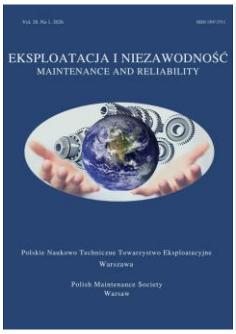


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# Visualization and Monitoring Algorithms for Multi-device Parallel Overhaul Progress at Substation Bases

Indexed by: Web of Science Group

**Yuping Yan[a], Fangfang Zhou[a,*], Zhongyue Cai[a], Hongzhi Lu[a]**

[a] Guangdong Power Grid Co., Ltd, China

## Highlights

- Lightweight BIM model conversion via triangle folding & QEM error reduction.
- Real-time 3D point cloud/depth image fusion for equipment progress tracking.
- Parallelized BIM modeling accelerates multi-equipment monitoring efficiency.
- Dynamo-based visual programming enables intuitive progress visualization.
- High-accuracy maintenance progress identification through BIM model comparison.

## Abstract

Aiming at the difficulties such as high misjudgment rate of progress and lagging monitoring of maintenance progress in the parallel maintenance process of multiple devices in substations, this study proposes a double-verification monitoring method. The QEM (Quadratic Error Measurement) algorithm is adopted to complete the lightweight transformation of the BIM model of the equipment maintenance plan within the substation base. Develop a progress monitoring algorithm and, through the collaborative collection of three-dimensional point cloud information and depth images from multiple sensors, achieve target recognition and matching. The monitoring results of the maintenance progress are visually presented by using the open-source visual graphic programming software Dynamo. The experimental results show that this method can accurately monitor the maintenance progress of different equipment in the substation and realize the visualization of parallel maintenance data of multiple devices.

**Keywords**
substation maintenance progress BIM model QEM algorithm 3D point cloud information



## 1. Introduction

With the development of the power system [1], the number of substation bases is increasing [2], and the types and number of equipment are also increasing. Under such circumstances, it is particularly important to ensure the smooth use of electricity by users. However, according to the statistics, 85%-95% of power outages are related to substation failures [3]. Therefore, the maintenance of substation base equipment has become crucial [4]. Substation is an important part of the power system [5], and its operational status is directly related to the stability and reliability of the power system. If the substation fails [6], it will not only affect the normal use of electricity by power users, but also bring great pressure and risk to the whole power system.

When the insulation of the transformer bushing breaks down or the circuit breaker fails to operate, it will cause

a regional voltage drop. A discharge fault of a certain 500kV GIS equipment once triggered a chain reaction, causing voltage fluctuations that lasted for 0.8-1.2 seconds in 8 surrounding 110kV substations, directly leading to the shutdown of the precision electronic manufacturing

(*) Corresponding author.
E-mail addresses: Y. Yan (ORCID: 0009-0009-8909-5555) yanyuping8912@126.com, F. Zhou (ORCID: 0009-0008-3955-0647) zhoufangfang668@163.com, Z. Cai (ORCID: 0009-0008-9797-1124) caizhongyue022@163.com, H. Lu (ORCID: 0009-0005-9599-1197) luhongzhi0012@163.com

production line. Meanwhile, faulty equipment will forcibly change the system topology. When the 330kV main transformer exits operation, the 400-600MVA load it carries will be transferred through adjacent lines, which will cause line overload under N-1 conditions and eventually lead to the meltdown of cable joints. Therefore, the maintenance of substation base equipment is an important measure to ensure the stable operation of the power system [7]. The traditional maintenance method is usually carried out manually, which is inefficient and prone to errors. Because of the large number of substation equipment, maintenance personnel need to check the operating status of the equipment one by one, and once a failure occurs, it takes a lot of time and energy to investigate and repair. In addition, due to the limitations of manual maintenance, for some hidden faults or subtle abnormalities, it is often difficult to find and solve in time, which may lead to the expansion and deterioration of the accident.

Equipment maintenance progress monitoring not only plays a certain role in supervising maintenance personnel to ensure that the maintenance work is completed on time, but also can reverse to remind the substation managers according to the progress of maintenance data to sum up the experience, timely detection of problems and deficiencies in the process of maintenance, the next maintenance plan for modification and optimization. Through real-time monitoring and data analysis, it can be more comprehensive understanding of equipment conditions and maintenance needs, and provide a basis for the development of a more scientific and reasonable maintenance plan. This can make the substation maintenance efficiency effectively improved, reduce the equipment failure rate, improve the stability and reliability of the power system, to provide users with more quality power services.

Based on the above situation, many scholars have studied the condition of equipment maintenance, such as the condition monitoring and predictive maintenance method of hydropower plant equipment proposed by Betti et al. [8]. Since renewable energy is used for power generation, their operation and maintenance costs are relatively low, so information and communication technology (ICT) and machine learning methods can be used for condition monitoring, and a new key performance indicator (KPI) is used to evaluate the maintenance of hydropower plants. Malhotra et al. put forward the management and maintenance algorithm of electrical equipment in industrial facilities [9]. Through the analysis of the electrical preventive maintenance (EPM) plan, because the electrical equipment is not properly maintained may affect the safety of workers due to unrecorded and unknown conditions. The new calculation method can reflect the results of evaluating the maintenance of electrical equipment in terms of short circuit capacity, arc flash hazard and equipment coordination. Rodriguez et al. proposed the on-site maintenance and cost-benefit evaluation of anti-corrosion coatings for equipment in Ohio in winter [10]. Through changing the anti-corrosion maintenance strategy, reducing downtime, improving public safety, protective coatings can extend the service life of equipment, reduce maintenance costs, and make an evaluation of the maintenance strategy, the maintenance can ensure the safe operation of equipment. Shamsollahi D et al. introduced deep learning models and ultra-wideband to locate the elements at the construction site and achieve automatic monitoring of the construction progress [11]. Pradeep M S et al. proposed an automated progress monitoring platform based on extended reality. By integrating automatic data collection and visual analysis, it solves the problems of progress management relying on manual input and insufficient visualization [12].

The advantage of visualization is to improve the readability and understanding of data, and at the same time, it can quickly identify trends and exceptions in data, so as to help people make better decisions and analysis. Parallel processing can enable multiple projects to work together. Based on this, the visual monitoring algorithm of multi equipment parallel maintenance progress in substation base is studied. By using BIM real-time model to compare the BIM model in the maintenance plan, the multi equipment maintenance progress of the substation can be monitored in parallel, effectively and visually.

## 2. Design of Visual Monitoring Method for Substation Maintenance Progress

### 2.1. Modular BIM modeling for substation equipment maintenance

Substation equipment usually has complex spatial layouts and precise installation requirements. Modular modeling allows for the independent handling of spatial constraints for each equipment unit. Meanwhile, during the maintenance of substations, equipment replacement or upgrading is often involved. The modular design ensures that the update of individual equipment models does not affect the overall structure. For instance, in a certain 500kV intelligent substation project, the gas-insulated switchgear (GIS) adopted a modular modeling approach, decomposing the GIS into independent units such as circuit breaker modules, disconnector modules, and grounding switch modules. Each module established a standard interface, and during maintenance, faulty modules (such as circuit breaker mechanism boxes) could be directly invoked for targeted inspections. Therefore, in the substation base equipment modeling will be modular idea introduced, with reference to the relevant content of the design manual, to solve the overall model drawing work is difficult to accurately grasp the spatial constraints, resulting in the displacement of equipment components and other situations. Figure 1 illustrates the modularization process of model building.

