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3D laser scanning applied in conjunction with BIM: a fast and automated approach to inverse modeling

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Abstract: Nowadays, 3D laser scanning technology is increasingly applied to the construction industry as a means of collecting real-life building information, which is highly accurate, fast, and visualized, and can improve the efficiency and quality of construction projects, saving time and cost. The integration of 3D laser scanning and BIM technology generally requires reverse modeling of the point cloud. There are many ways to reverse model a 3D model from a point cloud model, but how to reverse model more efficiently is still the current research direction. In this paper, we propose a method for reverse modeling of point cloud by combining 3D laser scanning technology and Dynamo visual programming platform, which can perform rapid and automatic reverse modeling of shaped components and add family libraries, which can be retrieved at any time in the subsequent projects and make secondary edits to the constructed model.

1. Introduction

The construction industry is highly complex and multidisciplinary. The traditional building design and construction process is characterized by problems such as information asymmetry, poor communication, and inefficient collaboration. The application of BIM (Building Information Modeling) technology can effectively solve these problems and improve the efficiency and quality of the construction industry.

The combination of 3D laser scanning and BIM technology for reverse modeling gives more structured and unstructured data to the point cloud model of the building surface obtained from 3D laser scanning to create a standardized and integrated building information model. The combination of 3D laser scanning and BIM for reverse modeling technology has significant advantages in the renovation of existing buildings, construction acceptance, and retention of building digital assets. Currently, building digitization and modeling is mainly carried out using mature commercial software for reverse modeling, which has the advantages of convenient operation and a high degree of visualization. Reverse modeling technology can be divided into two categories according to the degree of manual participation, one is purely manual reverse modeling technology: the point cloud is sliced or orthographic transformed to extract the building contour lines, and linked to the Revit software as a base map for manual modeling. 2017 Miao et al.1, scanned the existing buildings and linked the collected point cloud data to Revit software for manual modeling through orthographic transformation; in April 20202, Hui et al. proposed a method integrating multiple means of 3ds Max, CAD, and Revit for arch modeling; April 20213, Niu and Li used a 3D scanner to scan the ancient buildings, the point cloud data to tune different views and depth of section and extract feature points and feature line fitting to get the contour line, through the assembly of the ancient building model. Although the manual modeling technique can restore the model of complex structures, it usually requires a variety of software coordination and a lot of manpower and time to complete.

Also in the other is automated modeling techniques. 2018 Li et al.4, utilized the Scan to BIM plug-in to identify planes and build simple models, and then manually added to build special build models; in 2021 Xiong and Wang et al.5 proposed a PointNet-based BIM reconstruction method for semantically segmented point cloud data, using a deep learning network to semantically segment the point cloud dataset and extract the outer contour parameters for modeling, which can automatically classify the point cloud and extract the parameters for modeling using the wall and column features, but for doors and windows as well as furniture, etc., the assistance of family libraries is required; in 2021 Qin et al6. proposed a fully automated parametric BIM reconstruction method based on point clouds, using a bridge point cloud segmentation algorithm, which can separate the bridge-based point cloud from the whole scene and segment the unit structure point cloud. 2022 Rodrigues and Crovella7 proposed a method to semi-automatically reconstruct a BIM model of a pipeline network by steel skeletonizing the pipeline. For inverse modeling with obvious features and simple geometry the desired structure can be achieved.

At the same time, by investigating the rapid modeling functions of common commercial automation software or plug-ins on the market, such as Trimble RealWorks, As-built, etc., the software and plug-ins can realize the fitting

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and modeling of relatively regular components, such as wall structures, steel structures, standardized water pipes, and so on however, how to quickly model irregularly shaped components, whether manual modeling or automated modeling is still a major difficulty. This paper proposes an automated reverse modeling method for irregularly shaped components, using a 3D laser scanner to obtain the point cloud data of the target object, using Dynamo to carry out the secondary development of Revit, slicing and reconstructing the point cloud data, and realizing the point cloud automated reverse modeling of irregular shaped components.

