy Another relevant method that uses higher-level information such as the shape of the model or its topology. Existing approaches are mainly focused on recovering a skeleton of the shape [34]. Considerable attention must be paid when our goal is to compare different extraction methods because recovering a skeleton can be formed in various ways.

Structure A piece of important information can be obtained from the recovery of the model structure. This method is especially relevant when we deal with large scenes consisting of collection of objects. For these contained objects we can review characteristics such as their dimensions, interrelationships and regularities [4].

Except for afore-mentioned characteristic, it is important to evaluate the reproducibility of the reconstruction method. We can state the Poisson surface reconstruction method, which is widely used because code is reliable and stable. Complexity and algorithm robustness can adversely affect the applicability of the method.

There are still considerable characteristics with regard to reconstruction algorithm, for instance computational complexity, time complexity and memory complexity [14]. Considerable attention must be paid when the appropriate method is selected in terms of priors for the reconstruction output domain. For example, reconstructing tiny details like bricks on a building facade is unnecessary, but for small objects, it requires high-quality details.

3.2 Qualitative evaluation

Without the ground truth model, the situation is much more complicated. In this scenario, qualitative evaluation is the most suitable option. There exist several solutions based on different methods and the evaluation process does not rely solely on numerical characteristics. The research suggests that many investigated methods can be used to evaluate the quality of 3D models reconstructed from scans, however, with different levels of relevancy.

Exhaustive analysis of 50 research papers has been conducted on the evaluation of the 3D model reconstruction without the ground truth model. As a result, we compiled statistics of five most frequently used approaches. The number of occurrences of the five most used methods in 50 research papers can be seen in Figure 2.

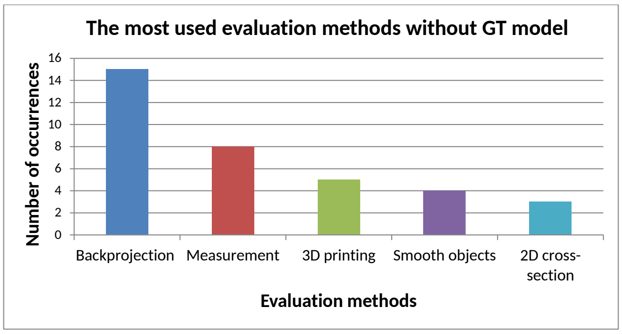

Figure 2: Statistics of the most used evaluation methods without GT model.

Perhaps, the simplest means of evaluating the quality of the reconstructed 3D model is a visual review by the user [34]. One of the most common methods in photogrammetry is the back-projection of the reconstructed model back into the photographs [17, 30, 24]. As a result, the reconstructed projection is compared with the isolated object from the initial photograph. Error metrics measure the number of pixels mapped incorrectly [21]. Beyond classic photographs, CT images [22] or aerial imagery can be used [23].

Another regularly used approach is combining and comparison of different reconstruction methods. Each method differs in accuracy, density or ability to deal with specific input data. In most instances were compared Structure from motion (SfM) [16] and laser scanning [26], terrestrial scanning [27] or medical images [31]. Other methods used a comparison of the two-dimensional model of the surface (2D cross-section) [33] or evaluation of the smooth object [36] that are suitable for automated processing. The last pair of the most used methods for evaluation without ground truth model are 3D printing [10] and manual measurement of distances between key points on real object [16] and comparing them with corresponding distances on reconstructed model. It can be seen in Figure 3 below. A number of other evaluation methods can be considered, but for lack of space, they are not addressed in this paper.

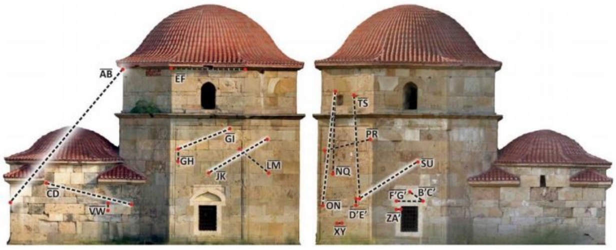

Figure 3: The pairs of defined feature points used for data accuracy verification [16].

