Topological Relationship Identification in 3D Cadastre

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Key words: 3D Cadastre, 3D Topology, 3D Property Unit, Validation

SUMMARY

With the accelerated urbanization process, the trend of three-dimensional land use makes the traditional model of 2D cadastral management encounter challenges, because of insufficiency to express in 3D. Therefore, the 3D cadastre and related concepts have been proposed. The breadth and depth of its research are gradually broadened and refined. Within all the studies, the core concept of the "cadastre" is not changed, the core purpose of which is to "guarantee the legitimate geo-space for the owner of property units", and to ensure that each property unit, whether it is two-dimensional or three-dimensional, is unique, non-overlapping. We can understand the “legitimacy” characteristics from two aspects: 1) The reliability for each property unit itself, that satisfies the definition of property unit, i.e., the property unit should be connected, closed and homogenous; 2) From the space view, a property unit is unique and occupies its space exclusively, and there is no overlap among them.

Therefore, in cadastral management work, managers must preserve the inviolability of the legitimate geo-space. In a 2D cadastre system, the main solution to guarantee a unique geo-space for every property unit is topological checking. But in 3D status, the situation managers have to face more complexity than with 2D cases. This is a technology problem, which should be solved with help of computational geometry, topology rules, theEuler–Poincaré formula etc. Some people have done research in these areas such as Verbree and Si(2008), Kazar et al. (2008), Brugman et al. (2011), Thompson and Van Oosterom(2011), and Karki et al. (2011).

In this paper, an approach based on a topology construction algorithm is introduced to check the validation of each property unit and among them. In other words, this paper mainly focuses on the topology checking among polyhedra in 3DGIS systems. Firstly, 34 topological relations among property units, which are classified as either correct relations or incorrect relations, are described in a 9-intersection model matrix. As to correct relations, they are sample relations to prove property units’ legitimacy. Conversely, incorrect relations explain their illegality. Secondly, it is elaboratedhow to identify these topological relations, which is the focus of the paper. At the end, an introduction is given regarding the 3D cadastre system in Shenzhen, China.

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1. INTRODUCTION

With the accelerated urbanization, it is much more obvious that 3D land use is employed. Its important characteristic is diversification of property right in vertical direction, i.e. land could be used and exploited above, on or below the land surface respectively and belongs to different owners.Traditional cadastral systems (2D cadastre) could not reflect the true situation. In order to overcome the situation, 3D cadastre is proposed and the corresponding cadastral management system also slowly becomes a real demand. A2D/3D cadastre hybrid management system is the best solution to deal with the current situation of complex land use. As a cadastral system, its core still has not changed, which is to guarantee the unique and exclusively legitimate geo-space of obligees.The difference to a 2D cadastre system is that the space is not a 2-dimensional but a 3-dimensional one. As a property unit that spaceis called 3D parcel.

A property unit is a closed legitimate geo-space. We can understand the "legitimacy" of each property unit from two aspects: 1) The reliability for each property unit itself, that satisfy the definition of property unit, that's, the property unit should be connected, closed and homogenous; 2) From the space view, property unit is unique and occupies its space exclusively, and there is no overlap among them.

Both two aspects are related to the validation of property units. The first aspect can generally be resolved with topological rules and the Euler-Poincaré formula. As for the second aspect, in the traditional 2D cadastre management we can generally use topological checking methods.Their core idea is to identify topological relations between different polygons. In this paper the topological relations are based on the interior, boundary and exterior of the geometric primitives, and are described in the 9-intersection model matrix. For 3D cadastre, the same situations are faced; furthermore, the identification/verification of topological relations between 3D units is more complex and difficult than that in the two-dimensional case. The solution of this problem is the core content discussed in this paper based on the precondition that the first aspect has been solved, namely property units are all reliable by themselves.

Before identifying the topological relations we must first make clear which topological relations need to be identified. From the point of view of a formal description model for topological relations, this problem is equivalent to thedetermination of the granularity problem in the description of topological relations. The different levels of granularity will bring about different numbers of topological relations. As to granularity, it is the extent to which a system is broken down into small parts, either the system itself or its description or observation. It is the extent to which a larger entity is subdivided. For example, a yard broken into inches has finer granularity than a yard broken into feet (Wikipedia,2012). In other words, for the topology relations view, the granularity is more detailed, if the number of identifiable topology relations is greater and the detail of description finer.

At the moment theoretical research about formal description models of topology mainly describes relationships among two-dimensional polygons. The various models are continuously improved, attempting to describe more topological relations in a more detailed granularity.But if the granularity is finer, there are more types of topological relations and the description can never be exhaustive.

If this problem is transfered to the three-dimensional space it will become more complex. On one hand the topological elements involved will increase, but on the other handthe variety of complex situations is not endless. As a consequence some scholars have pointed out that the exhaustive description of the possible topological relations among all objects is valueless, only the practical ones are of interest to users and therefore desirable.