2.Point cloud data acquisition and processing

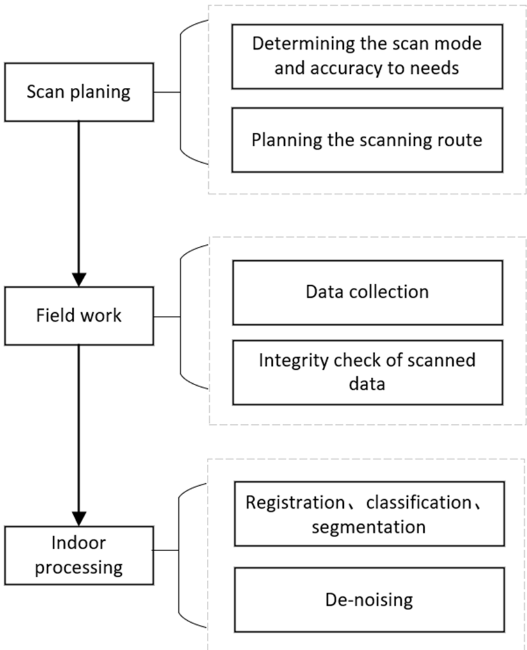

Figure 1. Schematic diagram of the 3D laser scanning process

The whole process of 3D laser scanning can be divided into three parts: scan planning, field work, and indoor processing, as shown in Fig. 1.

2.1 Scan planning

The scan planning stage refers to determining the mode and accuracy of the point cloud scanning based on the site conditions and factors such as the size and material of the detailed features of the object to be measured, carrying out site planning, and designing the scanning route. Too few sites may cause the density of the point cloud to decrease, thus affecting the accuracy of the point cloud. Too many sites may increase redundant data, and at the same time increase the consumption of manpower and material resources.

2.2 Fieldwork

In the field work stage, to obtain a complete point cloud model of the target object, it is necessary to scan the measured object from different angles, and the integrity of the scanned data of the target object can be examined in the field with the visualization point cloud processing software. 3D laser scanner through the emission of laser to obtain the object's surface information and acquire data for a series of discrete point collection - point cloud. The point cloud data can reflect the spatial, geometric, and color information of the target object. According to the principle of 3D laser scanning, the quality of the point cloud is usually affected by the following factors:

① Types of scanners: Different types of scanners use different technical principles and sensors, which make a difference in how the data is captured and the accuracy.

② Scanning environmental effects: Environmental conditions such as ambient light, background interference, and noise can interfere with scanner measurements.

③ Surface characteristics of the scanned object: The surface characteristics of the object, such as reflectivity, texture, color, etc., will have an impact on the scanning results.

During the scanning process, it is necessary to try to ensure that the scanning conditions meet the requirements to reduce errors and noise, but in the actual scanning process, there will still be unavoidable adverse effects, so it is necessary to carry out the indoor processing of the point cloud.

2.3 Indoor processing

In the indoor processing stage, the point cloud needs to be aligned, categorized, segmented, and point cloud denoising steps.

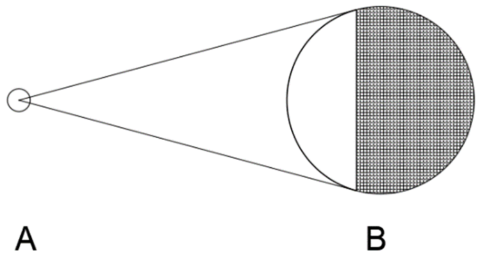

Figure 2. Schematic diagram of the scanner's single-station field of view

As shown in Fig. 2, scanner A for the target object B, a large shaded area for the invisible part of the single-station scanning to obtain information is limited, so it is necessary to carry out different angles of the scanning, to obtain the complete data of the target object. Data from different stations need to be stitched together by point cloud alignment to make a complete point cloud model. 3D laser scanning is the scanner itself as the origin to establish a coordinate system, the point cloud data of different stations need to be converted to the same coordinate system for splicing, this step is called point cloud registration. Since the target and the surrounding environment will be captured as a whole during the scanning process of the station scanner, the overall point cloud model needs to be segmented to separate the target objects for reverse modeling. The point cloud classification function accelerates this step. Basic structures such as walls, floors, and columns can be automatically identified and grouped by the software so that different objects can be modeled using different methods.

