Voxel Primitive Based Modeling and Simulating Method for Surface Micromachining Technology

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***Abstract*—To avoid the traditional inefficient mask-beginning design way of micro device, feature technology was introduced into the modeling method. However, the hindrance to the mapping process from the feature-based 3D model to the fabricating information is hardly to exclude without a reasonable way to make the model conform to the fabricating processes. For surface micromachining, the voxel primitive based modeling method is proposed to efficiently construct the 3D model. The primitives compose the features that have relationship with the upper levels of the design flow. Moreover, the primitives can be stored in library because of the parametric and reusable character. With respect to the fabrication, the simulation technology is presented, which is the fabricating-oriented revising procedure to ensure the manufacturability. Based on JAVA technology, the key algorithms are developed to implement the primitive-based modeling kernel and the fabricating processes simulation. With the proposed method, the micro device model is constructed more conveniently with the improvement of manufacturability.**

***Index Terms*—Micro Device, Voxel Primitive Modeling, Geometric Simulation, Model Optimization**

I. Introduction

Currently, the design flow of micro device is bottom up that begins with the mask design [1]. It is inherited from the integrated circuit (IC) design because of the similar fabricating processes. Although the modeling procedure is adopted from the well-established micro fabricating techniques to ensure the following manufacture, it is not intuitive enough for the designer and sometime unreliable for the long iterative design cycle contrasting with the top-down design flow, which lays emphasis on the more efficient flow of function-to-shape-to-mask [2]. Usually, physical and geometrical parameters of micro device are considered in lower levels of the design flow [3]. There have been many efforts to focus on system level modeling and simulation that is concerned with the sector of function-to-shape [4,5]. Nevertheless, with respect to the overall design flow of micro device, the research in the stage of shape-to-mask is still insufficient, which is the key point to improve manufacturability [6]. In terms of surface micromachining technology, taking the more complex layered structure into account, it is too much for the designer to construct the 3D model in mind just with the mask in advance. Therefore, 3D modeling technology is preferred to improve the design efficiency [7,8].

With respect to mechanical design, feature technology has been an active research area for many years [9,10]. The critical component to realize the feature modeling is considered as fabricating feature recognition that deals with the issue of generating machine path code for CNC machines and providing the data for computer-aided process planning [11,12]. In a sense, the shape-to-mask is the fabricating feature recognition procedure of micro device. So far, the tools developed from IC are popular, which belong to the process-based modeling way [13,14]. For bulk micromachined device, it is convenient with such tools to build the structure for the relatively simple structure [15]. In terms of surface micromaching, things are different. To improve design efficiency, some research was carried out by using the mechanical design tools [16,17]. While others focused on the feature technology in micro device design [18,19]. However, because of the complexity of the surface micromachining, effective combination of the feature technology with the standardized processes has been elusive, among which the MUMPs (Multi-User MEMS Processes) have emerged as the cost-effective and proof-of-concept MEMS fabricating processes [20,21]. To make the features accord with the MUMPs, the revision of the original model is indispensable. It is the cooperative design mode with Web support that suitably provides the strategy to carry out the revising procedure to strike the balance between the functional requirements and the manufacturability. JAVA technology has the inherent advantage to deal with the Web application [22,23,24]. However, there are few modeling kernel based on JAVA technology. To implement the primitive based modeling and according simulating method, the relative JAVA based algorithm is proposed, which is the foundation of the overall micro device design system.

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II. THE CONSTRUCTIVE VOXEL PRIMITIVE MODELING TECHNOLOGY

The framework of the 3D micro device construction based on the voxel primitive modeling and simulation is shown in Figure 1. The whole design environment involves three levels. The system level is on the top, which focuses on the modeling method on function and behavior. The process level, on the other hand, is on the bottom and works at manufacturability. This paper concentrates on the issues of middle level called device level, on which the activities of the 3D model construction are performed. With the parametric voxel primitives, the rough features are constructed, which consist the original model of micro device. By feature mapping method, the relationships are built up between the system level and the device level. Besides the design rules checking during the primitive modeling procedure, the constraint features are essential for the model optimizing process to improve manufacturability. The constraint features refer to a set of predefined fabrication-oriented features that restrict the geometric and positional parameters of the original 3D model for better manufacturability.