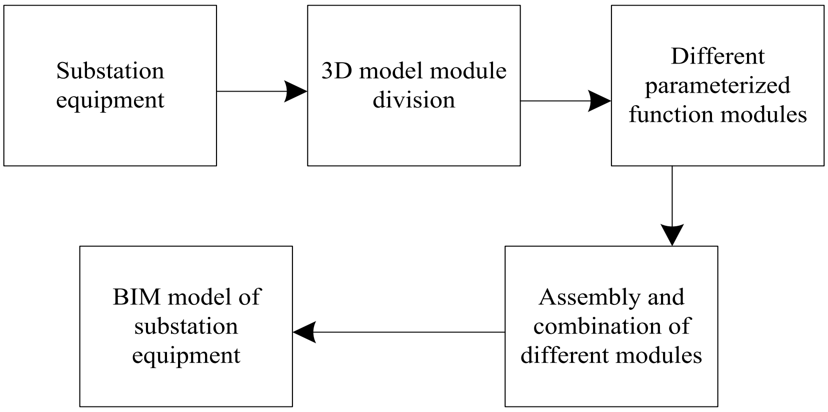


Figure 1. Modular modeling flow.

Before establishing the substation maintenance plan model, it is necessary to summarize the substation as built drawings in detail, understand the overall layout, equipment models and types, connection mode of equipment in the station, indoor building layout and equipment layout, conduct fine modeling of equipment in the substation according to the two-dimensional drawings of equipment and detailed instructions of equipment, and establish the substation base model according to the substation as built drawings, the BIM model of the equipment shall be placed in the corresponding position according to the as built drawing, and the required non geometric information shall be added. After the above steps are completed, the BIM model of the substation maintenance plan shall be established. Import the established BIM model of the substation maintenance plan into 3dsMAX for model rendering and equipment surface mapping, and then import the model into the open source visual graphic programming software Dynamo to realize the visual display of the substation model. When importing the BIM model of the substation established by Revit into 3dsMAX for rendering and mapping, the following key steps need to be taken to ensure data integrity and rendering quality:

(1) Data interface and format conversion: The FBX format is adopted as the intermediate transmission format, which can retain the geometric structure, material properties and hierarchical relationship of the model. When exporting in Revit, you need to check the "Keep Material ID" and" Embed Texture "options to prevent texture loss.

(2) Model optimization preprocessing: In Revit, reduce the number of Surface segments to 12-16 through the "Simplify Surface" function to decrease the mesh density in 3dsMAX; By using the "ProOptimizer" modifier of 3dsMAX to merge vertices with a distance less than 0.1mm and delete those that cannot meet, the number of faces can be reduced by 30% to 50%.

(3) Material and Texture migration: For Revit standard materials (Autodesk Materials), they need to be reconstructed through the "Arch & Design" material template in 3dsMAX.

Set the metal equipment of the substation at 0.7-0.85 and the insulating materials at 0.2-0.3. Convert the relief Map of Revit to a Normal Map and use the xNormal plugin to generate a map with an accuracy of 1024×1024.

(4) Rendering parameter optimization: Set the output resolution to 3840×2160 (4K), and select "Adaptive DMC" for the sampler; Enable the "Light Cache" pre-computation (subdivided into 1500) and "IRradiance Map" (medium-quality preset), and control the single-frame rendering time within 2 hours (NVIDIA RTX 5000 graphics card). The specific model establishment process is shown in Figure 2.

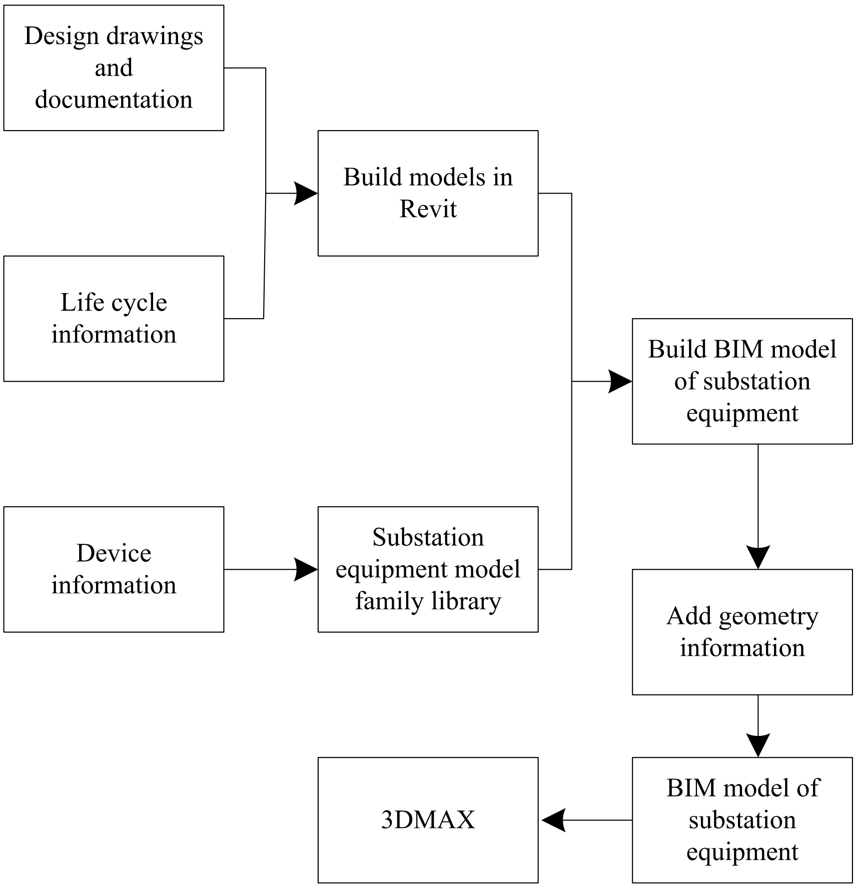

Figure 2. Substation modeling process.

In the process of building BIM model of substation equipment maintenance plan to realize visualization [13], many problems will be encountered, which will affect the quality and application effect of the model. For the above problems, the solutions are as follows:

(1) To solve the problem of non-uniform size in modeling, CAD drawings can be imported when building models, and the drawings can be traced directly according to CAD drawings, so as to unify the size of models and improve the efficiency of model building. In addition, the introduction of CAD drawings is conducive to the placement of equipment models in the substation [14], which can position the equipment according to the drawings and improve the modeling quality.

(2) The overhead line of the substation and the wiring between the equipment shall be connected by self building family. Because Revit software provides the function of cable drawing and automatic wiring, but this function is mainly suitable for building electrical, which does not conform to the substation wiring rules and customs. By creating cable family files in Revit software, and arranging according to the substation as built drawings, different types of cable families can be established for different cable sections using the lofting function to meet the substation wiring needs.

(3) After the completion of the project, a BIM family library of substation equipment will be formed. During the establishment of the family library, all equipment classifications need to be classified to facilitate accurate searching of related equipment when using family files; Classification of buildings in the substation, such as buildings

used in the substation, outdoor cable trench, equipment foundation pit, etc.

(4) The use of static LOD model requires the establishment of equipment models with different precision. You can delete edges and faces on the basis of precision die to obtain models with different precision. Practice has proved that this method is more efficient in modeling and faster in execution.