To further ensure the accuracy of the model, point cloud de-noising is required. In the 3D scanning process, the point cloud data acquired is inevitably affected by the surrounding environment, the characteristics of the scanned object, and the performance of the instrument itself, such as ambient light, object material surface texture, etc. The noise of the point cloud data is defined as the noise of the point cloud, which refers to the noise of the point cloud. Noise in the point cloud refers to the unwanted or irrelevant interference and errors in the point cloud data. The existence of noise points will greatly interfere with the accuracy of modeling, therefore, point cloud de-noising is an indispensable step for inverse modeling, and there are various ways to remove the noise points, such as large-scale noise points that can be removed artificially by cutting tools. For the details of the noise, it is difficult to remove it artificially and the workload is large, here we use the following two different ways of point cloud filtering for automated de-noising.

Statistical Outlier Removal filtering: SOR filtering is a spatial distribution-based de-noising algorithm, the basic principle of which is to carry out a statistical analysis of the K domain for each point, first calculate the average distance and standard deviation of a point to the K nearest neighboring points, and then add the average distance plus n times the standard deviation as a new threshold, and then remove the points outside the threshold as redundancy points. SOR filtering can be used to remove most of the noise, but it is still difficult to remove the noise attached to the surface of the object such as those caused by the reflection of the object itself, etc. The effect of SOR filtering is shown in Fig. 3, and to improve the display effect, the point cloud is uniformly colored in white.

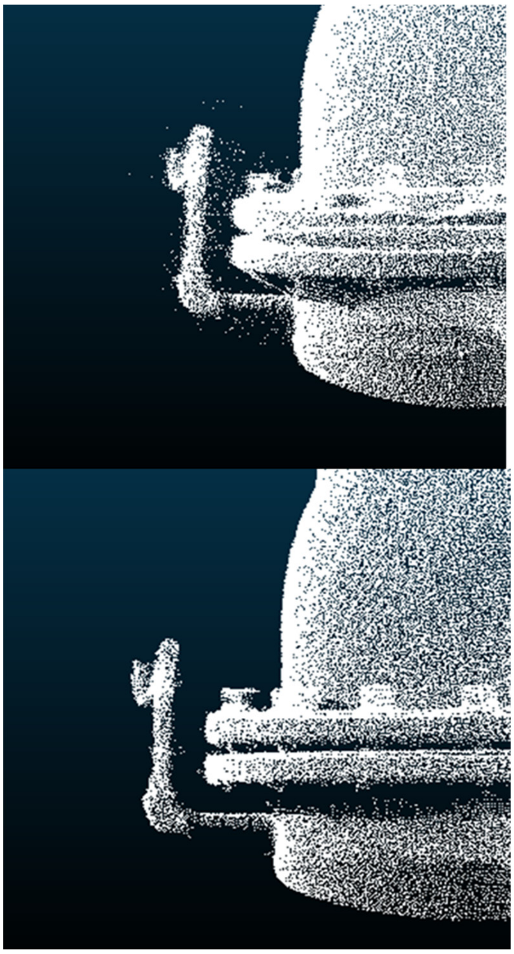

Figure 3. Schematic diagram of SOR filtering effect

Low-pass filtering: The principle of low-pass filtering is that for each data point, an appropriate threshold is set as the radius of the sphere range, and the surrounding neighboring points are extracted within the threshold, and if there are less than 3 points in the sphere, the point is considered isolated and removed. For surface noise, this method can be very effective in removing it. The effect of low-pass filtering processing is shown in Fig. 4

The processed point cloud model can be exported to ASCII cloud format, which contains the 3D coordinates and color information of the point cloud data.