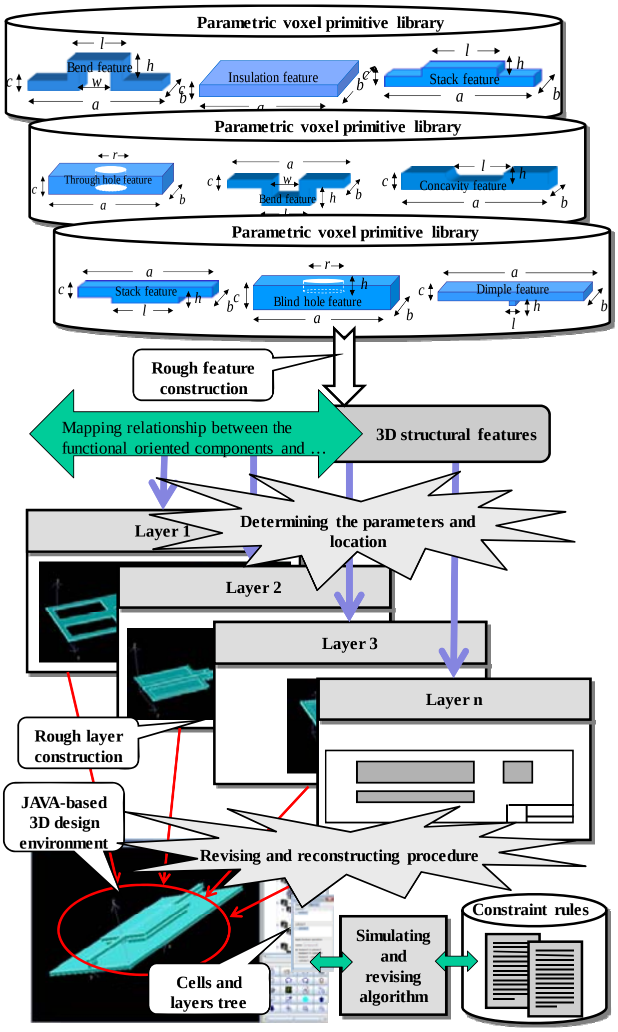

Fig.1 3D Micro Device Construction with the Voxel Primitive Modeling and Simulating Method

A. Voxel Primitive

In spite of the convenience for features to construct 3D model, the generality and reusability are not good enough to store the features directly in the common library because of the relatively complex structure. In contrast, the voxel primitives have the advantage to build up the library as the primary elements. They have more simple shapes that indicate the ability to be parameterized more suitably. They are primitive solids that are common elements to be reused to build up complicated features. Therefore, it is the reasonable way to break the feature up into more primary elements. The mapping relationship is constructed between the bond graph represented components of the upper design level and the function oriented structural features of boundary representation. As the constituent elements of the features, the voxel primitives are fabrication oriented in some sense.

B. 3D Design Envirenment

The Boolean operations allow building up more complicated features with the voxel primitives. The transforming operations allow repositioning the features from a canonical location to the required location. With respect to the irregular shape, because of the characteristic of the surface fabrication, the basic operations, like protrusion based on sketch, are available. To make the 3D environment conform with the JAVA represented data structure, JAVA 3D technology is employed to display the 3D models and render the scene.

C. Simulation and Constraint Rules

The structure and location of the rough feature are revised to optimize the original model because of the lack of assurance of fabrication. The algorithm of model revision is the geometric deduction that involves the simulation processes including deposition, etching and according operations of sacrificial layer. Therefore, the geometric simulation of the processes described above is essential to perform the model revising procedure, which is also the foundation of the following physical simulation with fabricating parameters. The model simulation is more the revising procedure than the fabricating analog to improve the manufacturability. The simulating processes are a set of reconstructing operations to rectify the original structure. The constraint rules are used to restrict the geometric parameters for better manufacturability. Here, MUMPs is adopted as the standard.

III. THE INFORMATION MODEL OF VOXEL PRIMITIVE BASED MICRO DEVICE

A. The Information Framework to Construct 3D Model

The hierarchical organization of the modeling information is shown in Figure 2. There are three levels to deal with the data and operations of different types. The data of the voxel primitive is on the lower level. Above it is the feature level, which involves the features, operations and the relationships. It is the device level that is related to the scene operations. The data structure is implemented with JAVA technology, which is invisible to users. To build up the interactive visualization environment, the 3D display kernel is indispensable. Here, JAVA 3D is adopted as the linkage between the designer application and the low-level data. The observing platform deals with the observation and operation of the designer. To realize the operations like scale and transform, the events of mouse are monitored and the data are transmitted to corresponding module to control the scene as the designer wanted. The designer can retrieve the low level data such as selecting certain faces of one structural layer, which is the common operation for the algorithm of etching simulation.