This paper aims to describe the topological relations among 3D property units. Before determining the granularity of description, two factors should be considered: 1) The correct topological relations between 3D property units. The correctness indicates that they should not overlap with each other. As a consequence there are two types of topological relations among them: “touch” and “disjoint”. 2) Incorrect topological relations, which violate the definition of property units. The interiors of property units intersect with each other, and the topological relations include “equivalence”, “intersection”, “overlay”, and “inclusion”.

The paper focuses on the description of correct topological relations in finer granularity. On one hand, reasonable description and identification of all possible topological relations may ensure the consistency of the spatial representations of 3D property units, and thus prove their legitimacy. After identification, the results should be represented by the underlying topological data model. On the other hand, reasonable descriptions and identification of all possible topological relations enable further spatial analysis.

For incorrect topological relations, the description granularity will be as simple as possible, because identifiable incorrectness of topological relations is the demand for validation, which does not need detailed granularity.

Finally, on the basis of the determined description granularity of the possible topological relations among property units, the paper analyzes the corresponding identification methods. The recognition of correct relations is equivalent to the issue of the topological construction of 3D property units, and should be represented in basic topological data structures; while for the verification of incorrect relations, it is of no use to store and deliver that information, it will provide technical support for the 3D cadastre management to exclude invalid property units.

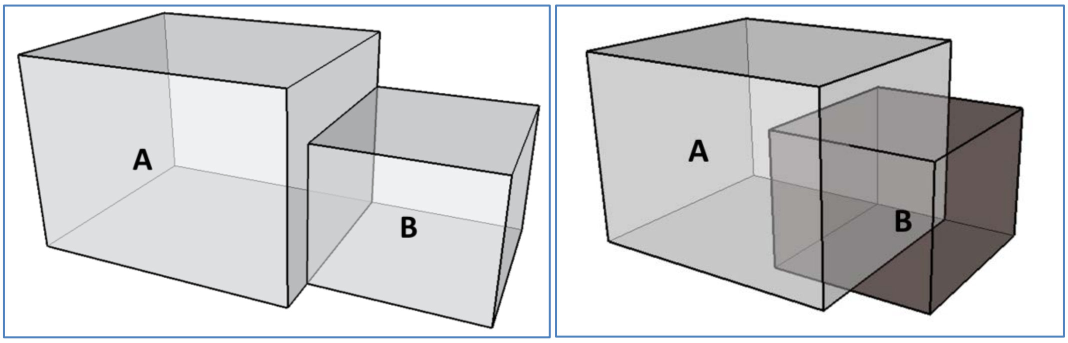


Figure 1. Correct topological relation (left) and incorrect topological relation (right)

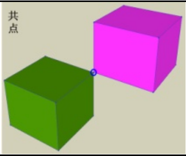
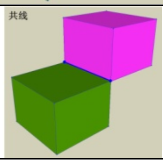
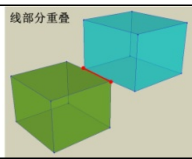
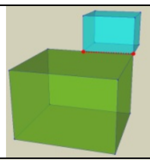
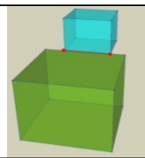
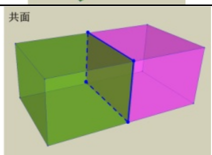
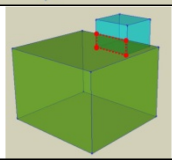
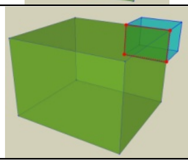
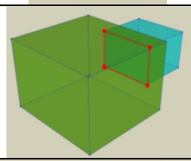
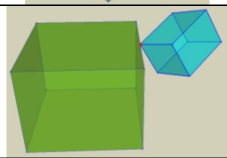
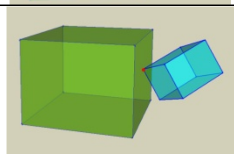
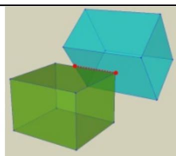
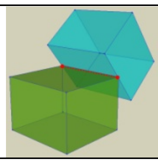
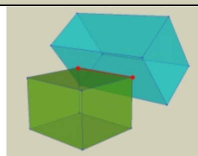
2. 3D VALIDATION

Validation studied by researchers includes two aspects to be considered just as described above. The first aspect is the validation for single primitives such as 2D polygons or 3D polyhedrons. The second one is validating the relationships among them in the whole space. Verbree and Si (2008)have employed Constrained Delaunay Tetrahedralization (CDT) to check the validity of a single 3D polyhedron. Brugman et al. (2011) developed a series of topological rules to validate a 3D topology structure for a 3D space partition. And later, Thompson and Van Oosterom (2011) extended these rules to axiomatic definitions to validate a 3D parcel and its relationship with adjoining parcels within a space partition. Karki et al. (2011) specifically discussed the data validation in 3D cadastre including a single 3D parcel and its relationships with other parcels. The four papers introduced or discussed the validation methods or rules mainly for single 3D polyhedronsusing computational geometry or topology rules. These studies are of great significance. But in this paper, a new method is described to mainly validate the relationship among 3D parcels.It aims at identifying either correct or incorrect topological relations in 3D by use of a novel approach. Before introducing the new appoach, we should first understand what topological relationships need to be identified. The next section wil describe this in detail.