(5) After the model is established in Revit software, it is imported into 3dsMAX for model optimization. The main purpose is to delete the redundant drawn faces, invisible faces, coincident faces and unrelated lines due to perspective problems in the modeling process. Before formal lightweight processing, there are no redundant geometric faces in the model, so as to minimize the memory occupation on the basis of ensuring that the model is not deformed.

## 2.2. Triangle folding and QEM BIM maintenance progress lightweighting

In order to ensure that the server of the substation can store more maintenance data, it is necessary to conduct lightweight conversion on the established BIM model, which not only reduces the storage pressure of the server, but also ensures the efficiency of maintenance progress monitoring.

### 2.2.1. Lightweight of three-dimensional models under the optimal vertex selection of triangular folding

The essence of 3D model lightweight is triangle folding. One triangle folding is equivalent to two sides folding. The higher the efficiency of triangle folding, the higher the quality of folding. Triangle folding is an iterative geometric element deletion method. The basic idea is to shrink the triangle into a point by taking the triangular face as the deletion element. By iteratively reducing the number of triangles in the three-dimensional model, the BIM model of substation maintenance plan can be lightweight. Different from the conventional vertex clustering or edge folding algorithms, the triangulation folding strategy adopted in this study can maintain the geometric characteristics of substation equipment more accurately. The regular geometric bodies that exist in large quantities in substation equipment (such as transformer bushings, insulator string, etc.) are usually composed of planar triangular meshing. The triangular folding takes the complete triangular surface as the operation unit, which can avoid the edge fracture phenomenon caused by edge folding. Compared with the traditional edge folding algorithm, it can reduce the contour distortion rate of key parts. Figure 3 shows the triangle folding, the folding front triangle $T_i$ is reduced to the folding back point $V$.

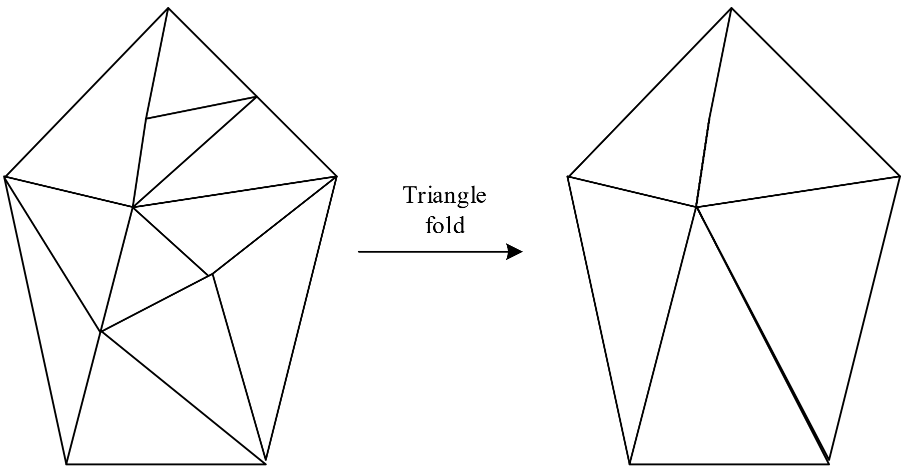

Figure 3. Triangle folding.

The effect of triangle folding depends on the size of folding error, so it is determined to minimize the folding error and improve the folding effect in the process of folding. The BIM model of the substation maintenance plan after lightweight processing does not change the details of the equipment, so it is necessary to select a new vertex $v_{i0}$ after folding. The selection of new vertex $v_{i0} = [x_{i0} y_{i0} z_{i0}\ 1]^T$ position determines the folding error. The smaller the error, the more similar the BIM model of the substation before and after lightweight processing. The advantages of the QEM algorithm are mainly reflected in two aspects: Firstly, through the quadratic measurement of the error matrix, the impact of each fold on the topological structure of the equipment can be quantitatively evaluated, which is particularly important for the equipment with electrical connection attributes in the substation model (such as the contact head position of the circuit breaker); Secondly, the seven-point candidate strategy automatically generated by the algorithm (including the midpoint of the triangular face, the midpoint of the edge, and the original vertex) provides redundant optimization space for irregular devices (such as the curved housing of a lightning arrester). In order to solve the optimal solution problem of new vertices, QEM (Quadratic Error Measure) algorithm is used to measure the folding error $4 \times 4$ of the matrix to represent the triangular error matrix $Q_i$, then the triangle folding error $\alpha(T_i)$ is:

$$\alpha(T_i) = v_{i0}^T Q_i v_{i0} = q_{i11}x_{i0}^2 + 2q_{i12}x_{i0}y_{i0} + 2q_{i13}x_{i0}z_{i0} + 2q_{i14}x_{i0}^2 + 2q_{i22}y_{i0} + 2q_{i23}y_{i0}z_{i0} + 2q_{i24}y_{i0} + q_{i33}z_{i0}^2 + 2q_{i34}z_{i0} + q_{i44} \tag{1}$$

In the formula, $v_{i0}$ is the new vertex position; the $x$, $y$, $z$ are the new vertex coordinate.

The triangular error matrix $Q_i$ is:

$$Q_i = \begin{bmatrix} q_{i11} & q_{i12} & q_{i13} & q_{i14} \\ q_{i21} & q_{i22} & q_{i23} & q_{i24} \\ q_{i31} & q_{i32} & q_{i33} & q_{i34} \\ q_{i41} & q_{i42} & q_{i43} & q_{i44} \end{bmatrix} \tag{2}$$

In the formula, $q_{i11}$ is one of the key parameters of the triangular error matrix $Q_i$ in the error measurement of the QEM algorithm. It plays an important role in measuring the error relationship between the position of the new vertex and the related triangular plane. This expression is used to calculate the folding error of the triangle. The various elements in matrix $Q_i$ work together to reflect the folding error through the combined operation of the coordinates of the new vertices. The new vertex optimal solution is to keep the fold error $\alpha(T_i)$ minimum.

For equation (1), take the partial derivative to $x_{i0}$, $y_{i0}$, $z_{i0}$ and make it zero, that is:

$$\frac{\partial \alpha(T_i)}{\partial x_{i0}} = \frac{\partial \alpha(T_i)}{\partial y_{i0}} = \frac{\partial \alpha(T_i)}{\partial z_{i0}} = 0 \tag{3}$$

According to Eq. (3), a system of linear equations can be obtained.

$$\begin{bmatrix} q_{i11} & q_{i12} & q_{i13} & q_{i14} \\ q_{i21} & q_{i22} & q_{i23} & q_{i24} \\ q_{i31} & q_{i32} & q_{i33} & q_{i34} \\ 0 & 0 & 0 & 1 \end{bmatrix} v_{i0} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{4}$$

If Eq. (4) has a solution, then the position of the new vertex$v_{i0}$can be found. If there is no solution, the midpoint of the triangle, the midpoint of the three sides of the triangle or the three vertices of the triangle are chosen as the new vertices, and among the seven points given, the point that minimizes the value of Eq. (1) is found, and this point is taken as the new vertex after the folding, so as to complete the lightweighting of the three-dimensional model of the substation equipment.

#### 2.2.2. BIM model folding error minimization conversion

Garland first proposed in 1997 that the algorithm uses triangles as folding objects to generate new vertices, and takes the square of the distance from the new vertex to the plane of the relevant triangle as the standard to measure the error. Using QEM algorithm for error measurement can obtain high-quality BIM simplified model of substation, which is characterized by high simplification efficiency and small memory occupation [15].