4 Virtual reality

The growing popularity of VR results from the immense progress in computer hardware and software [12]. Over the last decades, 3D visualization has received much attention mainly due to excellent display capability [15] that leads to improving understanding of visual content.

This technology is generating considerable interest in many fields. Some of them include architecture, games and archeology [8]. Despite the growing popularity of VR visualization, traditional 2D displays continue to enjoy active use. 3D visualization possesses the attribute of realism more than does 2D and improves an understanding of visual content. Animations and simulations are in the VR environment more intuitive, besides static 3D models [1]. VR with suitable equipment provides a sense of immersion and dynamic interaction with the virtual environment that leads to improving the process of 3D model reconstruction evaluation. VR decreases the time needed for verification, validation and evaluation of the result. Also with generally accepted benefits of immersive interaction and enhanced model presentation. Exploiting advanced visualization features, users can quickly spot weaknesses in reconstructed 3D models [1]. It is worthwhile noting, that visualization in VR can improve the presentation of the model to stakeholders and outside persons. Taken together, these advantages highlight a role for VR in 3D model quality evaluation.

VR clearly has some disadvantages. One of the major drawbacks of VR tools is more complicated and longer development [1]. However, this is not particularly surprising if we consider the diversity of platforms, technologies and corresponding equipment. Considerable care must be taken to hardware requirements because they are fundamental to achieve the superior VR experience [8]. The benefits of VR far outweigh the disadvantages with regard to longer development and higher costs.

5 Implementation

In order to develop a usable and flawless system, the work consisted of several steps. In the initial stage of the process it was important to define functional and non-functional requirements of the developed software. A list of use cases was not strictly defined at the beginning and was iteratively updated during development. After requirement specification, we needed to choose a platform for software implementation. Graphical engines were recognized as being the best option for our needs. The main advantage of using the graphical engines is their robustness, wide usability and VR equipment support. A list of the most popular graphics engines contains two rivals: Unity[1] and Unreal Engine[2]. After a brief research, the Unreal Engine (UE4) was chosen because it is more suitable to point cloud handling. When these steps have been completed, we were ready to implement our solution.

5.1 Existing software tools

In the field of the 3D model viewer in VR, several software tools can be found. To the best of our knowledge, in order to evaluate the quality of the reconstructed model, these solutions are the most suitable: *Sketchfab VIRTUAL REALITY*[3], *InsiteVR*[4] and *VR Robotics Simulator*[5].

One of the major drawbacks of using listed systems is missing the ability to work with multiple models at the same time and compare them with each other. There is also lacking the option to customize offered functionalities while working with the reconstructed or ground truth model.

5.2 Implementation details

Existing solutions have been identified as being an important part of the research. Various software tools have been analyzed and we decide to use the existing solution created by Lukáš Gajdošech[6]. This solution was implemented last year in UE4 and the main target is inspection and editing of 3D point clouds in VR. The tool enables the user to inspect, modify, edit, transform and export point clouds. It also supports additional data visualization and two rendering modes. Existing functionality for point clouds was adopted and customized for our needs, especially for 3D model and point cloud synchronization. Therefore, users can evaluate the quality of the 3D model as a final result of reconstruction and also the quality of point cloud as a result of scans registration. Functions for the 3D model were created from scratch because they were not obtained in the original solution.

[1] https://unity.com/
[2] https://www.unrealengine.com/
[3] https://sketchfab.com/virtual-reality
[4] https://www.insitevr.com
[5] http://vrrobotsim.com/
[6] http://www.st.fmph.uniba.sk/ gajdosech2/bachelor.php

UE4 enabled us to rapidly implement VR application and at the same time to develop a version for rendering to 2D display. An important challenge was to design and implement a suitable graphical user interface (GUI) for the VR scene. One of the biggest differences is that in VR are no viewing constraints (like for example on PC displays) and the field of view is more similar to the real world. A sense of immersion is one of the most remarkable advantages of VR and GUI must be designed to support it. In [15] the author provides several UI location types for VR applications. Considering implemented UI using panel attached to the hand of the user and statically positioned in the scene we decided to follow these principles. Existing UI was tailored and enriched for use with 3D models.