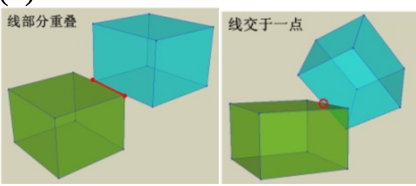
3. TOPOLOGICALRELATIONS AMONG PROPERTY UNITS

In discussion of topological relations, the property unit is not suitable because of its legal characteristic, instead we use the topology primitive”body” in the following paper, which corresponds to 3D polyhedron in 3D geometry space. For the description of topological relationships, their formal representation based on classical theories(mainly the intersection model based on Point-Set Theory and the RCC model based on logic inference) is necessary. Wewant to describe all of theserelationships as much as possible, but until now it is very difficult to achieve this goal. In 2D space there is no formal model by which all topological relationships amongpolygon domains could be distinguished and represented in finer granularity. The situation seems to be much more complicated when it is analyzed in 3D. In this paper, for representation of topological relationships, finer granularity is not desired, especially for relations between bodies in 3D cadastre. According to the definition and attributes of the 3D property unit, we will focus on the ”touch” relationship rather thanother topological relationships among them(they are often used for topology checking). It is often desired to distinguish the ”touch” relationships in finer granularity using models such as the DE-Model(Dimension-Extended Model).

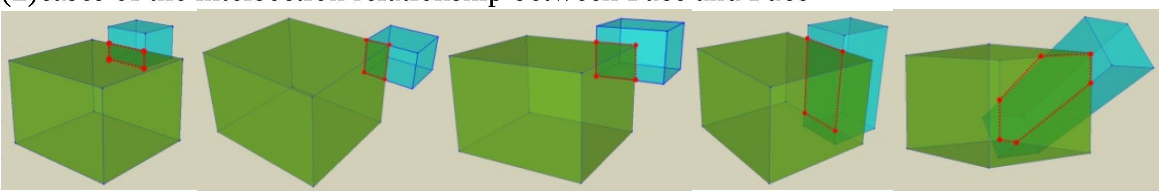
Table 1.”Touch” relations between bodies

primitives	Detailed primitives	Equal	Intersect	Cover	Contain
Between iD primitive and jD primitive(i=j)	Point and Point		None	None	None
	Edge and Point				
	Face and Face				
Between iD primitive and jD primitive(i!=j)	Point and Edge	None	None	None	
	Point and Face	None	None	None	
	Edge and Face	None			

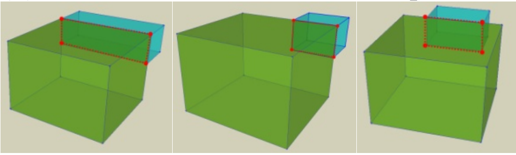
(1) cases of the intersection relationship between Edge and Edge



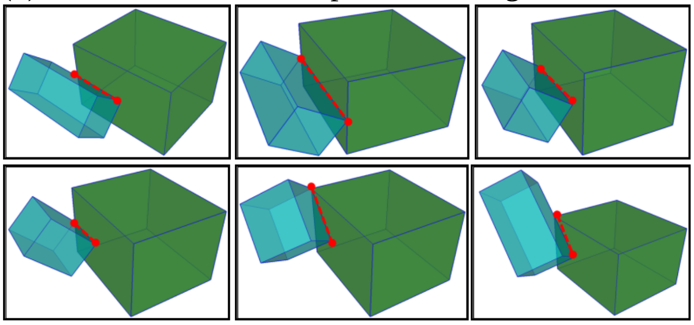
(2)cases of the intersection relationship between Face and Face



(3)cases of the cover relationship between Face and Face



(4)cases of the relationship between Edge and Face



These ”touch” relationships are the basic and also main topological relationships among bodies, despite far more relationships than these can be found in finer granularity. Following the method for identification of topological relationships based on combined inference proposed by Guo (2000) and Du(2005), these ”touch” relationships are only regarded as basic meeting relationships, because much more complicated cases could be derived from them, e.g. a combination of several basic ”touch” relationships. In other words this means that boundary primitives, which are the largest dimension coboundary primitive in the relationshipsamong bodies, are regarded as primary ”touch” primitives. For example, if two bodies meet at a common face, and simultaneously meet at a single common edgeas well as at a single common vertex (node), then the relationship is regarded as meeting at a common face (Figure 2). In addition, holes can exist in bodies, e.g. inner holes(i.e. cavities) and through-holes. Inner holes in the bodies are inner surfaces in the bodies, through-holes in bodies are inner rings in the boundary faces, and they can make the situation much more complicated.It is impossible to express completely all these topological shapes in a formal way.