Before simplification, each triangle $T_i$ in the triangle grid $TM$ has three vertices correlated and all triangles form a set of triangle $T_i$ correlated triangle set $C$. In three-dimensional Euclidean space,define the equation of the plane in which the relevant triangles in the mesh are located as $ax + by + cz + d = 0$, and is satisfied $a^2 + b^2 + c^2 = 1$ ($d$ is an arbitrary constant), which guarantees that multiple triangles are in the same plane. Triangles in the same plane are handled by an improved algorithm. Define the plane equation as $P = [a\ b\ c\ d]$, The square of the distance from new vertex $v_{i0}$ to the plane of the triangle in question is $(P^T v_{i0})$, taking the maximum distance from the plane from the new vertex $v_{i0}$ to the relevant triangle is located as the error metric, and the smaller the error metric is according to the standard, the better the model simplification effect is. The folding error is:

Of which: $P \in C$, $C$ is the set of triangle $T_i$ related triangles; $Q_p$ is the error matrix of $4 \times 4$, and is the error matrix that minimize the folding error $\alpha(T_i)$:

$$Q_p = PP^T = \begin{bmatrix} a^2 & ab & ac & ad \\ ab & b^2 & bc & bd \\ ac & bc & c^2 & cd \\ ad & bd & cd & d^2 \end{bmatrix} \tag{5}$$

The LOD grade is classified based on the importance of the equipment (for example, the main transformer equipment adopts LOD400 grade, with an error threshold of ≤0.5mm;) The auxiliary equipment such as busbar brackets adopts LOD300 level, with the threshold relaxed to 2mm. Determine the optimal parameters - when the Hausdorff distance between the simplified model and the original model exceeds the preset threshold (0.8mm for the main equipment / 3mm for the auxiliary equipment), the secondary optimization of the QEM algorithm is automatically triggered. Specifically, the vertex positions are dynamically adjusted through the error matrix of Formula (5), so that the geometric error of the GIS interval model is always controlled within the threshold range when the number of triangular faces decreases. Therefore, the lightweight conversion of BIM model of substation equipment maintenance plan is completed.

### 2.3. Substation equipment maintenance progress monitoring

#### 2.3.1. Design of the Monitoring framework for Equipment Maintenance progress

The architecture of monitoring equipment maintenance progress based on BIM model is shown in Figure 4.

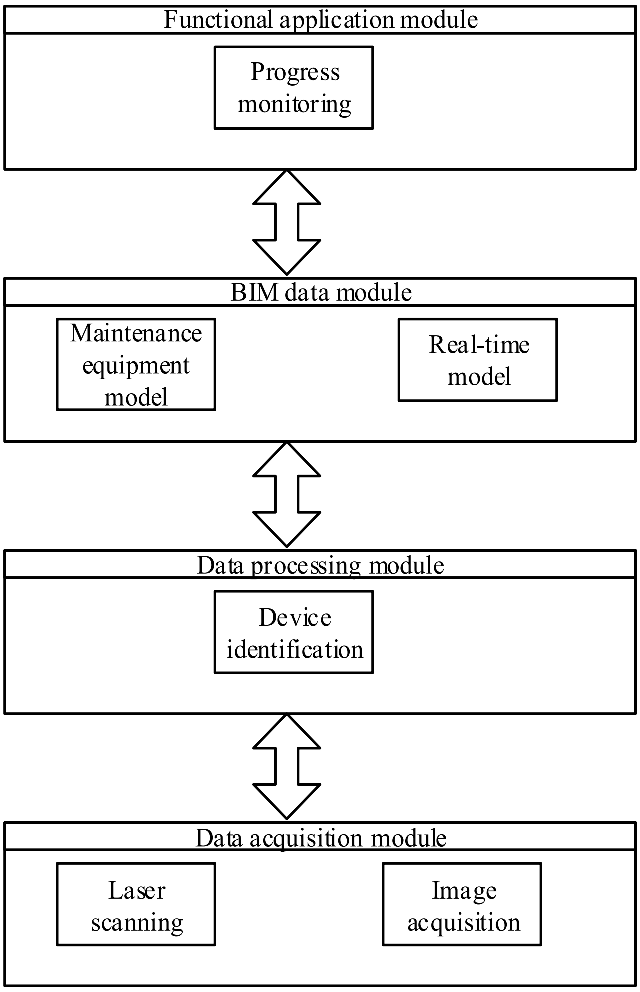


Figure 4. Overhaul progress monitoring framework.

The functionality of the hierarchies in Figure 4 is summarized as follows:

(1) Data acquisition module. In the maintenance of GIS equipment, a laser scanner is used to obtain the three-dimensional point cloud of the compartment, and at the same time, a camera is used to record the dynamic image of the operating mechanism of the circuit breaker, forming a complete digital record of the maintenance site. Collect the data information of the equipment maintenance site, and input the real-time data of the site to the data processing module. The real-time data includes 3D point cloud and depth image. The 3D point cloud collects the 3D coordinates of the completed maintenance part of the maintenance site through the 3D laser scanner, and integrates the data of different stations through data registration. The depth image is obtained by shooting the scene with camera measurement technology. In the monitoring of the maintenance progress of substations, laser scanners and depth cameras have formed a complementary data acquisition system. The laser scanner acquires high-precision 3D point cloud data by emitting laser

pulses and is suitable for the precise measurement of the geometric dimensions of a wide range of equipment, such as the flatness detection of the flange surface of GIS equipment. The depth camera generates depth images in real time through infrared structured light or the time-of-flight principle. It is particularly suitable for dynamically capturing the operation process of maintenance personnel and the status of equipment in a narrow space, such as recording the movement trajectory of the mechanical connecting rod of a circuit breaker. These two devices achieve data fusion through a unified coordinate system. Among them, the laser point cloud provides an accurate geometric reference, and the depth image supplements real-time dynamic information, jointly constructing a maintenance site model that not only has millimeter-level accuracy but also includes changes in the time dimension.

(2) Data processing module. The point cloud of the main transformer bushing is registered with the BIM planning model through the ICP algorithm, the installation deviation is identified, and the geometry generated by scanning is automatically replaced with the parameters of the standard model to maintain the consistency of model accuracy and attributes. The field data input by the data acquisition module is processed. By extracting the information of depth image and 3D point cloud, the object recognition and matching are carried out, and the real-time BIM model of equipment maintenance is generated. The object recognition and matching process effectively uses the information provided by the equipment maintenance plan BIM model to identify the equipment in the model, and replaces the point cloud with the object of the parameters in the plan model to generate the BIM real-time model.

(3) BIM data module. Store the maintenance plan model containing 287 equipment components, update the GIS equipment disassembly progress data in real time, and associate historical maintenance records. The BIM data module is the central database of the entire progress monitoring algorithm, which contains BIM planning model information and BIM real-time model information. The BIM plan model is based on the BIM model of substation equipment established in the earlier stage, combined with the maintenance plan information generated by the maintenance steps specified in the maintenance instructions. The plan model contains the specific maintenance steps and three-dimensional models of different equipment in the substation, BIM real-time model integrates a large amount of useful information generated from dynamic monitoring of maintenance process. The BIM data module is the data core of the progress monitoring module. The BIM data module is used to effectively integrate and manage the information of the maintenance project plan and the maintenance stage, and provide the required data information to the progress monitoring module through the BIM data module to realize the function of the progress monitoring module. At the same time, The BIM data module integrates the information of different maintenance stages through the central data, and can provide functional expansion for different equipment maintenance in different substations.

