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Automatic mesh generation of hexahedral elements using intelligent local approach and its application to nuclear structural components

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ABSTRACT
This paper describes a new automated mesh generation method named Intelligent Local Approach, which well controls both size and aspect ratio of quadrilateral element for 2-D plane and those of hexahedral element for 3-D solid, respectively. Here elements are created sequentially, considering local information on geometrical constraints and element quality surrounding one to few relevant elements to be created. A user can specify the two numerical fields, (1) a distribution of element size and (2) that of element aspect ratio. The algorithm also possesses a spatial distribution of priority for element creation. To efficiently deal with various complicated geometrical constraints for high quality quadrilateral or hexahedral elements in a local region, a fuzzy knowledge processing technique is effectively utilized. The algorithm is also well coded, effectively using an object-oriented programming technique. Fundamental performances of the algorithm are examined through some examples.

INTRODUCTION

Unstructured mesh generation for the FEM and the FDM is in general very labor-intensive and time-consuming. Numerous research activities have been devoted into the development of automatic mesh generation techniques. The Delaunay method, which automatically generates triangular elements for 2-D case or tetrahedral elements for 3-D case for a given set of nodes, has been well studied, and has already been implemented in several commercial systems. The present authors have developed a fully automatic mesh generation system for triangular or quadrilateral elements for 2-D plane and 3-D shell, and tetrahedral elements for 3-D solid using the fuzzy knowledge processing and some computational geometry techniques [1-3]. Thus, we can conclude that fully automatic mesh generation techniques for triangular elements and tetrahedral elements have already been established. On the other hand, the automatic mesh generation of quadrilateral elements and hexahedral elements is still an open problem, though these elements are strongly demanded for some problems. This is because compared with triangular and tetrahedral elements, those elements are more suitable to strongly nonlinear problems, and large aspect ratio elements are usable. For example, some automatic mesh generation systems such as HEXAR [4] can indeed generate hexahedral elements within an arbitrarily shaped domain. However, these systems cannot control element size and aspect ratio as human does manually or as human desires.

To solve such difficult problems, this paper proposes a new automatic mesh generation algorithm named Intelligent Local Approach (ILA), which well controls size and aspect ratio of quadrilateral or hexahedral element simultaneously.

BASIC CONCEPT OF ILA

The ILA was invented by analyzing human's generation process of quadrilateral or hexahedral element. As schematically illustrated in Fig. 1 it creates elements sequentially, by collecting local geometrical information and applying the fuzzy knowledge processing for the information . In the ILA, a closed volume to be divided into elements is first defined by a connected set of segments or quadrilateral faces as shown in Fig. 2, which is named "front boundary". The "Local" geometrical information includes segment lengths and angles of segments and so on. The "Fuzzy" knowledge processing is then applied to the following criteria corresponding to mesh quality : (a) proper angle ?, (b) proper size ?, (c) proper aspect ratio ? The whole process of the ILA consists of the following subprocesses :

(1) Collect geometrical information from a local region where one to few elements are generated.

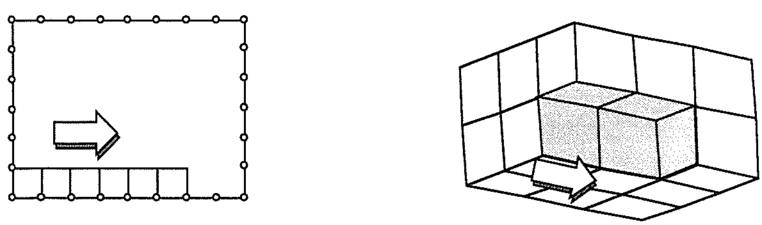
(2) Classify the geometrical situation in the local region into several categories or refine categories based on the local geometry information.

(3) Decide a node location to be created applying the fuzzy knowledge processing to the local geometry information, and generate elements.

(4) Repeat (1) to (3) subprocesses until a domain is full of quadrilateral or hexahedral elements.

DETAILS OF ILA

In this section, The basis of element creation is first described. The procedure to determine a position of node using the fuzzy knowledge processing is then described, including numerical fields of aspect ratio, element size and order of element creation. Some additional local mesh adjustment techniques such as insertion of irregular element and refinement of sharp angle of the front boundary are also described.



Quadrilateral Element (2D) **Hexahedral Element (3D)**

Fig.1 Sequential Node and Element Creation

Collection of Local Geometrical Information and Categorization

The ILA first requires a set of segments to define a whole model shape, i.e. surface line (2-D case) or surface area (3-D case), as shown in Fig. 2. Then the mesh generation is conducted in the following four steps.