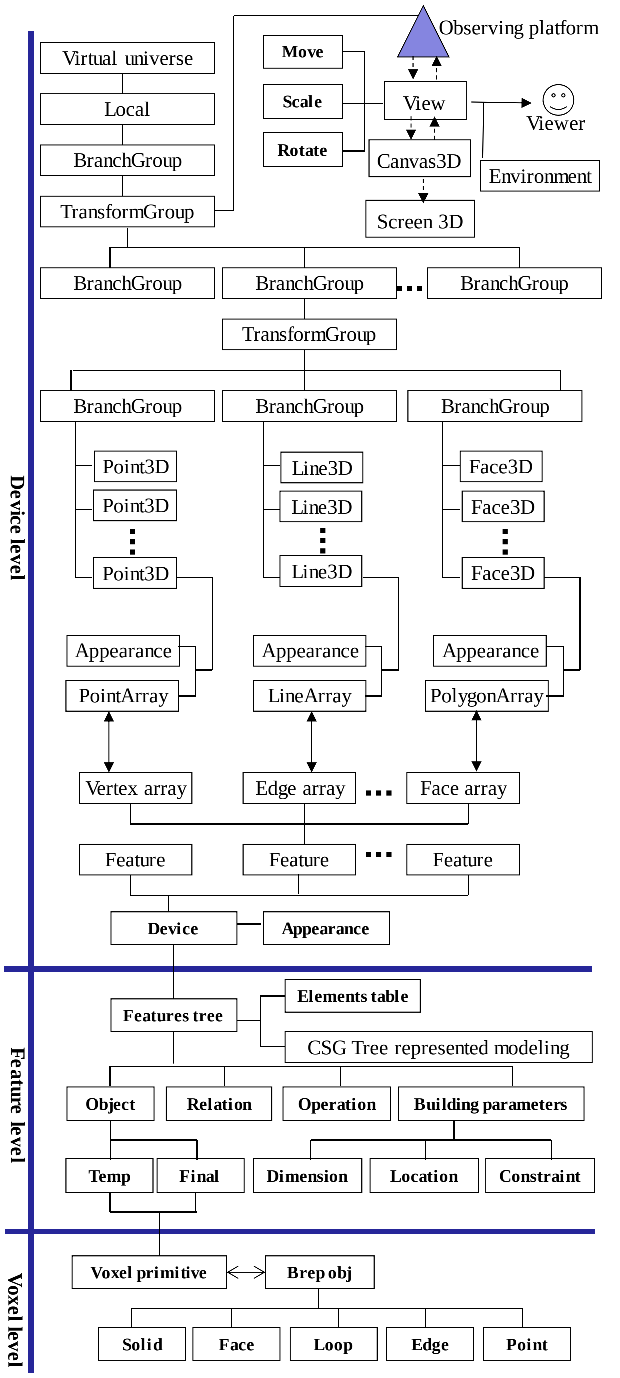

Fig.2 The Hierarchical Organization of the Modeling Information

Figure 3 illustrates the data structure of the voxel primitive based model. The data structure is based on the hybrid modeling technology, which means that the constructing processes is presented by CSG for both the features and the layers, while the inner data structure is boundary representation.

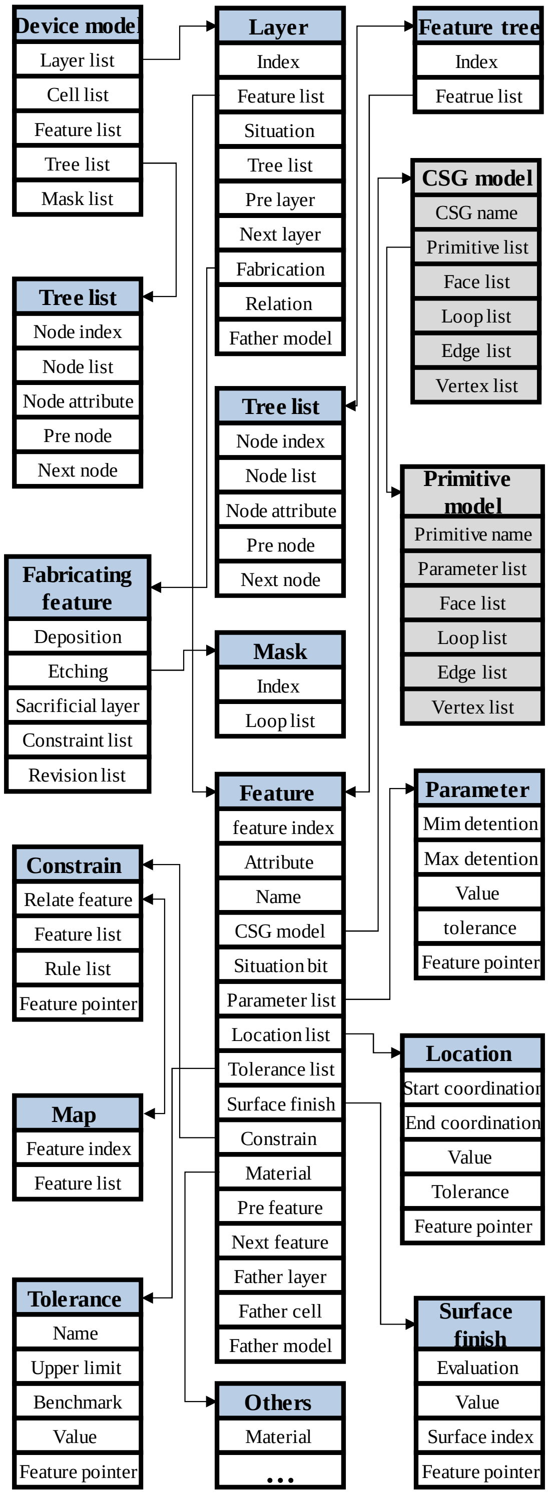

Fig.3 The Data Structure of the Voxel Primitive Based Model

The data structure is implemented with JAVA technology, which is invisible to users. To build up the interactive visualization environment, the 3D display kernel is indispensable. Here, JAVA 3D is adopted as the linkage between the designer application and the low-level data.