All functionality is available through these UI panels. Three new panels were added to existing ones. On the Model selection panel, the user can view all available models and choose one or more of them, show information about model or reconstruction details. On the Edit model panel, the user can transform the selected model (or more models at once), apply the texture of Hausdorff distance [2] color scheme as well as toggle between 3D model and the corresponding point cloud, as shown in Figure 4 bottom. Compare model panel contains functionality to align models to the center of the world coordinate system or align reconstructed models to the ground truth model. Users can also replicate a selected view on model to other available models. Every element of these panels can be used both in VR and in 2D mode through controller or keyboard and mouse, respectively.

The dataset used for tool testing contains 3D models reconstructed from real objects. Scans were captured with the help of experienced users by professional PhoXi 3D Scanner[7]. By having corresponding ground truth models for bear and spike (as shown in Figure 5), we are able to evaluate geometric precision (Section 3.1).

6 Results

We addressed the problem how to evaluate the quality of the reconstructed 3D model by proposing a new method involving multiple users and we have implemented software to apply it. The system was developed in order to benefit from the use of VR. The development of our software tool is still ongoing, therefore we opted for small sample size for evaluation. Having a set of real scans, we were able to create two triplets of 3D models, each model in triplet was reconstructed by a different approach, but from the same scans. Ground truth models were available for each triplet. A quantitative evaluation was performed using Hausdorff distance. Afterward, a group of 3 users performed qualitative evaluation exploiting our tool. The scale for evaluation the quality of the reconstructed model is ascending with 1 meaning very bad and 10 meaning very good. Users from selected group have average

[7] https://www.photoneo.com/phoxi-3d-scanner/

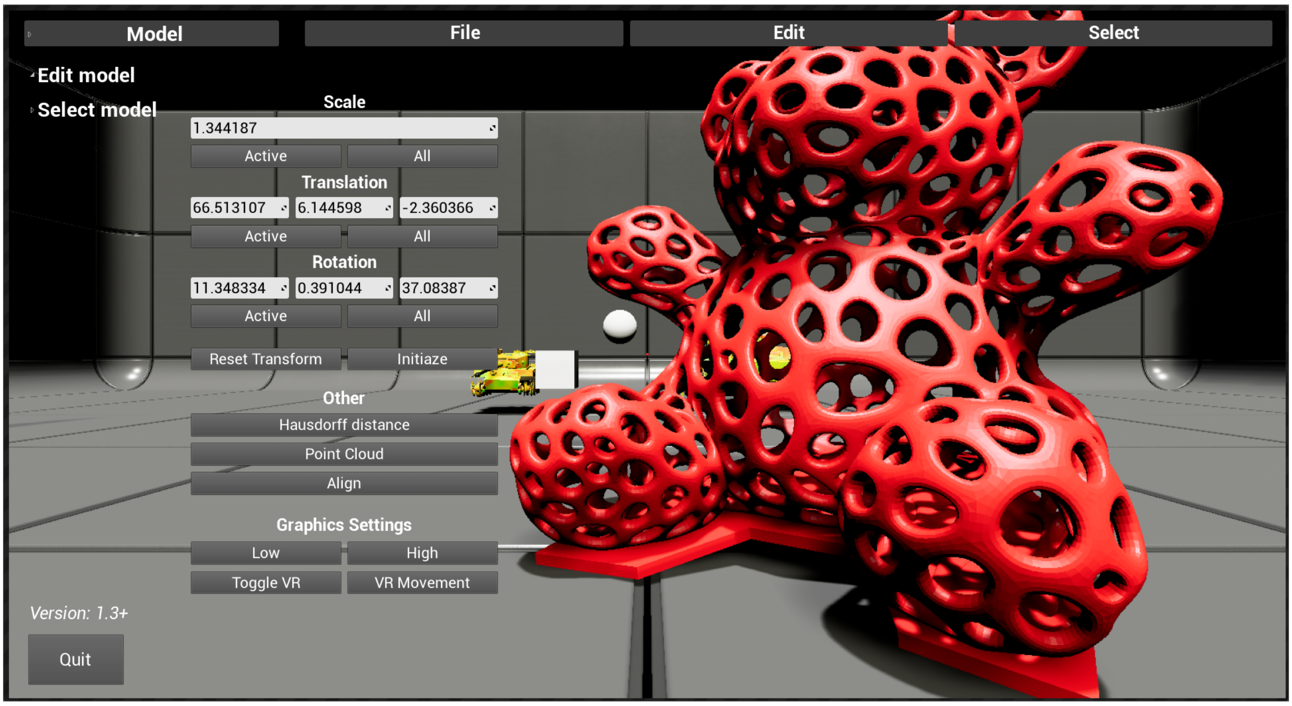

Figure 4: The edit model panel shows allowed operations for the selected model.

knowledge of model reconstruction pipeline and methodology for model evaluation. Table 1 summarizes the data of both types of evaluation.