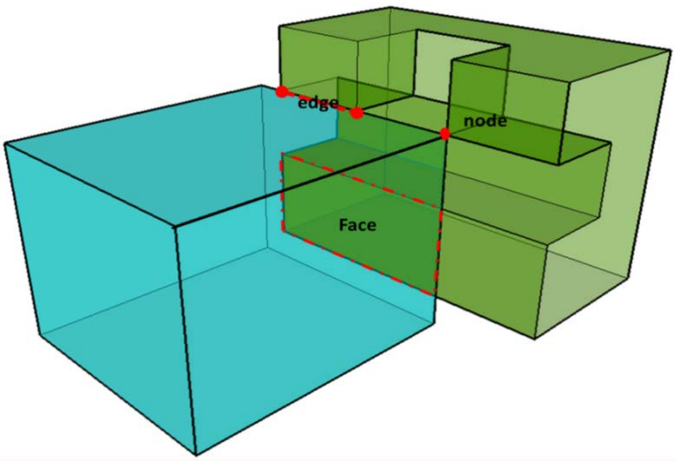
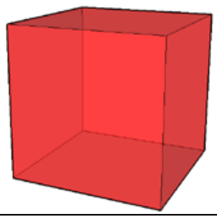
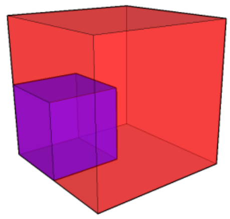
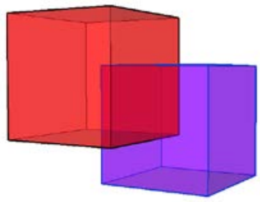
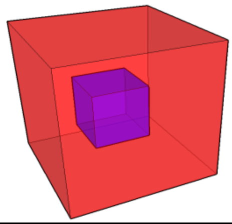


Figure 2. The main (co)boundary primitive relations between bodies

Other topological relationships among bodies are less prominent here. Only coarse-grained relationships are distinguished, e.g. the four relationships which have intersection parts in inner domains shown in Table2.

Table2. Other relationships than meeting between bodies

equal	cover	intersect	contain
			

4. IDENTIFICATION OF TOPOLOGICAL RELATIONS

The identification of topological relations needs the underlying topological data model and structure as the basis. Based on the determined data structure, an identification algorithm may be implemented. In this paper the data model (Figure3) is basedon a simplified topology model similar to 3DFDS(3D formal data structure). The underlying data structure (Figure4) is based on the radial edge data structure.It has been improved to satisfy the need of 3D cadastre topological identification and construction.