(1) One segment on the model surface, i.e. a part of front boundary is selected. Here one to few elements will be created.

(2) Geometrical information of several segments near the selected segment is obtained. The information includes lengths of the segments and angles between two adjacent segments.

(3) According to the angle between the selected segment and its adjacent segment, the geometrical situation in the vicinity of the segment is classified into the following five basic categories as shown in Table 1. In C1, the angle is not divided. In C2,

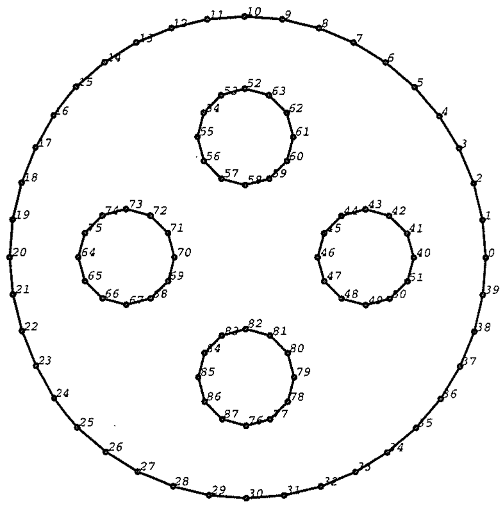


Fig. 2 Front Boundary in 2D

Table 1 Categorization

Number of Divisions	An Angle of Two Segments (degree)	Category
1	45 - 105	C1
1 or 2	105 - 155	C12
2	155 - 200	C2
3	200 - 300	C3
4	300 - 360	C4

C3 or C4, the angle is divided into either two, three or four smaller angles, respectively. In C12, the angle is divided into several angles, depending on other geometrical factors.

(4) One node and one segment are newly created in either C2, C3 or C4. One node, two segments and one element are newly created in C1.

The five categories mentioned above require only the angle data between the segment selected and its adjacent segment. In reality, the present algorithm can also deal with more complicated geometrical situation which requires several angles obtained from a wider area.

Fuzzy Knowledge Processing

According to the categorization at the first step mentioned previously, the number of nodes and that of segments to be created are determined. The appropriate locations of the new

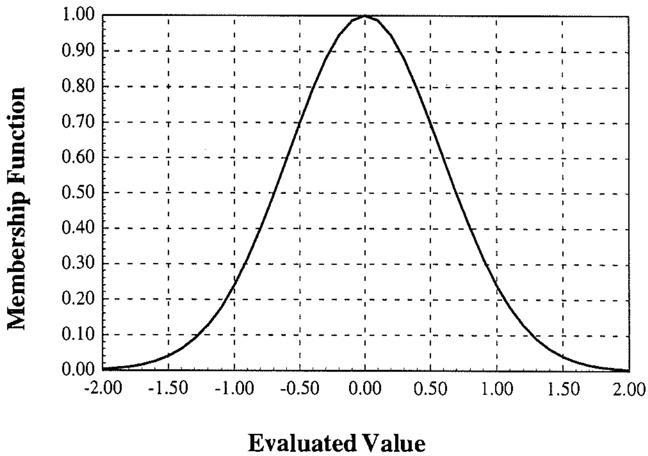


Fig. 3 Example of Membership Function

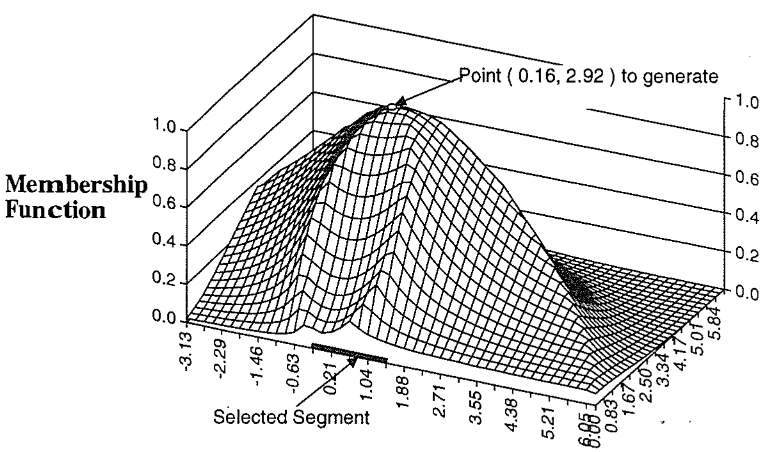


Fig. 4 Product Operation of Two Membershiop Functions

nodes have to be then determined. For this purpose, the fuzzy knowledge processing is effectively employed to take into account multiple different criteria for element quality and mesh specification.