(4) Function application module. The maintenance progress is visually displayed on the platform, the labor cost consumption is monitored in real time, and it supports clicking on the equipment model to retrieve relevant inspection reports. The function application module is the function module of the maintenance progress monitoring algorithm [16], which is the specific application of the information provided by the BIM data system to realize the system functions, including visual presentation of the maintenance degree, maintenance progress monitoring, maintenance cost monitoring, etc. The functional application system has good scalability, and can add functional modules realized by using BIM real-time model information according to the needs of maintenance projects.

### 2.3.2. Progress monitoring module

The progress monitoring module is a functional application module of the overhaul progress monitoring algorithm [17], which needs to realize the function of monitoring progress. The module contains three basic functions, i.e., maintenance information import and setup, maintenance quantity calculation and output, and parameter calculation and output [18]. The specific description of each function is shown in Figure 5.

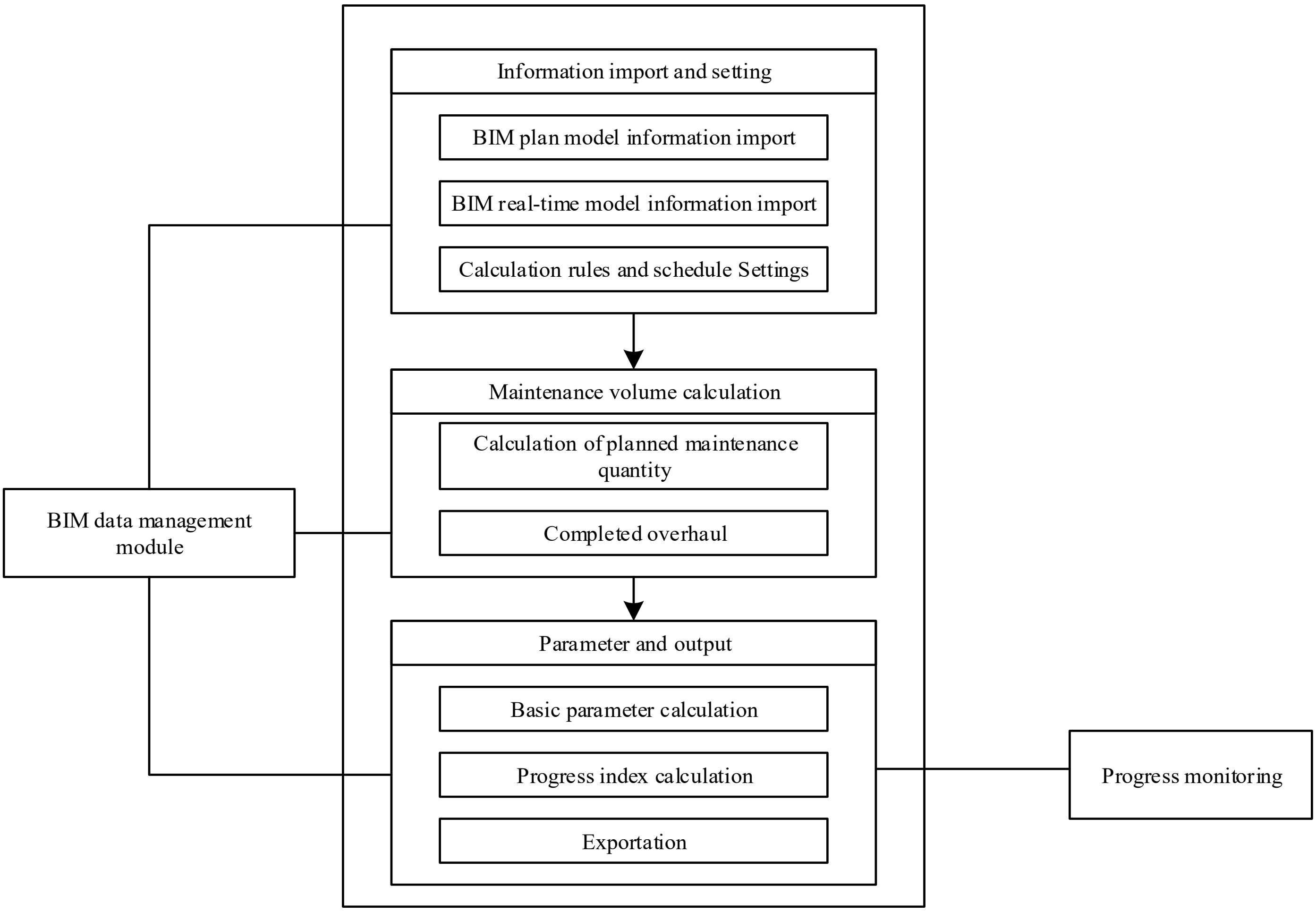


Figure 5. Structure of maintenance progress monitoring module.

### 2.4. Parallelized processing

To realize the parallel maintenance progress monitoring of multiple equipment in the substation, the main task is how to realize the parallel task allocation of each DSP (processing unit), which often determines the time efficiency of the whole maintenance progress monitoring to a large extent [19]. There are usually two parallel strategies:

(1) Segmentation of the whole algorithm, part of each DSP calculation algorithm, similar to the software pipeline method of DSP;

(2) The data source is partitioned, and each DSP calculates a part of the whole data source in parallel.

By analyzing the algorithm of this paper, it can be found that the most time-consuming part of the algorithm of this paper lies in the real-time modeling of the substation multi-device modeling, which can be split, so the parallelization of this paper chooses the first way.

In this paper, a total of four DSPs are used for real-time modeling processing, the real-time BIM model during maintenance is partitioned (total number of blocks M), and is cached in large capacity SDRAM (synchronous dynamic random access memory) in row and column order. Secondly, define a global variable N (N starts from 1) to represent the number of blocks of small data currently being read. Each DSP reads a small piece of data to be modeled into the memory in turn, and notifies the other three DSPs of the variable value N+1 through the ring LINK port, and then processes the data in the memory for BIM modeling. Once any DSP is processed, it will query the bus status and read the data of the next pending graph from SDRAM according to the N value until the real-time modeling of all devices is completed. Each DSP first accumulates the small pieces of data read in by itself. After traversing the entire model, the results of internal calculations of each DSP are accumulated through LINK ring transmission to obtain the mean matrix and covariance matrix of the entire model. Then the results are transmitted to other DSP through LINK ring. Finally, each small block model is spliced to form the real-time BIM model result output of multiple equipment in the substation. The parallel calculation flow of the algorithm is shown in Figure 6.