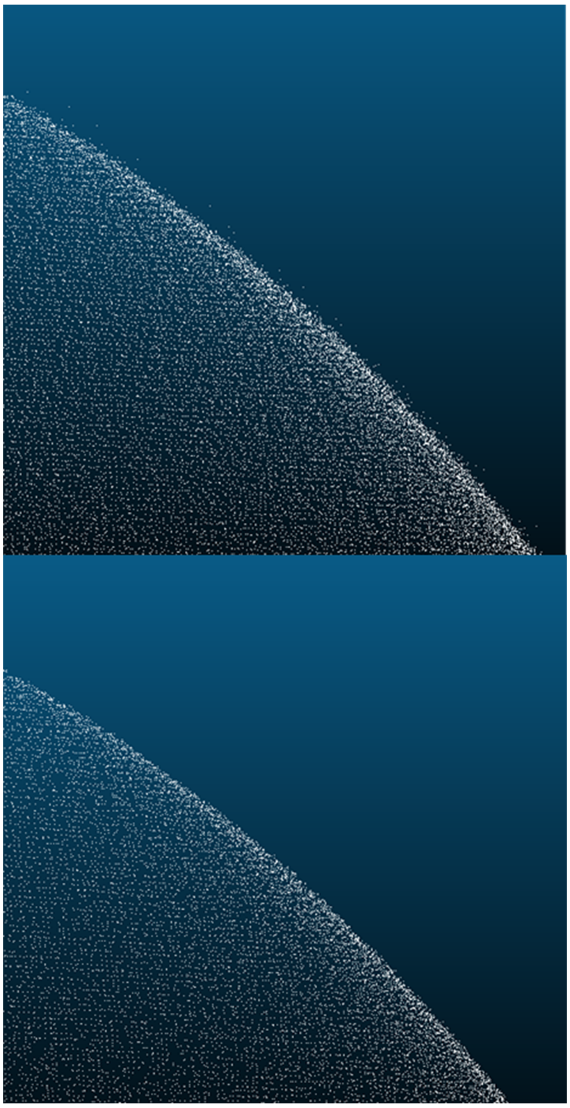

Figure 4. Low-pass filtering denoising effect diagram

3. Dynamo inverse modeling

Dynamo is a "graphical module pipeline" programming platform launched by Autodesk, which is also known as the visualization platform. Dynamo in the form of scripts to provide users with a graphical interface, the organization of the connection of pre-designed nodes to express the logic of data processing, to form an executable program to reduce the complexity of the actual operation of traditional programs, allowing developers to focus on the development of the function itself. The formation of an executable program reduces the complexity of the actual operation of traditional programs and allows developers to focus on the functional development itself. Due to the real-time linkage between Dynamo and Revit, there is no need for cumbersome format inter-conductivity, which is very useful for complex geometry, parametric modeling design, data connection, and automation of engineering processes. This also provides a theoretical basis for the Dynamo point cloud reverse modeling proposed in this paper.

The model reconstruction process can be divided into two parts: building the model and obtaining the parameters, the specific ideas are shown in the following figure:

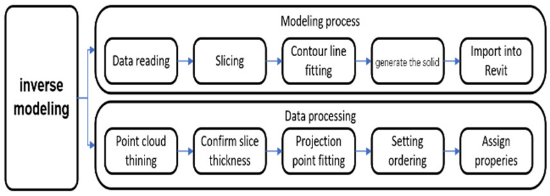

Figure 5. Model inverse modeling idea diagram

As shown in Fig.5, there are five steps to build a model: ① point cloud data reading (point cloud thinning) ② slicing the point cloud model (determining the thickness of the slice) ③ slicing the cross-section contour line fitting (projection point fitting) ④ sweeping the contour line to generate the solid (planar point set ordering) ⑤ importing into Revit to add the family example (give the class, material and other family instance attributes), all of the above steps can be realized through the Dynamo Node Library. BIM model is a data information base, i.e. data is the basic information for modeling, and the biggest feature of Dynamo is its powerful data processing capability. It is not difficult to find that in the above modeling process, corresponding to each step of modeling, it is necessary to determine the corresponding parameters before modeling operations, so the automatic acquisition of parameters is the prerequisite for realizing automated modeling. The modeling parameters are obtained and input into the Dynamo node library function as variables to call Revit API to ensure accurate reconstruction of the BIM model.