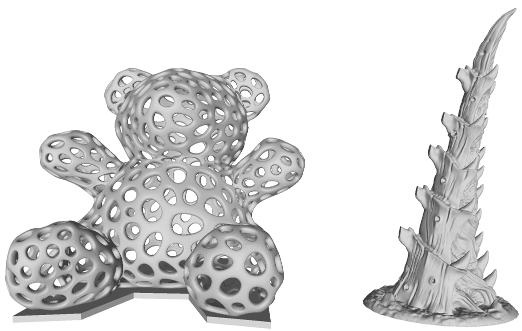

Figure 5: Models used as input for testing: bear (left) and spike (right).

The following methods for scans registration were used: Go-ICP[8] for the first model in triplet, Sparse ICP[9] for the second model and Symao ICP[10] for the last model. Surface reconstruction was carried out using Poisson surface reconstruction for each model. First, the model of a bear has a smooth surface without small details. Reconstructed models have very similar values of Hausdorff distance and also slightly different score from user evaluation. Second, the model of a spike is full of small features, that is one of the key factors for user evaluation. We can see, that Hausdorff distance does not fully correspond with user evaluation. Even though Hausdorff distance is highest for Spike5 in this triplet, from user study is the result opposite. The reason for this can be convergence to the nearest local minimum in scans registration using the ICP algorithm. Our findings would seem to suggest that the results from quantitative and qualitative evaluations do not have to correspond in certain cases.

Model	Hausdorff distance	Users evaluation score
Bear1	0.016480	8.2
Bear2	0.017194	8.0
Bear3	0.017189	7.7
Spike4	0.003947	7.5
Spike5	0.010048	8.0
Spike6	0.007872	7.2

Table 1: Results of the evaluation of the quality of reconstructed models.

Our findings are based on a limited number of samples, the results from such analysis should, therefore, be treated with considerable caution. Despite this limitation, the results are promising and will be validated by larger sample size. More details on future work will be given in the next section.

[8]https://github.com/yangjiaolong/Go-ICP
[9]https://github.com/OpenGP/sparseicp
[10]https://github.com/symao/libicp

7 Conclusions

To sum up, in the paper we described problems regarding the quality evaluation of the 3D model reconstructed from scans. Our study provides considerable insight into existing evaluation method, their strengths and their limitations. We addressed this problem by proposing a new evaluation method involving multiple users. Created system is based on the most advanced technologies with an easy-to-learn graphical user interface.

The result of this study supports the idea that VR is a versatile technology with a wide range of applications. The sense of immersion and dynamic interaction with the virtual environment leads to improving the process of 3D model evaluation. Our work clearly has some limitations, mainly because of work in progress state. Notwithstanding this fact, we believe that we have developed an innovative solution for 3D model quality evaluation in any case, whether the ground truth model is available or not.

Future work will focus on the implementation of missing functionality and finalizing the application, completing the dataset for user study and testing developed solution by a larger group of computer graphics experts. As soon as testing is ready, the final adjustments can be made. In the experimental study, we plan to investigate the correlation between results from qualitative and quantitative evaluation. To the best of our knowledge, no other authors have proposed a comparative analysis between quantitative and qualitative evaluation of the quality of the reconstructed 3D model in this way. The main idea of finding and testing this correlation is as follows. With a set consisting of several reconstructed models and ground truth model, we will measure geometric precision (compute Hausdorff distance between reconstructed models and ground truth model) and sort the results. Following this, qualitative evaluation by a set of knowledgeable users will follow for the same input data and the results will be sorted. Deviations between these sets will be analyzed. We hope that further tests will confirm our findings.

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