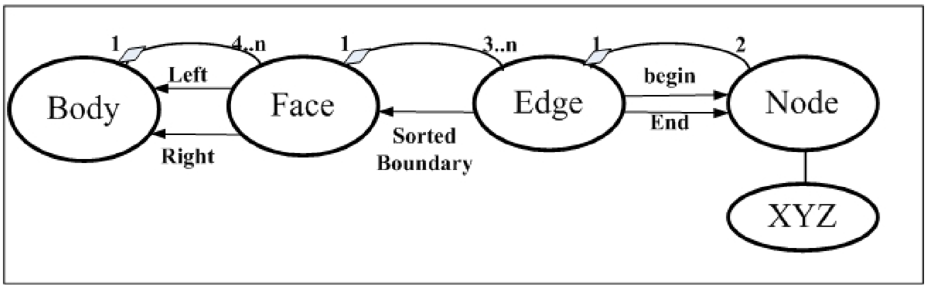


Figure 3. The topological data model

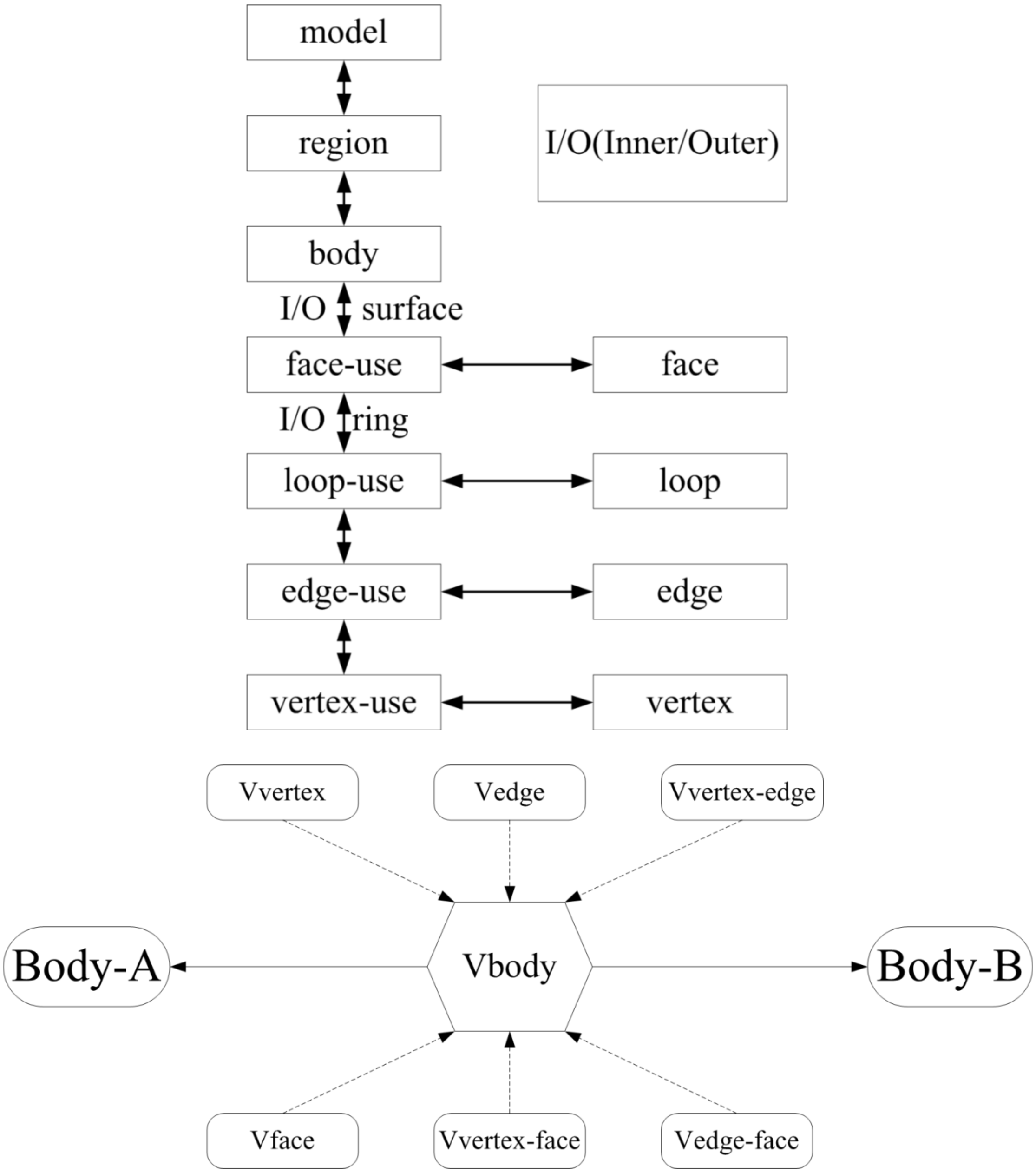


Figure 4. The topological data structure

In this paper,the topological identification algorithm is called ”the virtual pimitives method”. This method is considered to be based on the original data, but additionally newly-established middle pivot primitives are used to build the topology. It has three functions:

(1)One of the traditional purposes for building a topology is to reduce data redundancy, i.e. the redundant primitives representing the same object primitive must be removed. However, the possible tolerance between them could result in a perturbation of the original data, and therefore newly-established virtual primitives are regarded as the unique primitives, but the original primitives remain.

(2) Traditionally, the meeting relationships between high-dimensional topological primitives are represented by lower-dimensional topological primitives, e.g. a face is shared by two bodies; an edge is shared by multiple faces. In contrast, the shared face must be the component in both bodies, and it is a sort of representation of implicit topological relationships. However, these shared topological primitives will not always exist in higher-dimensional primitives, so data fusion is needed.Shared primitives will result from splitting of edges and partition of faces using computational geometry approaches so as to meet representation of the implicit topological relationships. However, these computational geometry approaches will lead to all kinds of problems mentioned above and will result in even more problems recursively.

In order to solve these problems, computational geometry approaches must be involved, but computing results are represented by virtual primitives instead of real primitives. Taking fusion of data primitives as example, only one virtual primitive is enough to represent the 'equal' relationship between several redundant primitives, and all sorts of relationships could be represented by virtual primitives explicitly after splitting of computing primitives, e.g. equal, cover, contain between edges, and faces.

In short, any relationship occurred between boundary primitives of bodies are represented indirectly by virtual primitives rather than by true computing results(i.e. real primitives mentioned above). As shown in Figure5(left), F1 in B1 and F2 in B2 are coplanar, and F1 contains F2. Following the automatic searching approach of bodies, F1 will be splitinto two parts, i.e. F2, the remaining part, and theadjacent (meeting) relationship can be represented by F2 implicitly. However, in the virtual primitive approach, the relationship between F1 and F2 is both represented and recorded in the virtual face VF0, i.e. the relationship is inferred from the record of virtual boundary primitives. As well, an example of fusion of virtual point primitives is shown in Figure5(right).

