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An Efficient Geometrical Model for Meshing Applications in Heterogeneous Environments

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ABSTRACT

This paper introduces a new neutral hybrid discrete (in the limit continuous) solid CAD model for meshing applications within the Integrated Computational Environments, based on subdivision surfaces. The model uses the Boundary Representation for the CAD model topology and the Butterfly Interpolating subdivision scheme for definition of underlying curves and surfaces. It is automatically derived from the original solid model, based on parametric surfaces, using a fast loop-traversal approach for identification of geometrical discontinuities. A curvature-based sizing function is introduced for generation of an optimal control mesh for subdivision surfaces. A new hybrid CAD model has significantly fewer faces, uses robust discrete structure, which simplifies computational meshing and geometrical model transfer within the heterogeneous components of computational environments.

Keywords: solid modeling, boundary representation, subdivision surfaces, surface mesh generation, surface data interpolation.

1. INTRODUCTION

Recent advances in numerical solution of differential equations and significant increase of power of affordable computers have largely extended application of the Finite Element (FEM) and the Finite Volume Method (FVM) in Computational Fluid Dynamics (CFD) and Computational Structural Mechanics (CSM) to simulation of a new physical phenomena on significantly more complex geometry. Nowadays it is common to deal in the FEM/FVM simulations with full configurations of aircrafts, cars, etc. defined by composition of thousands of free form faces [1,2]. Application of the FEM and the FVM requires meshing to be performed on the geometry and CAD models provide an effective input for the process [1,2]. However, the problem of efficient definition of the geometrical input for downstream engineering applications (i.e. mesh generation) is not solved for the Integrated Computational Environments (ICEs), frequently found in aerospace and automotive domains. Indeed, the ICEs are composed from numerous heterogeneous in-house and commercial software components and therefore require efficient exchange of geometrical and computational data [2] in the production cycle. This paper addresses the problem of automatic creation and seamless integration of an exchangeable solid CAD model to the ICEs with elements of virtual reality. The new model is designed for shape definition for volumetric mesh generation and virtual reality applications.

2. OVERVIEW OF THE EXISTING GEOMETRICAL MODELS

For a modern computational process unambiguous volumetric shape of an object in heterogeneous environments is defined in digital form, using a number of different approaches such as solid modeling, discrete modeling, etc. Most of the modern CAD engines uses the Boundary Representation (BREP) [3], when a solid is defined by the object boundary. The BREP definitions mostly rely on parametric surfaces [3-6]; however in many computational applications discrete models without parameterization and hierarchical topology play an important role due to robustness and simplicity of processing [7-10]. While parametric CAD models with topology are suitable for further geometrical modeling, discrete mesh-based representations are mainly targeted on efficient geometrical data transfer [6].

2.1 Parametric CAD models

In the BREP format [3] the boundary is typically composed in a hierarchical way from conformal parametric (as a rule topologically rectangular) free form faces (see Fig. 1 for an example of a topological tree, Fig. 2 for an example of a typical BREP geometry). Non-Uniform Rational B-Spline (NURBS) is a standard choice for definition of curves and faces [4], providing an accurate and robust framework for geometry representation. Unfortunately the original CAD in the BREP format often contains errors such as gaps, overlaps of faces, incorrect faces topology, etc. and requires special pre-processing to enforce conformal boundary definition, known as CAD repair [5,6]. For the mentioned complex CAD models the number of geometrical errors build up in the non-liner manner with the increase of the number of faces in the model, forming a major bottleneck in the FEM/FVM analyses workflow [5,6].

The ICEs require multiple export/import of geometrical models via exchange formats, such as IGES and STEP, thus introducing extra CAD errors due to tolerance problems and different CAD representation in different modules of the ICE. Therefore ICEs are obliged to use internal CAD repair tools after each geometrical model transfer to maintain consistent watertight CAD models [5,6]. Avoiding multiple CAD repair operations is a key requirement for the ICE efficiency. The repaired model approximates the initial shape within the given tolerance. Typically it removes or re-defines some features of the original CAD that affects quality of computational mesh – i.e. small and high aspect ratio faces, etc. The repaired meshing ready CAD model here is called a Neutral CAD Geometrical Model (NCGM). Indeed, the NCGM slightly changes shape and topology of the initial CAD within the given tolerance, so *a priory* the NCGM is not the same CAD, imported to the environment. We can formulate the following requirements for an NCGM [5]:

1. The NCGM should accurately represent complex 3D shapes with a minimal number of faces.
2. The NCGM should be suitable for computational meshing.
3. Interchange of the NCGM should be simple and efficient.
4. The size of the NCGM should not be prohibitively large.
5. The NCGM should be efficient for visualization.