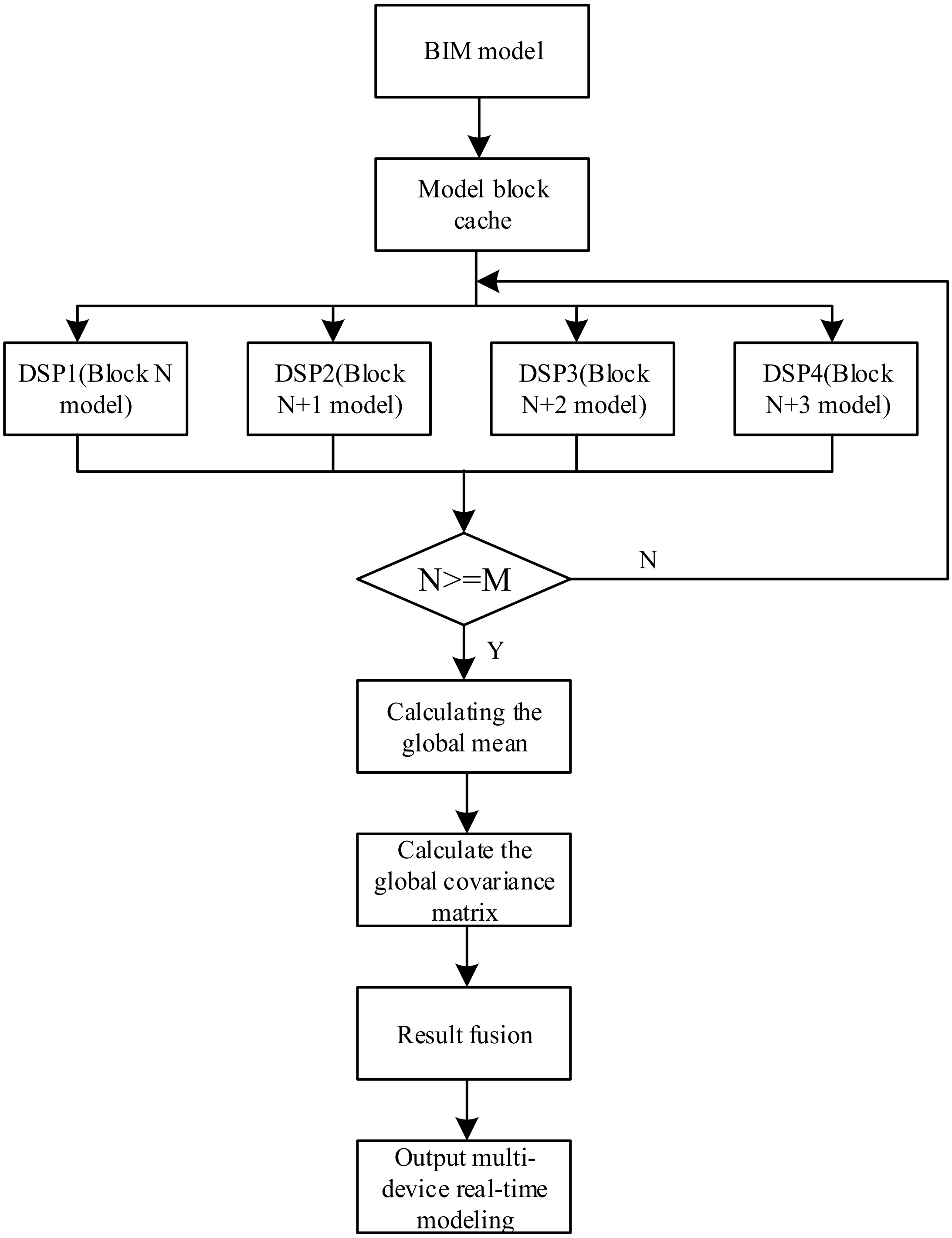


Figure 6. Algorithm parallel computing process.

**2.5. Visualization of overhaul progress**

The core part of realizing the visual monitoring of equipment maintenance progress is the visualization unit [20], as shown in Figure 7.

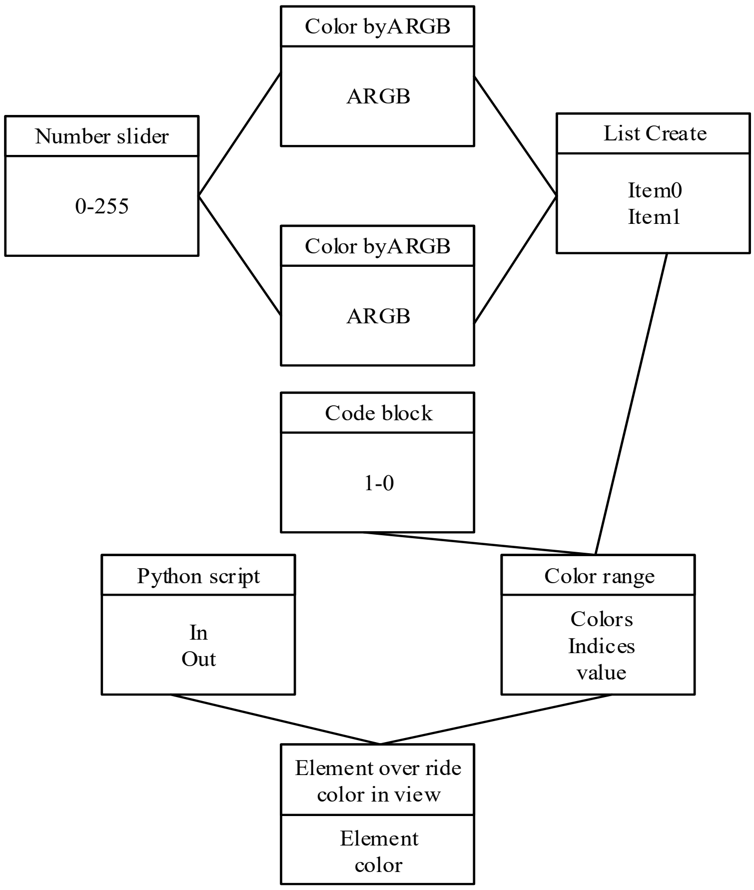

Figure 7. Visualize the unit.

The operational steps of the visualization unit are described below.

(1) The python script node is established, and the 3DMAX application program interface is called by Python to output the three-dimensional digital form of equipment maintenance status, which is converted from the graphic structure obtained by the sensor;

(2) Establish the Color range node, input the color list, and make the color correspond to 1 and 0 respectively. The returned color value depends on the analysis result of the data processing unit;

(3) Input the device BIM model and the color value of feedback in the Element. override color in view node, and run the script to provide technical support for the realization of reading visual monitoring of multi device maintenance.

In order to make the visualization unit run smoothly and efficiently, Dynamo, an open source visual graphic programming software, is used as a plug-in of Revitalizing platform, and a client display interface is established. This interface can improve the convenience of node connection by encapsulating complex program language on each node. The logic program of automatic workflow also helps to speed up the work. Dynamo software builds large-scale extension libraries at low cost, allowing users to apply expansion packs and Python scripts at will, so that corresponding functions can be realized.

## 3. Experimental analysis

### 3.1. Experimental subjects

In order to verify the actual use effect of the algorithm in this paper, a substation base in M city is selected for visual monitoring experiment of maintenance progress. The 110kV/25MVA main transformer (no-load current 0.78%) and 126kV disconnector (rated current 1250A) configured in this station are standardized equipment with typical designs of State Grid, and their maintenance regulations are industry-wide universal. The station simultaneously contains primary equipment (15m busbar) and secondary equipment (550kW DC generator), which can fully verify the applicability of the algorithm in the mixed equipment scenario. Meanwhile, the current transformer with a 256kV insulation grade and the parameter configuration with a dynamic stable current of up to

100kA at this station can fully test the monitoring stability of the system in a high-voltage and high-current environment. See Table 1 for details of primary equipment and secondary equipment in the substation.

Table 1. Equipment condition in substation.

| Equipment | | Stats | Argument |
|---|---|---|---|
| Primary equipment | Transformer | Rated frequency | 50Hz |
| | | Capacity | 25000kVA |
| | | Rated voltage high voltage | 110±2*2.5%kV |
| | | Rated current high voltage | 131.2A |
| | | No-load current | 0.78% |
| | Bus bar | Length | 15M |
| | Disconnecting switch | Rated voltage | 126kV |
| | | Rated frequency | 50Hz |
| | | Rated current | 1250A |
| Secondary equipment | Dc generator | Rated power | 550kW |
| | | Weight | 5000kg |
| | | Rated current | 850A |
| | Current transformer | Rated frequency | 50Hz |
| | | Rated insulation level | 256kV |
| | | Rated dynamic stable current | 100kA |

### 3.2. Experimental data

The BIM model of substation equipment is established using the algorithm in this paper. The BIM model of insulation terminals and grounding devices in the substation is shown in Figure 8.