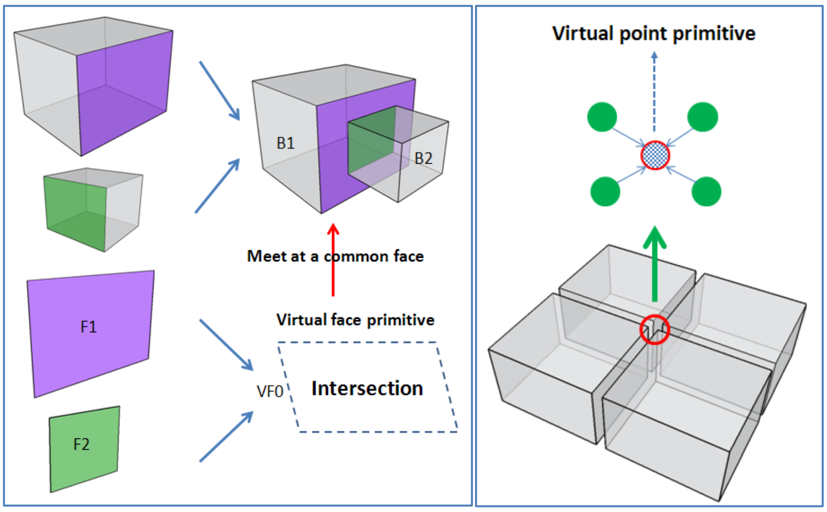


Figure 5. Representation of boundary primitives using virtual primitive approach

(3) Topological relationships between bodies including equal, intersect, cover and contain can be represented by virtual primitives. And these relationships are used to check topology of the 3D property units and verify data validity.

So, virtual primitives play a role in representing relationships between geometric boundary primitives in 3D, and not all of these relationships can be represented by dimension-reduction. A cross-type intersection relationship between F1 and F2 recorded by a VF (virtual face) is shown in Figure 6.

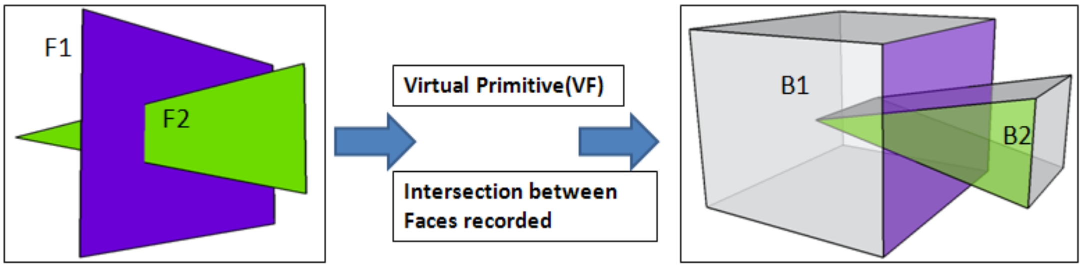


Figure 6. Cross-type intersection between two faces

There are three core ideas in building topology using virtual primitives:

(1)Representation of topological relationships between geometric primitives using virtual primitives;

(2)Inference by combining boundaries:
Topological relationships between higher-dimensional geometric primitives can be obtained from topological relationships between geometric boundary primitives belonging to different bodies and with certain computational geometry methods. In detail, for obtaining topological relationships between geometric boundary primitives, a rule must be followed: Firstly, the topological relationships between geometric boundary primitives which have the same dimensionality are computed where the dimensionality is ordered ascending; then, the topological relationships between geometric boundary primitives with different primitives are computed;thereby the sum of dimensions of two different primitives is ordered discerningly, e.g. firstly computing relationships between points and points, edges and edges, and faces and faces; computing relationships between edges and faces, points and faces, point and edges later which will be elaborated in the following.

(3)The relationships between geometric boundary primitives in bodies are compact, and those between bodies are coupled, and each body is a closed, oriented polyhedron whose structure can be represented by the radial-edge data structure whose advantages will be elaborated later.A rule is defined here: Topological relationships between geometric boundary primitives described in the later parts in this paper are regarded as topological relationships between different bodies while relationships in the bodies are considered known.

The first idea has been elaborated above.The second idea is used to show that topological relationships between geometric primitives which have the same dimensionality can be inferred from the relationships between boundary primitives and with the knowledge about computational geometry. Taking a simple example, whether two bodies are equal can be inferred from comparison between their faces; whether two faces are equal can be inferred from comparison betweentheir edges, etc.

In contrast, the relationships between points are recorded by virtual points, and these records can be used to learn whether edges composed by these points are equal.These edges are also recorded by virtual primitives, which can be used to learn whether faces composed by these edges are equal. These faces are also recorded by virtual primitives, which can be used to learn whether two bodies are equal. These results are also recorded. And it is relatively simple, because not so much knowledge about computational geometry is involved here(only computational works for matching 3D points in a certain tolerance is involved).