Point cloud inverse mode principle:

3.1Reading point cloud data

The technique of converting ASCII cloud format files into Excel files is mature and convenient, and will not be repeated here. After reading the point cloud data, it is necessary to carry out the point cloud thinning step. In the process of 3D laser scanning, the information of millions of points can be acquired per second, and the data of a single scanning can be 100MB-710MB, which is a huge amount of data, and the direct processing will be a great burden on the computer's computing power. However, drawing the contour of the target object does not require such a huge number of point sets, so before processing, the point cloud needs to be thinned, thinning processing can also be called down-sampling processing, the point set is uniformly sampled and stored to form a new sparse point cloud. This can effectively reduce the amount of data and improve the computational efficiency.

3.2 Point cloud slicing

Fig.6 shows the schematic diagram of slicing. In the point cloud model, if the length of one of the three dimensions is significantly larger than the remaining two dimensions, it is called the core dimension of the point cloud model. The direction of the core dimension is chosen to be the normal direction, and then the corresponding vertical plane is chosen as the slicing base plane (generally the XOY plane is chosen), and the tangent plane E is obtained by translating along the normal direction, and the family of planes $\Gamma = \{E_1, E_2, E_3, \dots, E_n\}$, which is a collection of parallel planes. The set of intersection points P obtained after intersecting the tangent plane E and the point cloud can be regarded as the point cloud slices at the plane. However, in practice, due to various factors, the points on the tangent plane may be locally vacant or sparse, resulting in missing features, and we cannot obtain the point cloud slices strictly by calculating the points on the plane. Therefore, the concept of "slice thickness" is introduced here. Specifically, the plane E is shifted along the normal direction by an equal width on each side to generate two new planes Er and El, which produce a new set of intersection points P1 and P2, and then the point cloud between these two new planes is the point cloud slice where the plane is located, and the spacing between P1 and P2 is the thickness of the slice D. Determination of the thickness of the slice is a key step in the slice-based surface fitting method, and in this paper, we adopt the density method[8] to determine the slice thickness.

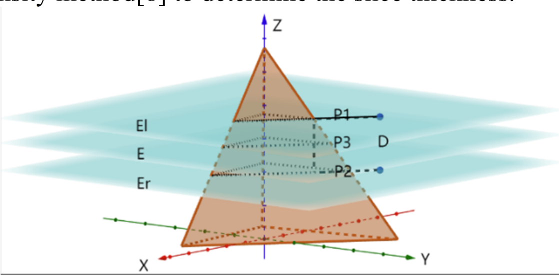

Figure 6. Schematic diagram of slicing

Fixed-width slicing is a common method for obtaining slice thickness, which is determined by calculating the point cloud density δ with an empirical coefficient k, which Eq gives:

$$D = k \times \delta. \tag{1}$$

According to the experiments, k is generally taken as 1~4, when the best results are obtained9. The point cloud density is determined by building a prediction model. In the point cloud data, m points are randomly selected, and the n points that are closest to them are taken, where the KDTree algorithm can be used to obtain the neighboring points, counting the distance between the j-th point and the i-th point among the m points that are close to the i-th point asd_{ij} The point cloud densityδ The calculation formula is as follows:

$$\delta = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}}{m \times n} \tag{2}$$

Point cloud density reflects the average minimum unit distance between points and is the basic characteristic quantity of a point cloud.

3.3 Fitting curves

To prevent the intersection of the tangent plane and the point cloud from having an empty set or being a sparse set of points, etc., the idea of least squares is used to add points to the tangent plane to fill in the gaps. Least Squares is a standard method in regression analysis, which is used to approximate the answer of an Overdetermined System (OSS). An OSS is a mathematical concept that a system of equations containing unknowns is an overdetermined system if the number of equations is greater than the number of unknowns. An OSS generally has no solution and can only be solved approximately. The method of least squares is a method to find the approximate solution of the hyper-definite system of equations. In the case of a planar point set, for example, where the goal is to obtain straight lines to fit the data, and the expectation is to find a straight line that best traverses these points, a linear regression equation can be constructed by least squares, as shown in Fig. 7.

