Title:
A Feature-based Automatic Model Construction Method in CAD for Material Distribution Structures

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Introduction:
The material distribution structure has been widely applied in research and industry, where the entire domain of the macrostructure has been equally or non-equally divided into several subdomains and each subdomain is regarded as a design space for local material distribution in the microstructure. Considering manufacturability constraints [1] and periodic boundary conditions [2], the geometries of microstructure design are usually parameterized and may have repetitive features in global spatial distribution for the macrostructure.

Over the past few decades, the data of material distribution structures were stored in a 2D or 3D matrix as the physical density field and such data can be plotted in software with matrix visualization functionality such as Matlab [3]. The design domain was discretized into small squares or cubes as basic elements and a marching cube algorithm [4] was designed for the plot. In this way, the visualization of material distribution structure models was realized. Then, an STL writer was applied to the matrix, where the matrix data was post-processed and the model was converted to STL format, which is friendly to manufacturing such as 3D printing [5]. However, for structural behavior analysis such as finite element analysis and thermal expansion simulation, the data and the model are not sufficient enough in numerical simulation environments. First, a good CAD geometry file is preferable in a simulation system, where a model with solid geometry will be much more compatible to be imported, simulated and exported than the tessellation model. Second, the structure geometry might be further modified based on the simulation results. Although some software provides users with auxiliary model conversion functions which may help to convert an STL file to a CAD geometry model, the converted model is not feature-based, which makes it not well-parameterized for model modification and not compatible with some CAD post-processing operations such as blending and chamfering. Therefore, a feature-based parametric CAD model of a material distribution structure is preferred in the numerical simulation environment for structure behavior analysis and further modifications of the model geometry. To the authors' best knowledge, such parametric CAD models are still constructed manually in most cases, which is tedious and time-consuming.

In this paper, an automatic model construction method for a feature-based parametric CAD model of the material distribution structure is proposed. The proposed method aims to improve the CAD modeling efficiency of a complex structure geometry with parameterized and spatial repetitive features of its microstructure geometry elements. The constructed CAD model is parametric and every component microstructure is editable for its design parameters. The model is also well-compatible with a numerical simulation environment and further geometry modifications are easy to be implemented.

Main Idea:

The proposed automatic CAD model construction method can be divided into 3 substeps and the flow chart of the proposed method framework is shown in Fig. 1. First, the data of the material distribution structure is mapped in a new format and a file is created to store the information. Second, the microstructure geometry elements are received from the structural optimization result and classified into several subtypes according to their geometric characteristics and are properly parameterized, encapsulated, and integrated. Finally, a plug-in of a CAD system is developed to read the data file and automatically construct the CAD model.