B. JAVA 3D Based Visualization

Java 3D is the application programming interface based on the scene graph mode, which is seamlessly integrated with the Java platform. The model visualization by JAVA3D technology is shown in figure 4. The key point of modeling visualization lies in the relationship built between the elements of features and the components of 3D scene.

IV. The Simulating Method for Surface Micromachining Technology

The simulation is for solving the processes-based model reconstruction problem that involves algorithm to simulate the depositing and etching results of the revised structural layer and sacrificial layer. Although the constructing processes are geometric simulation, once the fabricating parameters are concerned, the physical simulation is ready to perform with the geometric foundation. The core of the algorithm is conceptually a set of solid model operations with respect to the optimal parameters.

A. Deposition Process Simulation

Given the i-1th structural layer model revised in the previous step, the ith deposition model Dep_i is built up by using the constructing algorithm of boundary representation solid with the top faces of the i-1th layer and the depositing thickness. Along the depositing orientation, all the grown faces are offset to the location concerned with their grown thicknesses. Then, with these offset faces, the top faces of the i-1th layer and the new generated boundary faces, the deposition model is constructed. To avoid the calculating bug, the simplified trick is employed. With the topological relations remained, the related faces of the i-1th layer model are replaced by the offset faces to construct the regularized model that is the union of the i-1th layer and the ith deposition model. In this way, by the subtraction operation, the deposition model is obtained.

The algorithm for the simulation of deposition process is as follow:

Step 1, extracting the face set from the $Layer_{i-1}$.

$Layer_{i-1}$ is the solid model of i-1th structural layer. The data of face f ($f \in \mathrm{F}_{Layer_{i-1}}$, which is the set of faces of $Layer_{i-1}$) is extracted. Meanwhile, the index of the face $Index_f$ is recorded, which is the flag indicating the replaced face.

Step 2, extracting the loop set L_f from f .

The data of each loop l ($l \in \mathrm{L}_f$) is extracted. Meanwhile, the index of the loop $Index_l$ is recorded, which is the flag indicating the replaced loop.

Step 3, extracting the edge set E_l from l .

The data of each edge e ($e \in \mathrm{E}_l$) is extracted. Meanwhile, the index of the loop $Index_e$ is recorded, which is the flag indicating the replaced edge.

Step 4, evaluating the new edges after deposition.

$v \leftarrow e \cap e.next$

//($e.next$ indicates the next edge of e)

$if\ f_1 \in \mathrm{F\_contact}_{Depi}$

//(f_1 is one of the side faces, to which the halfedge e' belongs)

$f_1 \leftarrow Offset(f_1)$

$if\ f_2 \in \mathrm{F\_contact}_{Depi}$

//(f_2 is the other side face, whose edges involve the halfedge $e.next'$)

$f_2 \leftarrow Offset(f_2)$

$v_{new} \leftarrow f \cap f_1 \cap f_2$

//(evaluating the offset vertex by intersecting three faces)

$e_{new} \leftarrow Offset(e)$

//(reconstructing the new edge by offset the original one after evaluating the new start and end vertex)

$if\ e.next \neq e.initial$

$e \leftarrow e.next$

goto step 3

//(traversing the original edges)

Step 5, evaluating the new loops after deposition.

$l_{new} \leftarrow Offset(l)$

//(reconstructing the new loop by connecting the new edges)

$if\ l.next \neq NULL$

$l \leftarrow l.next$

goto step 2

//(traversing the original loops)

Step 6, evaluating the new faces after deposition.

$f_{new} \leftarrow Offset(f)$

//(reconstructing the new face with the new loop)

$if\ f.next \neq NULL$

$f \leftarrow f.next$

goto step 1

//(traversing the original loops)

Step 7, constructing S_{temp} with $\mathrm{F\_noncontact}$ and F_{new} .

In fact, S_{temp} is enclosed with the grown faces and the unaffected faces.

Step 8, constructing the deposition feature of the ith layer Dep_i .

$Dep_i \leftarrow S_{temp} - Layer_{i-1}$

End Step

To provide the intuitive view of the method, the processes of the simulating algorithm for deposition are illustrated in Figure 4.