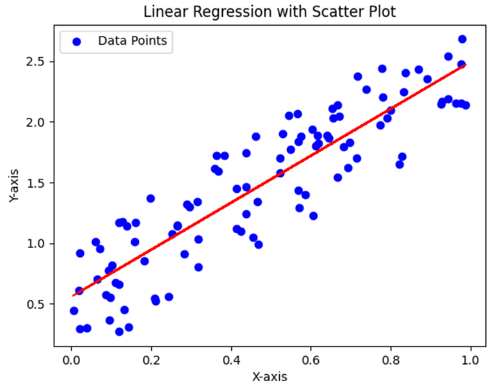

Figure 7. Schematic diagram of the least squares method of fitting a straight line

In three-dimensional space, the point set inside the largest spatial envelope box generated by the planes P1 and P2 is used to fit the projection to the tangent plane P. The specific method is as follows: the point cloud inside the envelope box is divided into the upper and lower part of the point cloud with the tangent plane P as the dividing surface, and the point cloud inside the lower box is traversed to the point cloud inside the upper box in turn, and the shortest Euclidean distance is taken as a pairing condition to be matched. Establish a linear equation between two points, and the intersection point with the tangent plane P is the projection point, as shown in the Fig. 8.

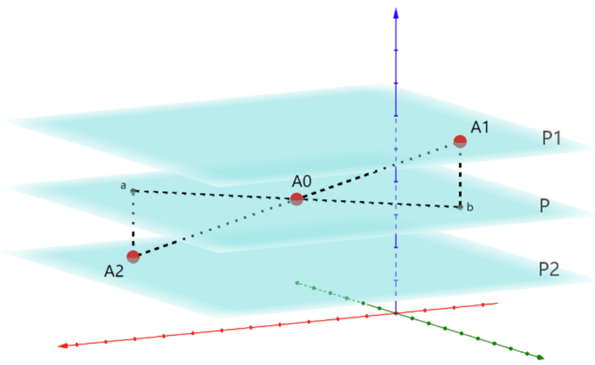

Figure 8. Schematic diagram of upper and lower point pairing projection

Projected points according to the similar triangle formulaA_0 Coordinate solution, the formula is as follows:

$$\begin{cases} x_0 = x_1 - (x_1 - x_2)\left|\frac{z_1 - z_p}{z_1 - z_2}\right| \\ y_0 = y_1 - (y_1 - y_2)\left|\frac{z_1 - z_p}{z_1 - z_2}\right| \\ z_0 = z_p \end{cases} \tag{3}$$

The x, y, and z within the formula are respectively A_0, A_1, A_2, and the three-dimensional coordinates of plane P.

3.4 Sweeping contours to create solids

After the additive point processing, the points on each section are planar scattered, and unordered. To fit the point cloud contour curve in Dynamo, it is also necessary to arrange the set of points on the cut surface in closed order. The specific method is as follows: take the X-coordinate of the point set to be a very large and very small valuex_{max}, x_{min} The linear equations are established by selecting the endpoints A, and B corresponding to the horizontal coordinates.10 The established straight line divides the point set into two regions, as shown in Fig. 9. The points are selected from left to right. $p_i(x_i, y_i)$ and projected them vertically onto line AB to obtain the projected point $p_{li}(x_i, y_{li})$. Compare the size of the vertical coordinates of the two points, if$y_i \geq y_{li}$, it is put into the point setΩ_1 and vice versa, it goes to the set of pointsΩ_2 The points will be grouped into a set of points. Once the selection is complete, place the Ω_2 reverse order withΩ_1 merge to get the closed order sorted point setΩ. The closed sequential point set is fitted to obtain the contour line of the model. The closed graph formed by this curve is the cross-section of the target object, which in turn generates the solid model.