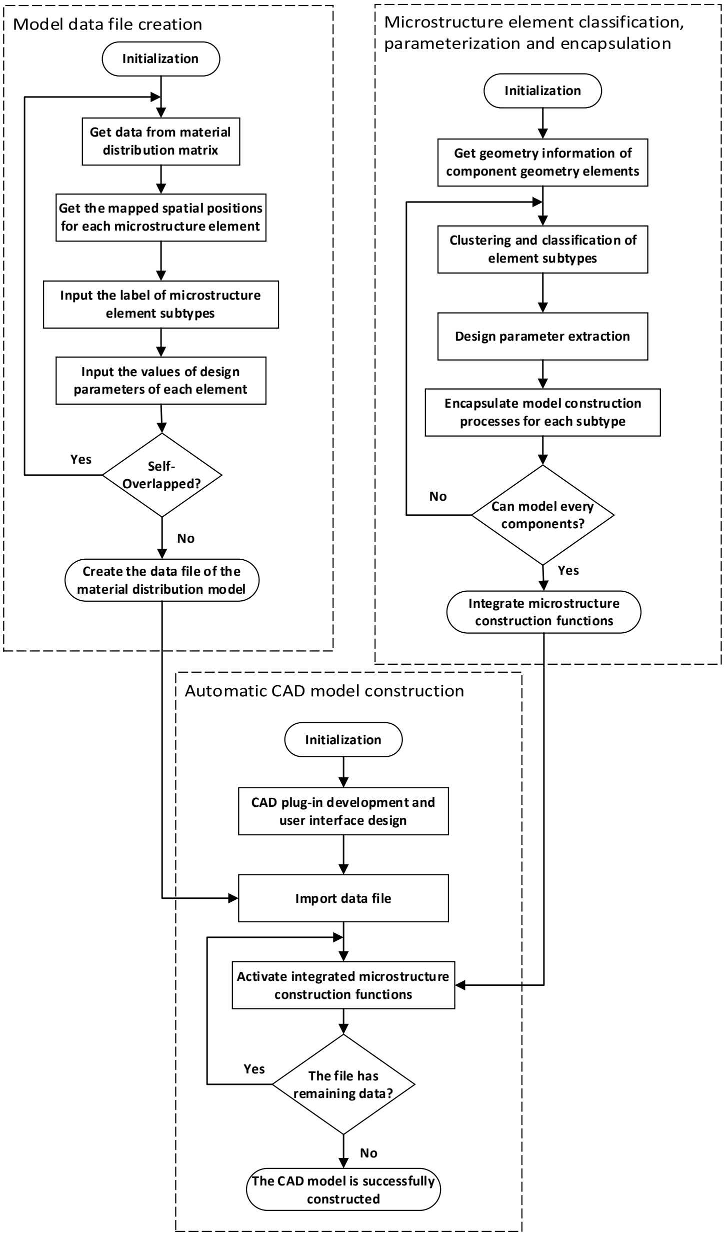


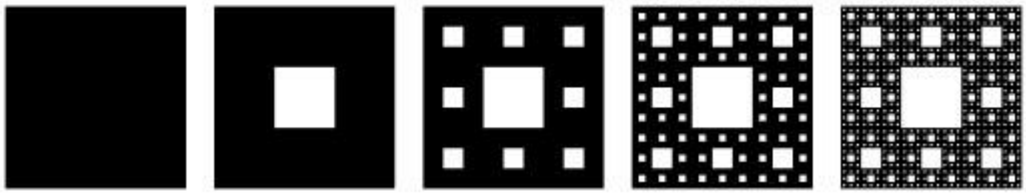
Fig. 1: Flow chart of the proposed method framework.

Model data representation and data file creation

In this subsection, a new mapping relationship between the geometry of the material distribution model and the material distribution data is introduced. The new data format originates from traditional data representation and more information is added to improve design flexibility.

In the traditional data representation of a material distribution structure, a 2D or 3D matrix was used. The matrix was a binary matrix with all the elements taking the value of either 0 or 1. Here, the value 0 means the region should be left void without being filled with material and value 1 means the region should be filled with material. Taking the models of Sierpinski Carpet [6] as an example (see

Fig. *2*), a 2D binary material distribution matrix was used to represent a model of each iteration level.



(a)

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

(b)

(c)

Fig. 2: The Sierpinski Carpet and its data representation: (a) The models of Sierpinski Carpet, (b) The binary matrix representation of the 1st iteration model, (c) The 1st iteration model of Sierpinski Carpet.

The traditional data representation was simple, and the modeling process was of high efficiency. However, the microstructure elements were not parameterized, and their geometries would be fixed after being defined. To improve the design flexibility of the constructed model, the component microstructure elements are classified into many subtypes according to their geometry feature and each subtype is parameterized with its unique design variables. In our proposed method, the material distribution model is mapped by a material distribution list with the information on spatial distribution, microstructure element subtype and relevant parameter list of the related design variables for each of the component microstructure elements. The new data format requires more storage space because more parameters are included. However, compared with the size of the model, such an increase in storage resource consumption is negligible. Here, we take the 1st iteration model of Sierpinski Carpet as an example (see

Fig. *2*(b) and

Fig. *2*(c)). In our proposed method, its component microstructure will be rectangles with variable lengths and widths. The spatial distribution information is extracted from the original matrix data, where the (i, j) element of the original matrix is regarded as a rectangle element with its centroid position of (i-1,j-1) in the 2D Cartesian coordinate system. The material distribution list of the 1st iteration model of Sierpinski Carpet is shown in

Tab. *1*. A data file is then created and stores such information of the model.

Element Number	*Centroid Position*	*Element Type*	*Length (mm)*	*Width (mm)*
1	(0,0)	Rectangle	1	1
2	(1,0)	Rectangle	1	1
3	(2,0)	Rectangle	1	1
4	(0,1)	Rectangle	1	1

5	(1,1)	Rectangle	Null	Null
6	(2,1)	Rectangle	1	1
7	(0,2)	Rectangle	1	1
8	(1,2)	Rectangle	1	1
9	(2,2)	Rectangle	1	1

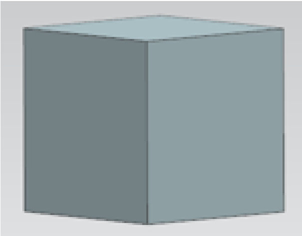
Tab. 1: Material distribution list of the 1st iteration model of Sierpinski Carpet.