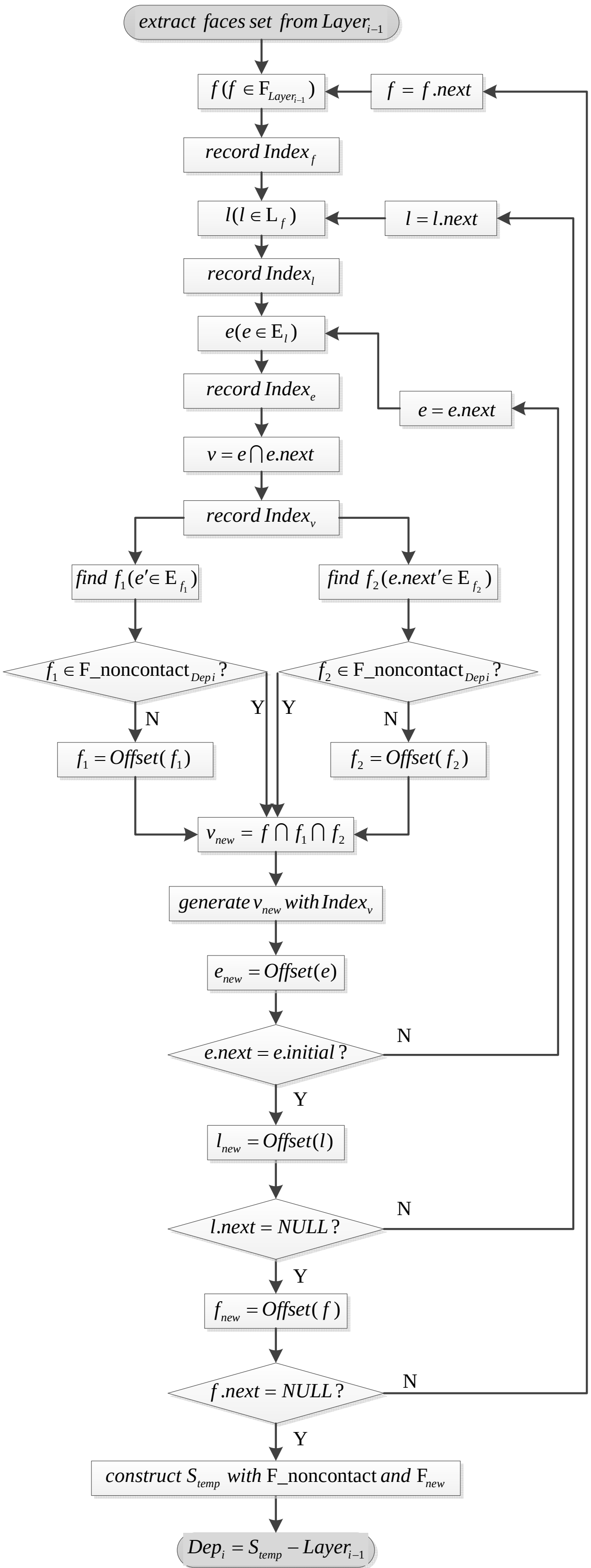

Fig.4 The Algorithm for the Simulation of Deposition Process

B. Evaluating the Data of Mask

To evaluate the data of mask involves the operations on the geometric elements. The geometric viewpoint of constructing the mask set is to reorganize the vertex, edge, loop and the face of the etched solids in order to build up the faces indicating the mask. With these geometric features, the output interface of the CIF file interchangeable as the standard format of mask information is available. The algorithm for mask evaluation is shown in Figure 5.