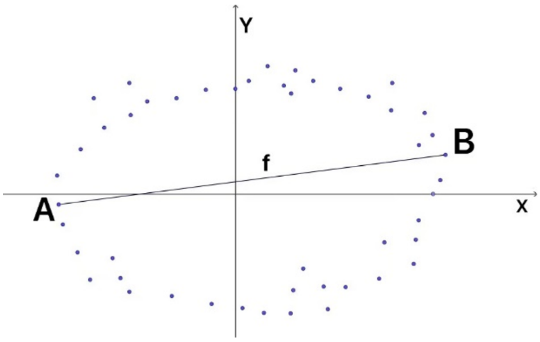

Figure 9. Schematic diagram of point set ordering

3.5 Import Revit to add examples

The solid model created by point cloud inverse modeling does not have surface material information, to truly reflect the information of the model, you can give the model material, as well as the relevant performance attributes and other information. Dynamo and Revit software has a very good compatibility between the models built in Dynamo can be directly imported into the Revit family library, which is convenient for subsequent use in the project.

4. Example applications

In this paper, the construction of eccentric tubes of different diameter point cloud models is shown as an example. This scanning uses a Trimble X7 3D laser scanner, the specific process parameters are shown in Table1:

Table 1: Trimble X7 3D Laser Scanner Process Parameters Table

scanner (device)	Trimble X7
Measuring range	0.6-80m
Scanning Angle of View	360° x 282°
scanning speed	500Hz max.
laser class	1550nm, not visible
ranging noise	<2mm@30m
Compensation coverage	±10° (mapping grade), ±45° (rough)
Goniometric accuracy	21″
operating temperature	-20℃~50℃
Storage temperature	-40℃~70℃
endurance	4 hours (per battery)

The processed point cloud model is shown in Fig. 10. The smoothness of the surface point cloud determines the smoothness of the point cloud contour after slicing.

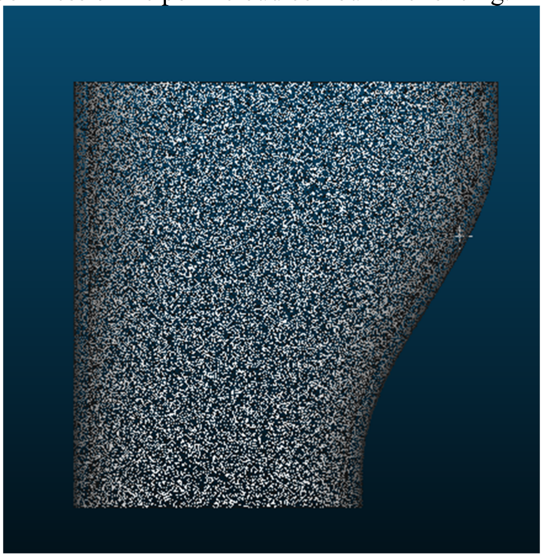

Figure 10. point cloud model of eccentric tubes of different diameter

Dynamo point cloud reverse modeling mainly constructs four main functional node chains: (1) point cloud reading, (2) point cloud slicing, (3) plane point cloud filling and ordering, and (4) entity establishment and attribute conferring. The key programs are (2) and (3), which involve bulk data processing and algorithm construction.

Point cloud slicing: this step mainly involves the calculation of slice thickness and the establishment of the envelope box. To reflect the general law, it is necessary to follow the principle of probability statistics, through the List. Shuffle command to randomly disrupt the point cloud, and then determine the number of samples m and the value of the number of neighboring points n as mentioned above. In this case, a sample selection rate of 0.01 is chosen, i.e., one point is recorded every 100 points, the number of neighboring points is defined as 10, and the point cloud threshold is calculated.

Plane point cloud filling sorting: this part of the program can be divided into four parts, ① screening the box point cloud ② matching the shortest Euclidean distance point pair ③ filling the plane point cloud ④ plane point cloud closure sorting. At this point, the profile of the member in different slices can be obtained, which is shown in Fig. 11.