"Appropriateness" of node location can be measured in terms of those of shapes and sizes of quadrilateral or hexahedral elements. Angles between two adjacent segments, segment lengths, aspect ratios of elements to be created are considered simultaneously. They are well expressed in terms of the membership functions of the fuzzy knowledge processing. They are utilized as follows.

First assuming a candidate location for a new node, we evaluate shapes and sizes of virtual elements to be created from the new node. Second, we evaluate the "appropriateness" of the candidate location through the fuzzy set operation for different criteria for "appropriateness" of element shapes and sizes. Figure 3 shows an example of the membership function, i.e. that for expressing the appropriateness of angle of segments. Figure 4 shows the membership function to express the "appropriateness" of the 2-D candidate location near the segment selected. This figure is obtained through the product operation for multiple different criteria of mesh quality, each of which has the membership function as shown in Fig. 3. A new node is then generated at the location where the membership function takes the largest value.

In general, characteristics of any system using the fuzzy knowledge processing depend on shapes of the membership functions employed. However in the ILA, the shapes of membership functions are not so important. We simply use membership functions with a normal distribution as shown in Fig. 3.

Numerical Fields

A user can provide his desire on mesh quality into the ILA algorithm, through an interactive definition of the two different numerical fields. The one is a distribution of element size, while the other is that of aspect ratio of element. Element distortion can also be avoided automatically as much as possible, owing to some embedded information on element quality. In addition, the system possesses the third numerical field to control the order of element creation. We name the last numerical field as "Potential", which is illustrated in Fig. 5. Owing to this potential field, the element is created starting from the bottom (a location with the lowest potential value) to the top (that with the highest potential value) of the geometry as if water is fulfilled in a vase. The three numerical fields are discretely represented on a simple uniform grid. Each grid point has three different numerical values for the fields. A value at any position between grid points is easily interpolated from values on the grid points.

The numerical fields are considered into the construction of membership functions mentioned previously.

The numerical field for element size determines the element sizes to be created at some location. The position determining element size is the middle of a segment (2-D case) and the gravity center of a quadrilateral surface (3-D case).

The numerical field of element aspect ratio can also be defined in the same way.

EXAMPLES

Fig.6 shows only examples of quadrilateral meshes generated by the ILA. Fig. 6(a) shows the mesh for a triangular domain. Fig. 6(b) shows the mesh for a square domain, while Fig. 6

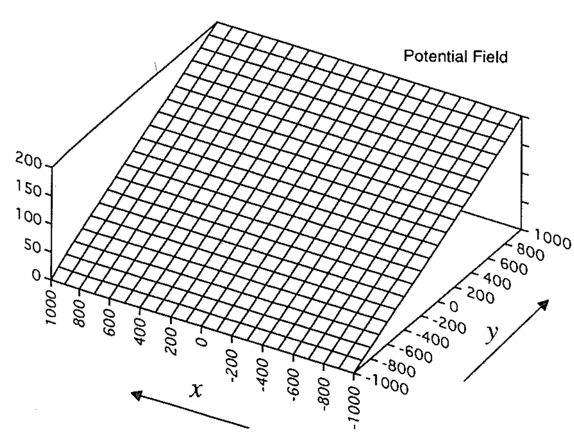
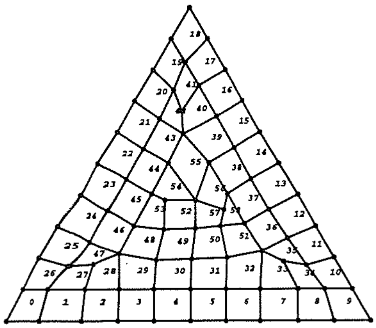
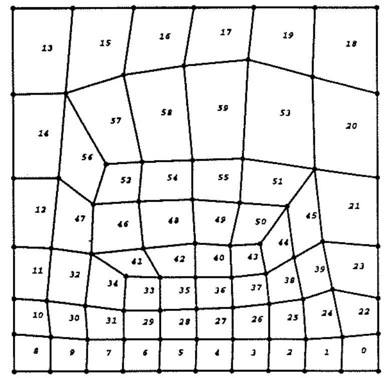