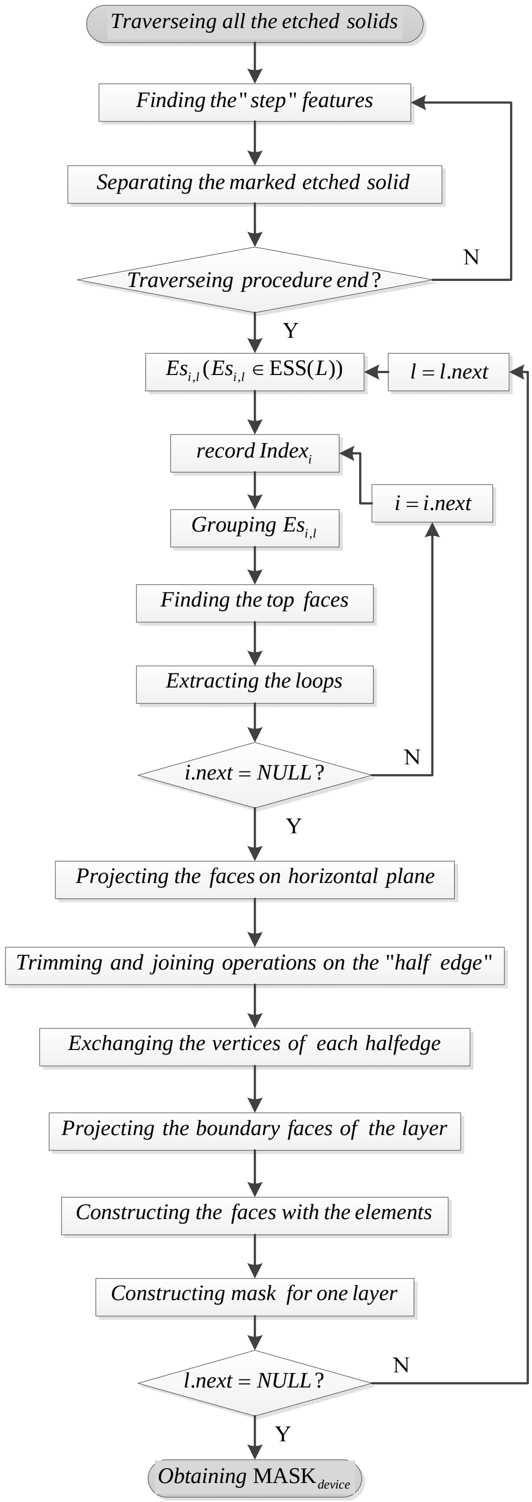

Fig.5 The Algorithm for the Mask Derivation

To derive the mask, there are four aspects of this problem have to be solved. The first problem relates to the indication of multiple etching. Above all, all the etched solids with similar thickness are uniformed and treated as one etching procedure. Then, the "step" structure of the etched solid is found, which indicates the multiple etched results. Therefore, it is separated into parts treated as individual etching procedure accordingly. The etching order depends on the vertical locations. Obviously, the upper parts are etched prior to the lower ones. The second question involves the grouping of the etched solids. The thickness of the etched solid has to do with the etching depth. Thus, the etched solids are grouped by thickness. As a result, the etching feature is related with the arranged group. Simultaneously, the mask is attached to the etching feature as one parameter. The third aspect deals with the data construction of the mask. Firstly, the loops of the etched solids are extracted, which have to do with the constructing procedure of the mask face. The loops belonging to the top faces of the etched solid are traversed. Especially, the trimming and joining operations are performed in the situation of multiple top faces existing. To implement the operations, all the elements are projected to the same horizontal plane. As a result, the information to construct the inner loops of the mask face is obtained. Secondly, the inner loops are constructed by the inverse operation. The inverse operation means inversing the direction of the loops obtained from the etched solids. To implement the operation, the start vertex and end vertex of each halfedge in these loops are exchanged to make the outer loops into the inner loops. Finally, the outer loop of the mask face is build up by projecting the boundary faces of the layer on the horizontal plane. Meanwhile, a trimming and joining operation are carried out if the halfedges have an overlapping relation on the horizontal plane.

Taking the first etched solid of the ith layer $Es_{i,1}$ for instance, the operation is illustrated in Figure 6.

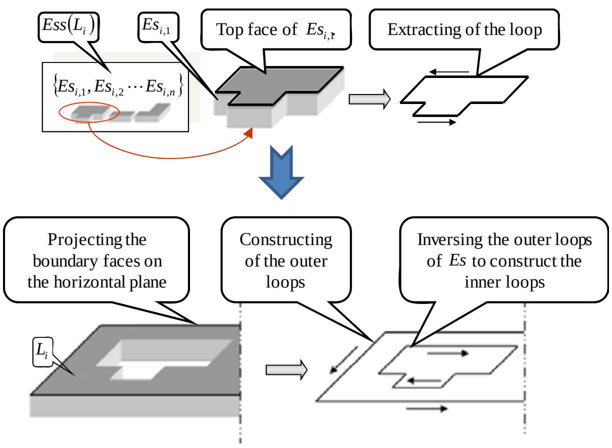

Fig.6 Generating the Data of the Mask Face

For better illustration, as an example, the mask set of the 4th layer of the micro motor and corresponding etched solid set are shown in Figure 7. $mask(Str)_{(4,1)}$ is the first element of $\mathrm{MASK(Str_4)}$. $\mathrm{Ess(Sac_4)}$ is divided into two groups, $Ess(Sac)_{(4,1)}$ and $Ess(Sac)_{(4,2)}$. Accordingly, $\mathrm{MASK(Sac_4)}$ is expressed as $\{mask(Sac)_{(4,1)}, mask(Sac)_{(4,2)}\}$.