However, inference of some relationships could be obtained only by relationships between geometric boundary primitives and knowledge about computational geometry as shown in Figure7. It is assumed that F1 and F2 are coplanar, and F1 covers F2. But by only comparing the edge sets, we only know that F1 covers two edges of F2 which is not sufficient to determine the relationships between two faces. If the relationships between other points in F2 and F1 can be obtained, the relationships between these two faces could be obtained as well, if computational geometry approaches are involved, e.g.testing whether a point is located in a polygon.

In Figure7(right), there is no relationship between boundaries of F1 and F2, so only the algorithm testing whether a point is located in a polygon is needed to determinethe relationships between the two faces.

Figure 7. Inference of relationships between faces

Relationships between boundary primitives are not limited to those having the same dimensionality where relationships between boundary primitives which have different dimensionality are involved, e.g. between edges and faces, points and faces, points and edges. In Figure7(left), not only the relationship between faces(i.e. F1 covers F2), but also the relationships between the edges in each face are involved implicitly which is not desired by us. What we want are “simple” relationships between primitives which have the same dimensionality. In “simple relationships”, additional relationships like between edges and attached faces in relationships between faces must be removed.

There is not a strict definition about “simple relationships”, because no isolated primitives can exist in 3D property units. If there are relationships between edges and faces, there are also relationships between faces to which these edges belong to. These “simple relationships” have common points usable to express relationships between bodies independently.This mainly focuses on the meeting relationships between bodies at boundary primitives with different dimensionality.Figure8(right) and Figure9 are both examples of these “simple relationships”.

“Simple relationships” and “additional relationships” are represented and distinguished in Figure8. Here F1 and F2 intersect, and E1,E2 in F2 and F1 also intersect.The latter can be regarded as additional relationships of the former. In Figure8(right), F1 in B1 covers E1 in B2, and the relationship between F1 and E1 is a kind of “simple relationship”, because there is no relationship between faces incident to E1 in B2 and F1 in B1.

These “simple relationships” are represented and recorded by virtual primitives. If only these “simple relationships” exist in boundary primitives of these bodies, they are regarded as “singularities”. Figure8(right) and Figure9 both show “singularities” between bodies which are not allowed in automatic searching of bodies.

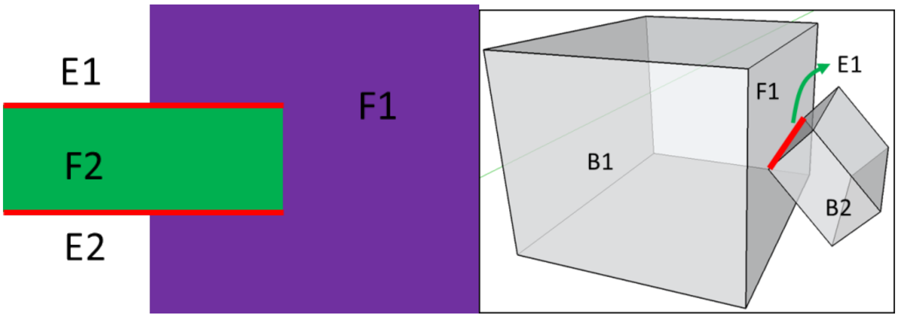


Figure 8. “Additional relationships” and “simple relationships” between primitiveswith different dimensionality

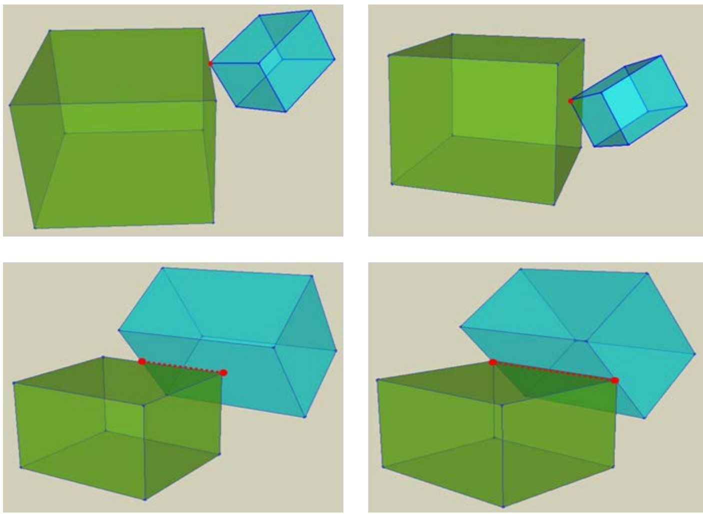


Figure 9. “Singularities” between boundary primitives of bodies

In addition, some rules must be followed in inference of topological relationships, i.e., topological relationships between higher-dimensional primitives can be inferred from topological relationships between lower-dimensional primitives, e.g. relationships between edges could be inferred from relationships between points, etc.