Microstructure element classification, parameterization, encapsulation, and integration

The component microstructure elements are classified into many subtypes according to their geometry characteristics and each subtype is parameterized with its unique design variables. For example,

Fig. *3* shows three subtypes of basic 3D geometry elements, a block, a sphere and a honeycomb cell and

Tab. *2* shows their design parameters respectively. For each type of geometry element, an associative parameter list is encapsulated as the input parameter set for a microstructure model construction, and these design parameters are initialized with default values if not input by the user to improve the robustness of the model construction algorithm. Finally, the construction functions of all the subtypes are integrated as a function named *BuildAMicrostructure()* with input data as follows: *BuildAMicrostructure(Element Type, Centroid Position, Sketch Plane, Design Parameter List).*


(a)

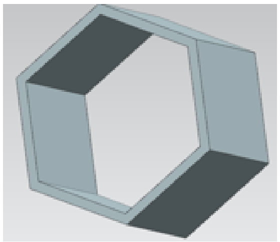
(b)

(c)

Fig. 3. Three subtypes of basic 3D geometry elements: (a) A block, (b) A sphere, (c) A honeycomb cell

Type	*Design Parameters*		
Block	Length(L)	Width(W)	Hight(H)
Sphere	Radius(R)		
Honeycomb cell	Incircle radius(r)	Circumcircle radius(R)	Extruded Length(L)

Tab. 2: Design parameters of three geometry elements.

Automatic CAD model construction

A plug-in is developed in a CAD system, which can read the data file of the material distribution list. A traverse algorithm is designed for the CAD system to read every line of the data file. While reading each line of the data file, the *BuildAMicrostructure()* function is activated with the inputs as the current line of the data and a parameterized microstructure CAD model is constructed automatically.

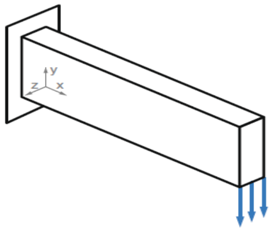
In our proposed method, more information is added and stored. The efficiency of the modeling process is slowed down because more design parameters are included. However, the model constructed is a feature-based parametric model, which has better compatibility, editability and design flexibility.

Case Study:
In this section, the proposed method is validated with an automatic CAD model construction of a topology optimized 3D cantilever. Following the numerical example of Kai Liu et al [3], a cantilevered beam is optimized with the objective of minimum compliance under the maximum material volume constraint. The design domain is a 60mm×20mm×4mm block which is fully constrained in one end and a unit distributed vertical load is applied downwards on the lower free edge (see Fig. *4*(a)). The domain is meshed by 1mm size cubes of 60×20×4. The maximum volume fraction is set to be 0.3 and the filter radius is 1.5 element sizes.

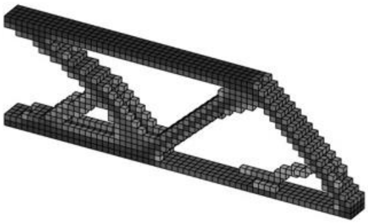
The optimization process and result are reproduced by the authors. The design has been tested to be mesh independent.

Fig. *4*(b) shows the Matlab plot of the physical density field matrix.

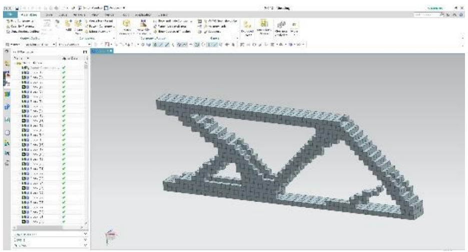
Fig. *4*(c) shows the CAD model of the topology optimized structure based on the proposed method. Every geometry element of the CAD model is set as a block of 1mm×1mm×1mm. The model constructed is a feature-based parametric CAD model with 1434 block features and the parameters (length, width, and height) of each block element can be edited by the user for post-processing. The CAD model is automatically constructed within 30 seconds which demonstrates our proposed method is of sufficient modeling efficiency. Compared with the Matlab plotted optimized structure, the constructed CAD model is the same in geometry which validates our method is applicable.



(a)



(b)



(c)

Fig. 4: Topology optimization of a 3D cantilever beam: (a) Design domain and boundary conditions, (b) Matlab plotted optimized result (reproduced), (c)Automatic CAD model construction.

Conclusions:
In this paper, an automatic CAD model construction method for material distribution structures is proposed as conceptual framework, developed in a CAD system and validated by a case study. New data format is applied for representation of material distribution structures. Microstructure elements are classified, parameterized, encapsulated and integrated in a CAD local microstructure construction function. A plug-in is developed in a CAD system to read the proposed data file and activate the integrated microstructure construction function to realize automatic CAD model construction for the entire material distribution structure. The CAD model constructed is a feature-based parametric model which is compatible with a numerical simulation environment and the model is easy to be further modified. In our case study, the proposed method is validated to be of sufficient design flexibility and

modeling efficiency. The proposed modeling method can also handle more complex cases for microstructures with more design parameters.

In the future, a library of commonly used parametric geometry elements will be integrated into the microstructure construction function and parameterized multi-variable lattice structure [7] CAD models will be automatically constructed for further validation and application of our proposed method.

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