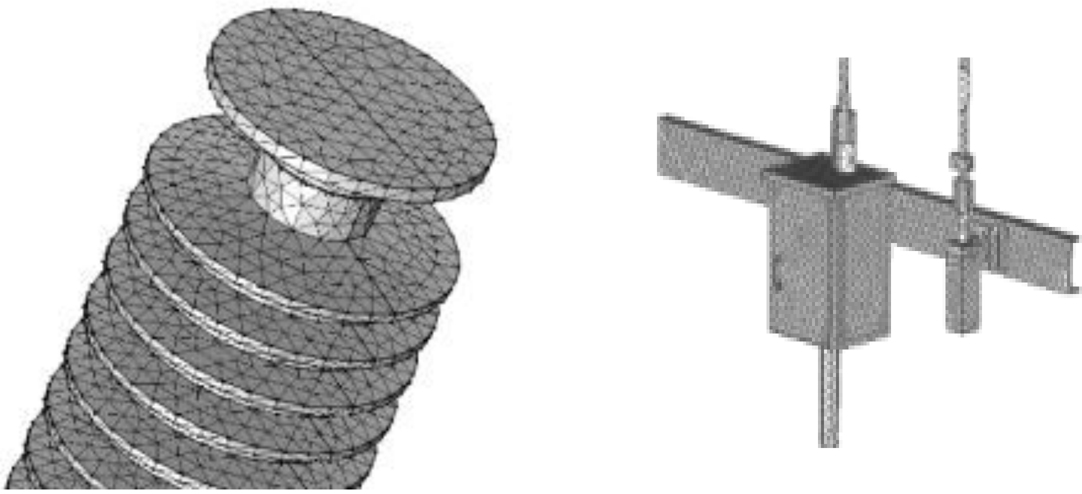

Figure 8. Part of the equipment BIM modeling.

By observing Figure 8, we can clearly see that the BIM model established by this method has obvious details, accuracy and complete structure. This feature enables the model to show the overall situation of substation equipment in detail, and provides a solid foundation for subsequent maintenance progress monitoring. This accuracy and integrity is not only reflected in the appearance of the model, but also in its internal data structure and information expression. Such a model can provide more accurate, more intuitive and more complete information, which is helpful to improve the efficiency and accuracy of maintenance work. At the same time, the model can also realize real-time monitoring and prediction of equipment status by combining with real-time monitoring data, which further improves the progress monitoring of equipment maintenance.

The number of triangular faces and points in the model are shown in Table 2 after different degrees of lightweight conversion of BIM model by the algorithm in this paper.

Table 2. Model parameters of different simplified proportions.

| Simplification rate /% | Number of triangular surfaces | Number of points | Simplified error /mm | Run time/ms |
|---|---|---|---|---|
| 15 | 753428 | 2081673 | 0.513 | 81 |
| 35 | 689752 | 1922617 | 0.662 | 297 |
| 45 | 631408 | 1614085 | 0.717 | 408 |
| 55 | 505235 | 1330811 | 0.809 | 563 |
| 75 | 221084 | 815826 | 1.028 | 868 |

From Table 2, we can deeply observe that although the algorithm in this paper has the ability to highly simplify the original BIM model, with the increase of the simplification rate, the simplification error of the model is also gradually rising. This means that while pursuing a high simplification rate, we must consider maintaining the accuracy of the model. At the same time, with the increase of the simplification rate, the simplified running time will also increase, because the high simplification rate requires more complex calculations and more processing time. Therefore, in practice, we need to choose an appropriate simplification scale. This scale needs to be able to quickly obtain the simplified results while ensuring a high simplification rate, while keeping the simplified model error low. In order to achieve this goal, we can use the iterative optimization method to gradually adjust the simplification rate to find an optimal balance point. This balance point will maximize the storage efficiency and management efficiency, while maintaining the quality and accuracy of the model. After several simplifications, this paper chooses the simplification rate of 55%. Observed from the dimension of model accuracy, the error of 0.809mm corresponding to a 55% simplification rate only increases by 12.8% compared with a 45% simplification rate, but decreases by 21.3% compared with a 75% simplification rate, indicating that there is a significant advantage in error control in this range. From the perspective of computational efficiency, 55% of the 563ms operation time saves 35.1% compared to the 75% scheme, and the retention of the number of triangular faces (505,235) can still fully express key features such as the flange connection surface of the equipment. In the application of 2000kV substations, the 55% solution not only meets the 200ms-level response requirement for real-time path planning of inspection robots, but also can control the key dimensional deviation of the LOD400-level model within ±1.5mm. Its comprehensive performance is superior to other simplification rate solutions.

For the purpose of testing this article, The lightweight conversion effect of BIM model is to conduct lightweight conversion on the BIM model of the above substation equipment. The converted BIM model is shown in Figure 9.

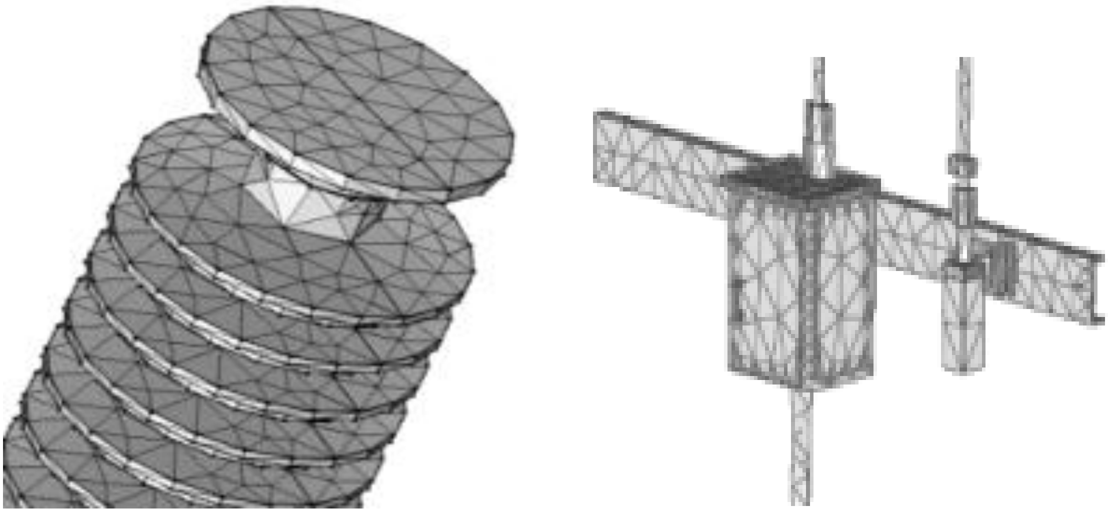

Figure 9. Converted BIM model.

By observing Figure 9, we can see that after the application of the BIM model lightweight conversion method proposed in this paper, the triangular surface in the model has significantly decreased, but the overall structure and results of the model have not changed, and information has not been missing. This means that this method can effectively reduce the size of the model, while still accurately reflecting the equipment information in the substation. In addition, this lightweight conversion method can also use smaller storage space for storage, which has important practical value for the storage and management of substation equipment information. Therefore, the lightweight transformation method of BIM model proposed in this paper can not only meet the needs of practical applications, but also effectively improve the storage efficiency and management efficiency.