The key is that inference between primitives which have different dimensionality must follow the rule that the sum of the dimensionality of these primitives is sorted discerningly whereas relationships between primitives which have the same dimensionality have been inferred already.“Simple relationships” between primitives which have different dimensionality are preferred rather than “additional relationships”.An example is shown in Figure9.

In Figure 10 (left), “additional relationships” between F1 and E1(i.e. F1 contains E1) are derived from relationships between F1 and F2(i.e. F1 covers F2). In Figure 10 (right), therelationship between F1 and E1 is a kind of “simple relationship” where two faces of B2 are incident to E1 have no relationships with F1. However, whether the relationship between F1 and E1 belongs to “additional relationships” or “simple relationships” could only be inferred before the relationships between faces are computed.Similarly, “simple relationships” between points and edges, as well as points and faces can only be assured with relationships between edges and edges, edges and faces, as well as faces and faces provided.

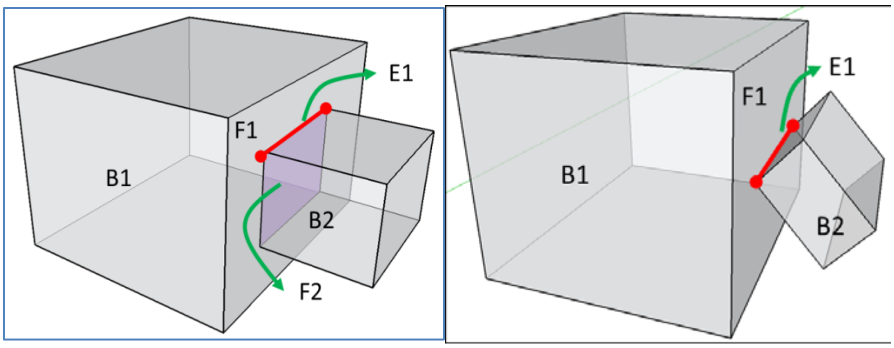


Figure 10. “Additional relationships” and “singularities”

Relationships between bodies can be inferred by the second idea as follows:
(1) Whether points are equal must be assured, and they should be recorded by virtual primitives.
(2) Relationships between edges can be obtained by relationships between points and applying knowledge about computational geometry.They are represented by virtual primitives.
(3) Relationships between faces can be obtained by relationships between edges and applying knowledge about computational geometry. They are represented by virtual primitives.
(4)Inference of “simple relationships” between faces and edges: Relationships between faces and edges are obtained firstly using knowledge about computational geometry, then “additional relationships” should be excluded by judging the relationships between faces, at last they are recorded using virtual primitives.
(5)Inference of “simple relationships” between faces and points: Relationships between faces and points are obtained firstly using knowledge about computational geometry, then “additional relationships” should be excluded by judging the relationships between edges and faces, at last they are recorded using virtual primitives.

(6)Inference of “simple relationships” between edges and points(i.e. whether points are located in edges): Knowledge about computational geometry must be employed first to judge whether points are located in edges. Then relationships between edges and edges, edges and faces, as well as faces and faces can be used to obtain the relationships between faces and edges incident to these points. If such relationships exist, they are regarded as “additional relationships”, otherwise, they should be regarded as “simple relationships” and recorded using virtual primitives.
(7)At last, topological relationships between bodies can be inferred using relationships between boundary primitives and knowledge about computational geometry.
The third idea is elaborated from the perspective of the data model.Virtual primitives must be supported by and reflected in the data model.

The topological relationships between primitives in bodies should be factored in using a hierarchical topological structure. And both top-down organizing approach and bottom-up searching approach are swiftly supported in this hierarchical topological structure which is implemented by radius edge structure.

5. CONCLUSION

As core of this paper, topological identification and algorithm constructing using virtual elements are described in brief. All kinds of topological relationships they can represent are illustrated. The topological data structure and algorithm designing ideais given. Three core ideas of using virtual elements are shown:Definition and function of virtual elements, designing of “impactness/coupling” in the topological structure, and the overall designing idea called ”reasoning method by combing boundaries” which is also the deducing principle for topological relationships between geometrical elements of overlaying body boundaries. This method can identify correct and incorrect topological relations among bodies. Therefore it could be used as topology checking module of a 3D cadastre management system. The algorithm has two design purposes: 1) resolving the 3-dimensional parcel conflict in 3D space and guarantee its unique and exclusive legitimacy space; 2) correct topological relations represented in the underlying topological data structure and stored in a database could be the basis for the following space analysis.

In general, the design of topological construction algorithms needs acomputational geometry algorithm as underlying implementation, at least as core algorithm. The algorithm in this paper still applies many computational geometry algorithms, but the whole frame is based on a compositional reasoning method. The reason is the hope that designinga topological identification framework, a series of reasoning rules could be added to itconstantly, so that more and more topological relations could be identified.

In future, topological maintenance algorithms will be studied. It is also the core module of a cadastral management system to guarantee consistency after a merging or segmentation among 3D parcels, i.e. to update parcels simultaneously and in real-time.

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