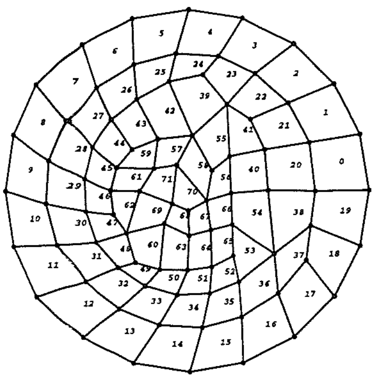
Fig. 5 Simple Ascending Numerical Potential Field



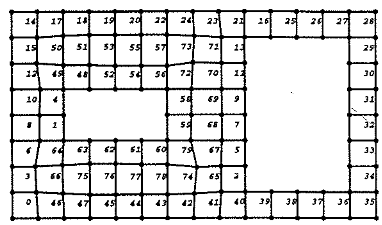
(a) Triangular Domain



(b) Square Domain



(c) Circular Domain



(d) Rectangular Domain with Two Holes

Fig. 6 Examples of Mesh

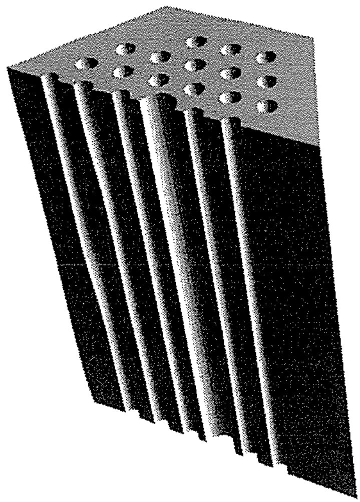
(c) that for a circular domain. Fig. 6(d) shows the mesh for a rectangular domain with two rectangular holes. Here only uniform size and aspect ratio of element are specified. In all the cases, appropriate quadrilateral elements are generated. The present algorithm is basically applicable to hexahedral mesh generation through only slight modification. Such modification is now in progress.

Application to Nuclear Structural Components

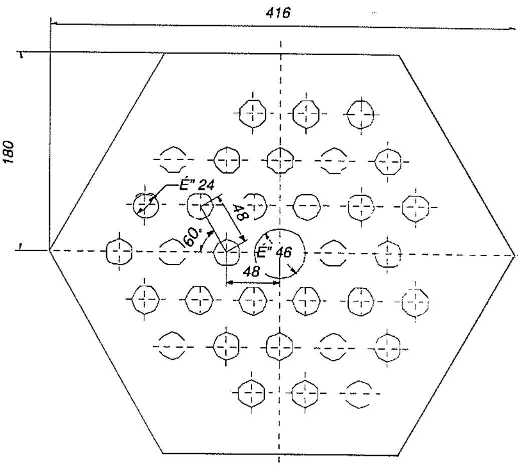
The present ILA is the aggregation of very simple rules and can be extended to 3-D hexahedral problems easily. Fig.7 (a) and (b) show that an analysis model of High Temperature Engineering Testing Reactor (HTTR) graphitic block. The structure holds fuel assemblies. 2-D initial model to be meshed is shown in Fig.7 (c). Examples of mesh generation of the block in 2-D and 3-D will be presented.

CONCLUSIONS

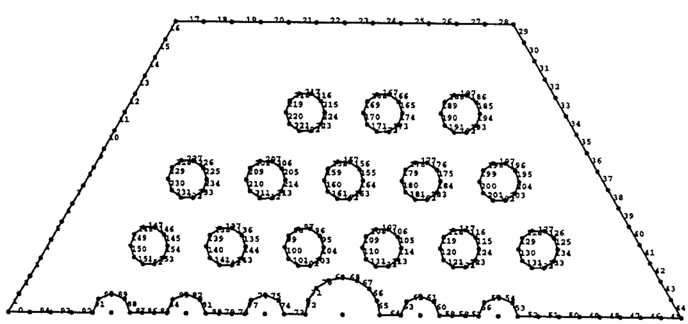
In this paper, we propose the new mesh generation algorithm, named Intelligent Local Approach, which can automatically controls size and aspect ratio of quadrilateral or



(a) 3-D Illustration of Analysis Model



(b) Specification of Analysis Model



(c) 2-D Boundary Segments for Mesh Generation

Fig.8 HTTR Graphitic Block Modeling

hexahedral elements, with maintaining element quality.

In order to deal with multiple complicated criteria for geometrical constraints and element quality, the ILA effectively employs the fuzzy knowledge processing. Its fundamental performances are demonstrated through some mesh generations.

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