In order to verify the algorithm of this paper, in the actual maintenance process, for the maintenance progress of the monitoring effect, in the substation for maintenance, at the same time using the algorithm of this paper to monitor the monitoring results as shown in Table 3.

Table 3. Maintenance progress monitoring.

| Equipment number | Device name | Progress monitoring result | Actual progress |
|---|---|---|---|
| 1 | Transformer 1 | 40% | 40% |
| 2 | Transformer 2 | 20% | 20% |
| 3 | Smart Switch1 | 18% | 20% |
| 4 | Smart Switch2 | 47% | 47% |
| 5 | Bus bar | 50% | 50% |
| 6 | Voltage transformer | 70% | 70% |
| 7 | Current transformer | 30% | 30% |
| 8 | Dc generator | 45% | 45% |
| 9 | Circuit breaker | 80% | 80% |
| 10 | Lightning arrester | 90% | 90% |

By observing Table 3, we can find that this paper is able to accurately monitor the progress of overhauling different equipment in the substation when carrying out substation progress monitoring. This provides substation managers with sufficient information so that they can better understand the experience and condition of equipment overhaul and provide more reasonable planning data for the next overhaul.

The advantage of this kind of accurate monitoring is that the managers can adjust the maintenance plan and strategy according to the real-time data and information to ensure the normal operation of the equipment and improve the service life of the equipment. In addition, this kind of monitoring can also help managers better assess the performance and status of the equipment, timely detection of potential problems and take appropriate measures to avoid equipment failure on the operation of the entire substation. The algorithmic substation progress monitoring method in this paper has high practical value. It can provide accurate and comprehensive maintenance progress information to help managers better understand the equipment condition and formulate more reasonable maintenance plans and strategies.

In order to verify the effect of this paper's maintenance progress visualization, using a computer to check the interface of this paper's algorithm, the results of this paper's maintenance progress monitoring algorithm visualization are shown in Figure 10.

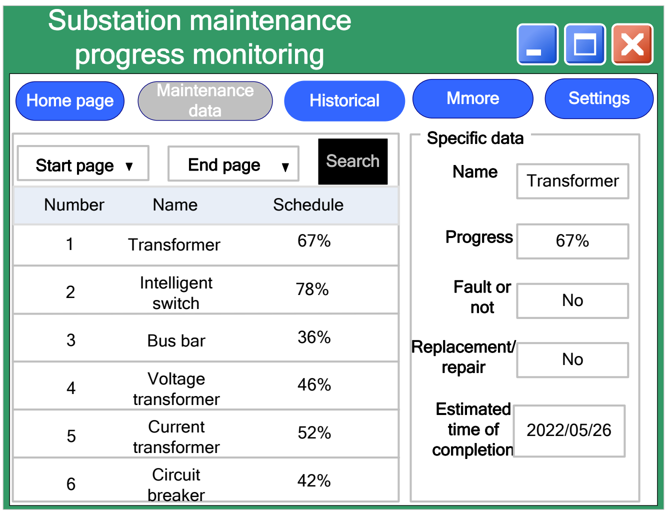


Figure 10. Visualization of maintenance progress.

By looking at Fig. 10, we can clearly see the effect of the algorithm in the visualization application. The maintenance data of different equipment in the same period of time can be presented in an intuitive way during the parallel maintenance of equipment, so that the managers can easily obtain and understand the progress of the maintenance of each equipment at the current moment of the parallel maintenance of multiple equipment. In addition, the method in this paper not only shows the current parallel maintenance data, but also retains the past parallel maintenance data, so that the managers can update each parallel maintenance plan according to the changes of the historical parallel maintenance data. The advantage of this visualization method is that it allows substation managers and maintenance personnel to quickly and accurately understand the status and progress of parallel maintenance of substation equipment. By observing the changes in historical data, managers can assess the performance and status of equipment, predict possible failures and take appropriate preventive measures. This not only improves the service life of the equipment, but also reduces maintenance costs and the impact of equipment failure on the entire substation.

Combined with the substation's historical maintenance data, the use of this paper's algorithm in maintenance, for the substation multi-equipment maintenance of the maintenance time changes are shown in Table 4.

Table 4. Comparison of maintenance time.

| Equipment number | Device name | Historical maintenance time/hour | Actual maintenance time/hour |
|---|---|---|---|
| 1 | Transformer 1 | 18 | 14 |
| 2 | Transformer 2 | 22 | 15 |
| 3 | Smart Switch1 | 4 | 2 |
| 4 | Smart Switch2 | 5 | 2 |
| 5 | Bus bar | 24 | 20 |
| 6 | Voltage transformer | 5 | 3 |
| 7 | Current transformer | 7 | 4 |
| 8 | Dc generator | 13 | 7 |
| 9 | Circuit breaker | 3 | 1 |
| 10 | Lightning arrester | 8 | 5 |

By observing Table 4, we can find that the overall maintenance time has been significantly improved after using the algorithm in this paper to monitor the maintenance progress. The reason for this improvement may be that the real-time BIM model can ensure the progress of work when the maintenance is interrupted again. The real-time BIM model can record and update the status and maintenance progress of the equipment. Even if there is an interruption in the maintenance process, it can quickly restore the working status when it is overhauled again, reducing repeated work and wasting time. By reducing unnecessary repetitive work and waste of time, this algorithm can enable maintenance personnel to spend more time and energy on the maintenance of other equipment in the substation, so as to ensure the stable and safe operation of the substation. This is of great significance to the stability and reliability of power systems. The adaptive mechanism of this algorithm originates from the dynamic matching characteristics of the BIM model and the laser point cloud. For large equipment such as transformers with complex structures, the algorithm retains the topological relationships of key components through QEM lightweight processing. Combined with laser scanning to capture millimeter-level changes such as bolt displacement in real time, it makes the progress backtracking after maintenance interruption more accurate. While small devices such as smart switches benefit from the rapid recognition of modular components by depth cameras, they can still maintain the characteristics of contact points after being lightweight through the triangulation folding method. This hierarchical processing strategy based on the physical characteristics of the equipment enables the lightweight degree of the model and the monitoring accuracy to be automatically adapted according to the type of equipment, ultimately reflected in the shortened maintenance time of the transformer.

## 4. Conclusion

Through experiments, we can clearly see that the algorithm in this paper performs well in building BIM model of substation equipment. The BIM model established not only has a high degree of detail accuracy and structural integrity, but also provides complete information, providing a solid foundation for subsequent parallel maintenance work. In addition, when simplifying the BIM model, the algorithm in this paper can maximize the retention of various information to ensure that the structure and details of the model are not damaged. This feature makes the model can still accurately reflect the actual situation of substation equipment after simplification, while using smaller storage space for storage. This optimization method not only improves the storage efficiency and management efficiency, but also ensures the quality and accuracy of the model. More importantly, the progress monitoring algorithm in this paper can accurately calculate the real-time maintenance progress of an equipment during parallel maintenance. By visualizing the progress data in real time, managers can quickly understand the status and progress of equipment parallel maintenance. This monitoring mode provides convenience for the management personnel of the substation, enabling them to update the parallel maintenance plan in time according to the changes of historical data, so as to ensure the rapid and safe completion of the multi equipment maintenance work of the substation.

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