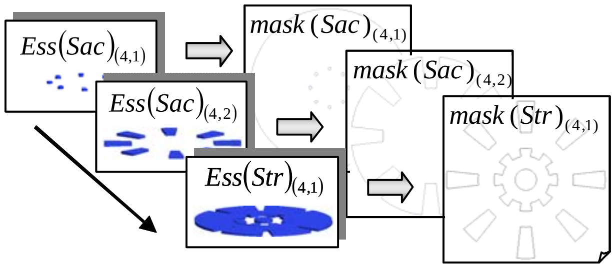

Fig.7 The Mask Set of the 4th Layer of the Micro Motor

In designing stage, function is a main factor we need to consider carefully. Thinking from the viewpoint of process is insufficient with this design mode. Some process problems crop up with the original design model, e.g., the redundancy of the etching features. Therefore, the suggestion from the process planning stage is feedback to the design stage to optimal the original design model. The height of cantilever face and the thickness of the design features are the main parameters for coordination. The aim is to make the vertical parameters of different design features in one layer more uniform. The cooperative module is in charge of the information exchange between the design stage and the process planning stage. The model revision can be transmitted easily in terms of the "command" transferring technology with the "interpreters" in both sides.

C. Etching Process Simulation

In a sense, the etching simulation is the inverse procedure of the mask derivation. However, the mask is revised in advance according to the constraint rules. Therefore, the etching simulation is more the model revising procedure than the fabricating analog. In contrast, the previous mask generation process is based on the original layer model usually with poor manufacturability.

The etching process simulation is carried out by exerting the etching feature on the structural layer, which relates to the operation of subtraction from the perspective of computer graphics. Above all, the etching feature is evaluated. Given the revised mask, the etching feature is built up by the union of all the etched solids, which indicate the etched parts from the structural or sacrificial layer. With respect to each etched solid, the data and topology are derived from the mask and etching parameters.

The algorithm for the simulation of etching process is as follow:

Step 1, inversing the loops of the mask face.

$\mathrm{L}_{etch} \leftarrow Inverse(\mathrm{L}_{mask})$

Where:

L_{etch} is the set of loops belong to the upper face of the etched solid.

L_{mask} is the set of loops enclose the mask face.

$Inverse(\mathrm{L}_{mask})$ means inverse the direction of each loop $l(l \in \mathrm{L}_{mask})$ except the outer loop. As a result, the inner loops turn to outer loops, which enclose the top faces etched solids.

Step 2, extracting the data of one loop $l(l \in \mathrm{L}_{etch})$.

The index of l is recorded.

Step 3, extracting the data of one edge $e(e \in \mathrm{E}_l)$.

The index of e is recorded.

Step 4, offsetting the edge.

$e_{half} \leftarrow Halfedge(e)$

//(e_{half} indicates the corresponding halfedge of e. The operation $Halfedge(e)$ means exchanging the vertices of e.)

$e_{new} \leftarrow Offset(e_{half})$

//(e_{half} is offset along the etching direction to get the new edge e_{new} that indicates the etching boundary of this etched solid. The offset distance is determined by the top face of the etch stop layer.)

Step 5, constructing the side edges.

$e1_{side}.v_{start} \leftarrow e.v_{start}$

//($e1_{side}.v_{start}$ indicates the start vertex of one side edge)

$e1_{side}.v_{end} \leftarrow e_{new}.v_{start}$

$e2_{side}.v_{start} \leftarrow e.v_{end}$

$e2_{side}.v_{end} \leftarrow e.v_{end}$

Step 6, constructing the side loop l_{side} with e_{half}, $e1_{side}$, e_{new} and $e2_{side}$.

The four edges consist the side loop.

Step 7, constructing the side face f_{side} with the l_{side}.

$if\ e.next \neq e.initial$

$e \leftarrow e.next$

goto step 3

//(traversing the original edges)

Step 8, constructing the bottom loop l_{new} and, in turn, the bottom face f_{new} with all the offset edges.

$Dep_i \leftarrow S_{temp} - Layer_{i-1}$

Step 9, constructing the etched solid S_{etch}.

S_{etch} is enclosed with f_{etch}, f_{new} and all the f_{side}.

$if\ l.next \neq NULL$

$l \leftarrow l.next$

goto step 2

//(traversing the original loops)

Step 10, constructing the etching feature of the ith layer Etc_i.

$Etc_i \leftarrow \cap\{S_{etch}\}$

Step 11, reconstructing the structure layer Str_i.

$Str_i \leftarrow Dep_i - Etc_i$

End Step

To provide the intuitive view of the method, the processes of the etching simulating algorithm are illustrated in Figure 8.