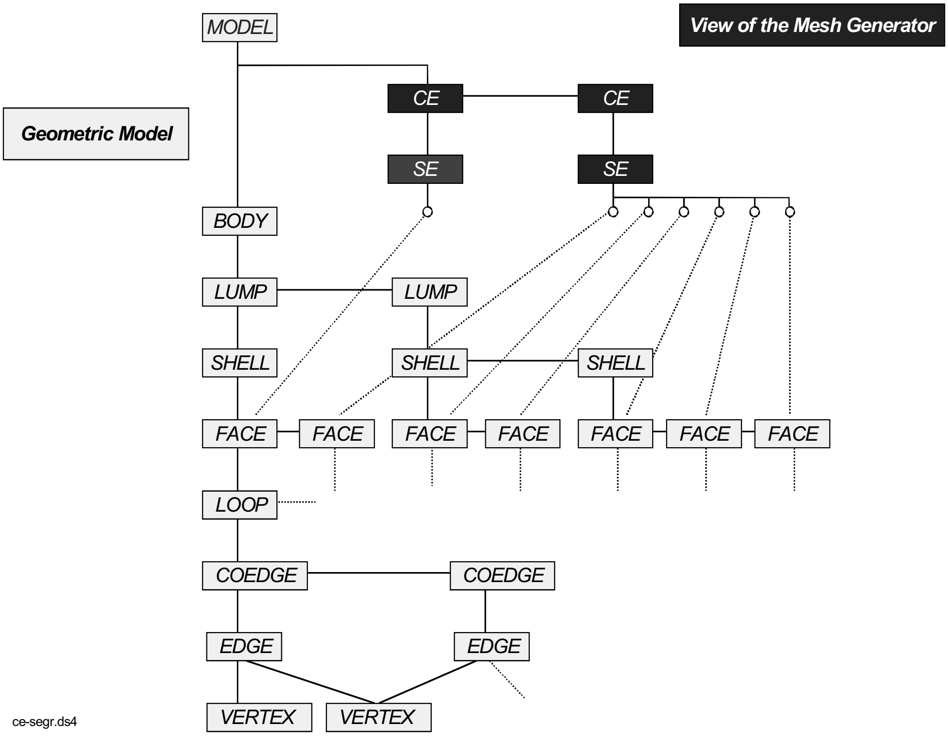


Fig. 1 The topological tree of a classical BREP geometrical model: CAD and mesh generation representations. Meshing requires automatic unification of faces to Super and Constructive Elements (SE and CE) for better mesh quality.

2.2 Discrete CAD models

Considering complexity of the solid NCGM exchange within engineering applications, many authors advocate polyhedral discrete mesh-based geometry without topological tree. It is the most stable format for exchange of geometrical data between inhomogeneous components of the ICEs [2,7,8]. The idea of a discrete geometry definition is certainly not new. There are a large number of publications on the subject to mention few: Lohner [7] has effectively used polyhedral representation for geometry definition in the context of advancing front mesh generation scheme. Recently Owen and White [8] have developed an efficient polyhedral geometry definition and provided an algorithm to extract model topology from the volumetric mesh-based definition. Also the motivation of [8] is in support of the legacy FEM geometrical data, when traditional CAD definition is no longer available. Strong point of the proposed approach in [8] is a possibility to deal with deformed geometry, resulting from the FEM/FVM coupled problems. The surface feature extraction have been studied in References [19,20] and other papers. Lang and Borouchaki [9], Frey [10] have proposed geometrically optimal mesh and a procedure to define shapes of objects with minimal number of nodes, preserving geometrical features. All mentioned geometry definition assumes a priory absence of full topological information between the elements of the CAD model. Weak point of the discrete geometry is related to the necessity of the C_1 smooth shape representation, so the authors typically use smooth faces as format extension: Bezier-patches in [8], Coons patches in [9], quadratic patches in [10]. Therefore it is very attractive to develop a discrete geometrical scheme capable of representing the C_1 smooth shapes.