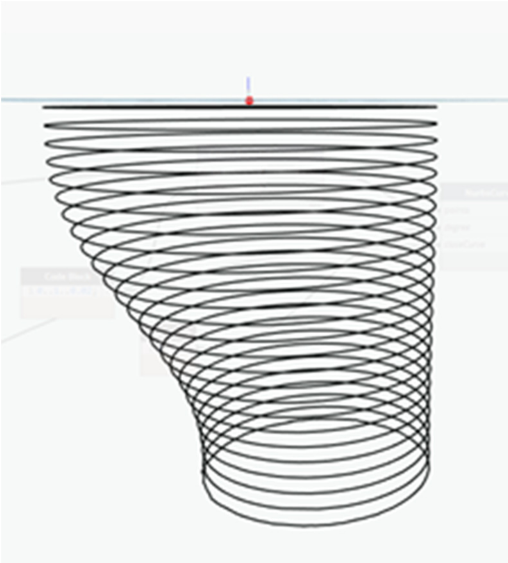

Figure 11. Slicing diagram of eccentric tubes of different diameter

Based on the contour curves fitted to the point cloud, the solids are created by placing samples between cross-sections, which have no attributes, and the Revit API needs to be called to export the geometric solids created by Dynamo to the project file and define their materials and categories. Curves are simulated at once with a lot of overlapping points, which is prone to the risk of intersection between surfaces, resulting in runtime errors. If the entity is not reconstructed successfully, it is necessary to split and fit the contour curve twice to get the canonical closed curve, and re-import the nodes for entity reconstruction, the model is shown in Fig. 12.

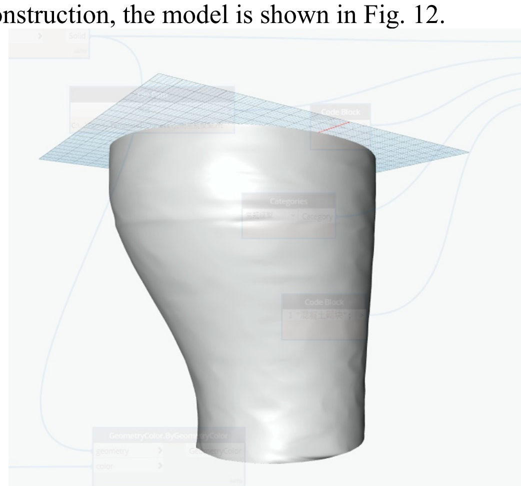

Figure 12. BIM model of eccentric tubes of different diameter

5. Summary and outlook

The combination of 3D laser scanning technology and BIM technology provides strong support for the digitization of buildings. 3D laser scanning can quickly obtain the current status of the building or structure information data, but at present there is no mature technology application for the rapid establishment of BIM model, especially for the reverse modeling of shaped components, and it still relies on manual modeling.

Combined with examples can be seen, this paper proposes the combination of 3D laser scanning and Dynamo - rapid establishment of BIM model workflow is indeed feasible, and to a large extent to improve the efficiency of the work, this method relative to the traditional workflow to add the following optimization points:

Automating the point cloud inverse modeling method reduces the part that needs to be operated manually and saves the time of the point cloud model flipping.

Provides new modeling ideas for shaped objects, - Further ensures consistency between actual and model.

The automated reverse modeling method proposed in this paper can solve the problem of difficult and time-consuming modeling of shaped objects. The secondary development of Revit using Dynamo can not only reduce the time of manual modeling but also articulate the point cloud processing software and design software. It is of great significance for the establishment of special family libraries in buildings and the protection of cultural relics. However, there are still some challenges and room for improvement in the automated reverse modeling method. Due to the limitation of computer arithmetic power, the automated reverse modeling function still needs to be optimized for the existence of deep pits, skeletons, and other special structures on the surface, and future research can explore how to accurately restore the details of these special structures through a small number of data points, to improve the accuracy and precision of modeling.

Acknowledgments

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