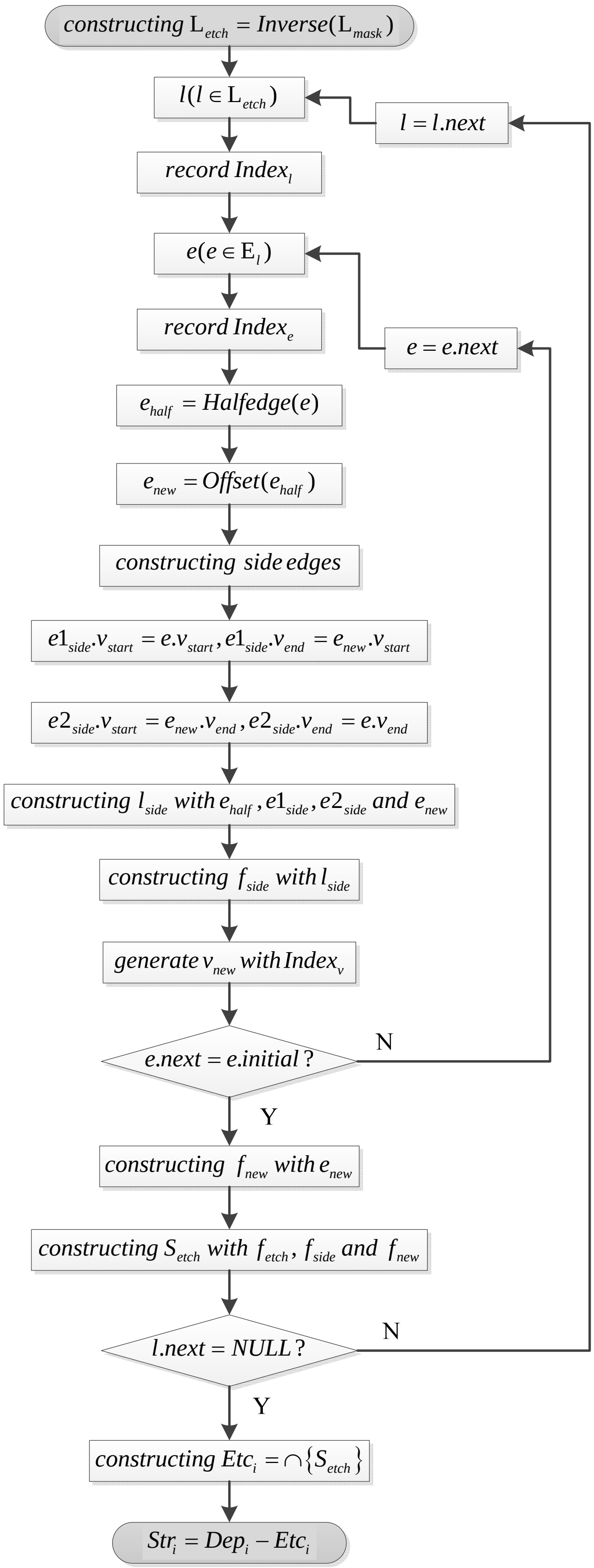

Fig.8 The Algorithm for the Simulation of Etching Process

V. IMPLEMENTATION

The implementation of the voxel primitive based modeling and simulating method is performed by JAVA technology. Taking the micro motor as the running example, Figure 9 shows the snapshot of the model construction and process features derivation that is based on the simulating method described above. By the cooperative activities management module, the original 3D model constructed with voxel primitives is revised following the rules of constraint features to improve the manufacturability.

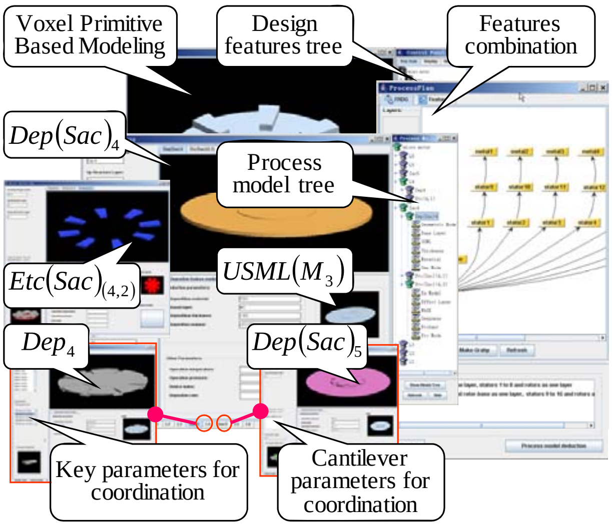

Fig.9 Implementation of the Method

VI. Conclusion

Above all, the overview of the modeling evolvement of micro device is presented to show the state of the art: where the hindrance of feature modeling for micro device lies and how our work deals with the issue. On one hand, the feature modeling technology in some ways improved the designing efficiency. On the other, the model is hardly conformed to the fabricating processes. The purpose of this thesis is to create an architecture that combines the primitive based 3D modeling technology with the surface micromachining process. To accomplish the 3D model environment, the voxel primitive library was built. Based on the voxel primitives, feature constructing and layered model generating strategies were presented, which involve the parametric solid modeling and locating. Besides the low level data structure, the visualization of the model is accomplished by deploying the JAVA3D technology. The model simulation is more the revising procedure than the fabricating analog to improve the manufacturability. As the modeling foundation of the overall design system, this paper focuses on the model constructing and simulating algorithm with JAVA technology. This method may give some indication of the balance between the efficiency and manufacturability, which is the inevitable issue emerging with the new design methodology.

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