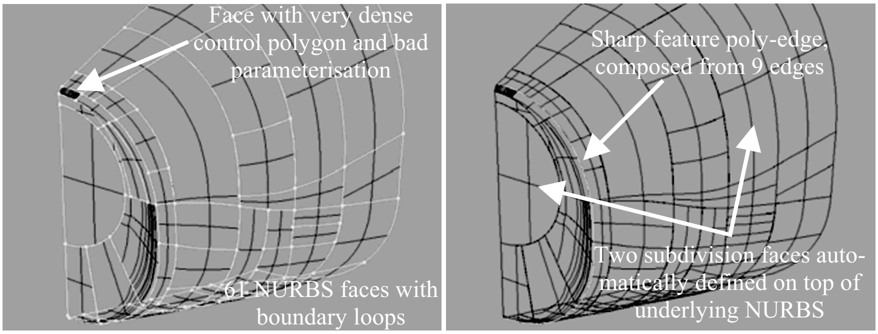


Fig. 2 Comparison of the BREP geometrical model for the rear fuselage section: left - classical NURBS (61 faces) bounded by trimming loops and vertexes, right - Subdivision Surface faces (2 faces) with just one sharp edge curve.

2.3 Closing the gap between parametric and discrete geometry

On the other hand, there is a large class of problems, when the original topological CAD model information could be used for an effective definition of the NCGM. One of the most important cases is found in the context of the ICEs, where elements of the CAD repair are used to maintain consistency of the CAD model during transfer. However, we want to avoid application of the CAD repair after each export-import operation in the ICE workflow. This paper assumes that we have a watertight BREP geometry definition, resulting for example from the basic CAD repair [5], developed by the authors. The challenge is to define an effective hybrid geometrical model that could combine robustness of the discrete geometry representation with the strength of the full topological information of the BREP model tree (Fig. 1).

Researches have proposed a number of alternative schemes for the definition of smooth faces. One of such approaches uses Subdivision Surfaces [11,12,13]. Originally, subdivision surfaces were developed in computer graphics for visualization of complex free form objects [15,17]. In the context of mesh generation Kobbelt et al. [11] pioneered the usage of interpolating subdivision surfaces as the basis for geometry definition, Rypl and Bittnar [12] have used subdivision geometry for advancing front meshing in physical space. Later Lee have developed an effective parametric mesh generation approach, based on the Butterfly subdivision geometrical model [13,14]. However, all mentioned work did not use initial topological information of the solid model. Mezentsev et al. [16] have proposed to combine subdivision surfaces with elements of topological information in the classical BREP model (the so-called S-BREP definition) however limited to scanned objects and to sub-set of the BREP tree. This paper develops an idea of a hybrid geometrical model further on, introducing the methodology for generic geometry definition, subsequent surface meshing and computational data interpolation. It focuses on application of the S-BREP geometry for direct mesh generation, using local subdivision rules formulated in [17]. Initial control mesh for the S-BREP faces is generated on the NURBS BREP geometry.

The paper is outlined as follows: Section three discusses specifics of the NURBS BREP model and provides fundamentals of the Butterfly subdivision scheme. It gives the background for a proposed hybrid subdivision surface model with the boundary representation. Section four discusses automatic generation of the S-BREP model from the solid BREP model. In Section five examples of the S-BREP models are given. Section six gives some implementation details and Section seven provides conclusions.

3. Geometrical BREP model based on subdivision surfaces

Developed geometrical model is tailored for an efficient application within the ICEs as discussed in Section 1 and is targeted for the mesh generation and the FEM computational data applications.

3.1 The Boundary Representation - BREP

As it has been discussed in Section 2, the BREP model is an efficient way of geometry definition for the ICEs. Downstream engineering applications, i.e. meshing or computational data related, frequently operate on the level of faces, therefore most of the NCGMs [5,8] apply a middle range subset of the BREP topological tree – just faces with boundary loops, as shown in Fig. 1. Frequently the BREP models contain faces that are too small or badly parameterized for quality mesh generation. In the process of the CAD repair such faces are typically logically grouped to form bigger entities (in terms of Fig. 1 the so-called Super Elements (SE) and Constructive Elements (CE)). In our approach we retain the complete topological tree of the initial BREP model, performing geometric continuity analyses and generating bigger subdivision geometry faces over the smooth regions of the model. The S-BREP model tree will be similar to the tree, shown in Fig. 1, however, subdivision faces will be larger spanning over a number of underlying NURBS faces.

3.2 Subdivision Surfaces

Interpolating subdivision represents a smooth curve or a surface as a limit of successive subdivisions of the initial mesh. By starting with the coarse (so-called control) mesh new positions of the inserted points are calculated according to pre-defined rules. In most cases local rules how to insert points [15,17] (i.e. weighted sum of surrounding nodes coordinates) and how to split the elements of the previous mesh are used. The resulting subdivision mesh will be "smoothed" out so the angles between adjacent elements will be nearly flattened (see Section 4). Eventually, after an infinite number of refinements, a smooth curve or surface in differential geometrical sense can be obtained.

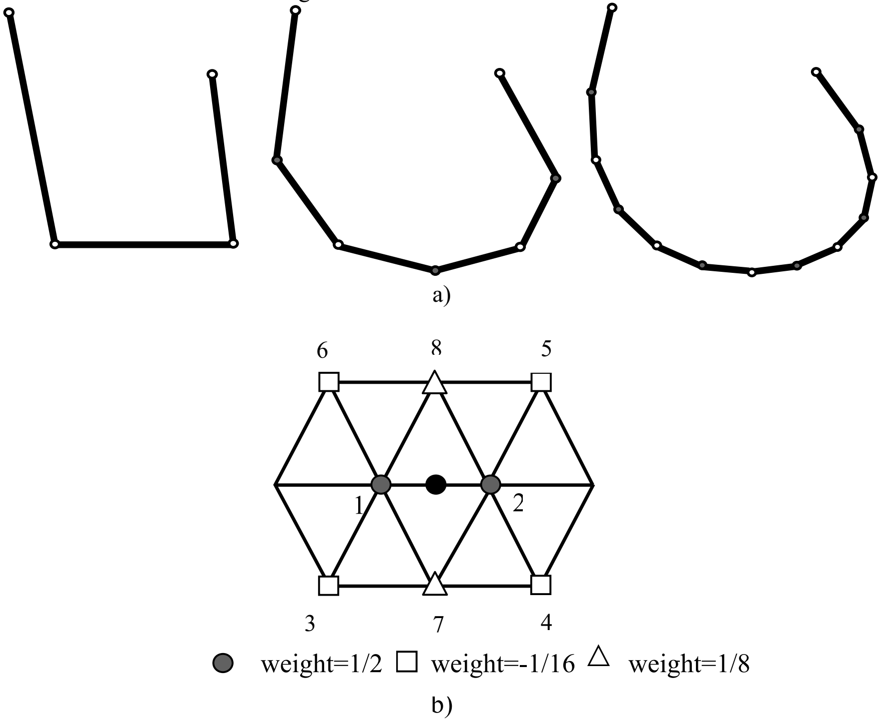


Fig. 3 Principles of subdivision: a) Successive subdivisions of interpolating subdivision curve b) Butterfly subdivision scheme

For example, Fig. 3 a) shows a number of successive subdivisions for a curve. Initial coarse mesh (left, nodes are represented by hollow points) is refined by insertion of new nodes (shown as filled points) to obtain smooth curve representation (right). The advantages of subdivision algorithms are that the schemes are local and surface representation will be good enough for most applications after a small number of subdivision steps. On first steps the initial position of control mesh nodes could affect surface quality, therefore it is advisable to provide subdivision-optimal control mesh as discussed in Section 4.3. Moreover, surface at any point can be improved arbitrarily by applying more local refinements (see Reference [16] for details). As a geometrical basis for the BREP-type geometry the so-called interpolating Butterfly scheme is used, initially proposed by Dyn et al. [15] and later modified by Zorin et al. [17]. The scheme could be applied for an arbitrary connectivity pattern of initial triangular mesh and uses eight points of the coarse level (Fig. 3 b), hollow points, triangles and quads) to compute position of the node on the new level of refinement (filled point). Note that the position of nodes on the previous subdivision level is retained.

The following formula is used for computation of the regular node position:

$$x_p = \frac{1}{2}(x_1 + x_2) - \frac{1}{16}(x_3 + x_4 + x_5 + x_6) + \frac{1}{8}(x_7 + x_8) \qquad (1)$$

Where x_p is the coordinate (or nodal variable, see Section 6 for example) of the interpolated subdivision point and $x_1 - x_8$ are coordinates (nodal variables) of the points in the vicinity of the interpolated point. For nodes with valence different from six (extraordinary internal and external boundary nodes) different subdivision rules with different weights are applied. A complete set of rules for the modified Butterfly scheme could be found in [17].

Interpolating subdivision surface is a generalization of spline surfaces for control net (polygon) of arbitrary topology [15,17]. Modified Butterfly scheme gives in the limit a C_1- continuous surface and tangent vectors could be computed at any point of the surface. With reference to the triangular surface meshes considered in this study, it is also possible to apply the Loop [18] scheme. However, the modified Butterfly scheme provides better results on sharp corners without dedicated insertion of boundary curves with different subdivision pattern, producing only minor smoothing (Fig. 4, right). Our approach models C_0 features of geometry (sharp corners) using the NURBS BREP to S-BREP curve mapping process, as described in Section 4. This is the main difference between the models developed by Rypl and Bitnar [12] and by Lee [13], who proposed application of subdivision geometry for meshing without dedicated discussion of the CAD model creation.

4. Automatic generation of the S-BREP models

Subdivision surfaces provide an effective framework for free form faces representation in the BREP model. However up to now formalisms for automatic definition of the composite CAD models, based on subdivision surfaces were not developed. Open problem is mostly related to automatic detection and representation of the BREP model discontinuities requiring definition of the adequate subdivision surfaces boundary curves and corner points. The problem could be illustrated by the following example of a typical rear part of the fuselage geometry (Fig. 4). Should the whole rear fuselage be represented just by one subdivision surface, certain smoothing of sharp features will occur on further levels of subdivision. To overcome this difficulty, an automatic procedure for analyses of a classical NURBS BREP model is developed. The general idea is rather simple: detection of a classical BREP model geometrical discontinuities and later definition of the respective boundary edges for subdivision faces. A similar procedures for discrete mesh based geometry have been developed in Reference [8]. Frey [10] and Lee [13] have proposed respectfully geometrical mesh simplification and tagging processes, not using the initial parametric CAD model. In terms of the methodology, most of the proposed algorithms for feature edges extraction are working on the 3D discrete polyhedral models (see, for example Owen and White [8] for volumetric, Baker [19] or Yamakawa and Shimada [20] for surface features). In our approach we are interested in the extraction of feature edges from the parametric BREP models, keeping in mind that cylindrical or closed surfaces could be effectively represented by the subdivision surfaces. In the area of the BREP analyses for sharp features, the work of Lu, Gadh and Tautges [21] is rather close to our BREP traversing, however current paper focuses on a sharp features extraction for subdivision geometry definition and on generation of an optimal control mesh, therefore it differs from the approach in Reference [21].

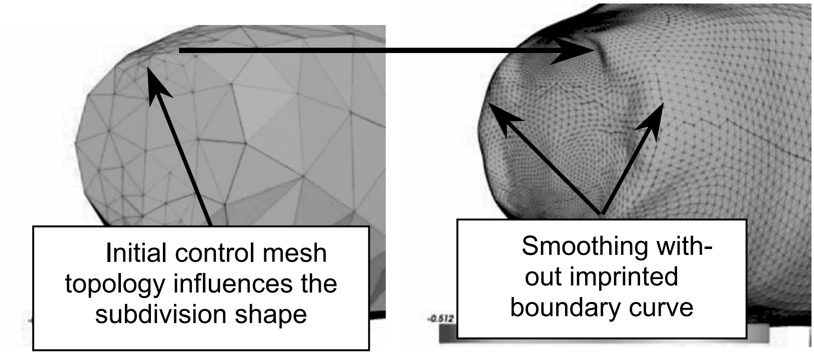


Fig. 4 The rear fuselage, represented by one subdivision surface face on two levels of subdivision without imprinting of subdivision curve at rear tip of the geometry. Smoothing of the C_1 discontinuity is clearly visible on the cylindrical part.

Proposed method works on a classical solid BREP (for example CATIA or ACIS with a full topological tree, similar to shown in Fig. 1) model and contains the following main stages:

1. CAD repair for enforcing conformal properties of the NURBS BREP model.
2. The NURBS BREP model geometrical analyses with automatic flagging of geometrical discontinuities: cusp and corner features (see [13] for definitions).
3. Automatic geometrical surface mesh generation on the NURBS BREP model, using a special curvature-based mesh sizing function.
4. Identification of the flagged discontinuity curves and assignment of subdivision faces. Typically the S-BREP faces are composed of 10-100 NURBS faces.
5. Application of the generated mesh as the subdivision surface control mesh.
6. Storage of the S-BREP model within the ICE.

Due to the assignment of the S-BREP faces to larger geometrically smooth regions, the number of faces in the S-BREP model is significantly reduced. The coarse nature of the S-BREP control mesh generated on stage 3 of the proposed approach, guarantees low storage requirements of the NCGM model. Further subdivision refinement of the initial control mesh provides in the limit smooth faces as in the Butterfly subdivision scheme [17]. As compared to the NURBS BREP model, each face is defined by control points and weights, while in the S-BREP only the control mesh (polygon) is stored and weights are constant and are not variable in the geometry, therefore reducing storage requirements.

4.1 CAD repair

The automated CAD repair process is carried out only once in the proposed workflow. Later on numerous exchanges of the watertight S-BREP geometrical model are performed in the discrete form and no geometrical data exchange errors are introduced. Specifics of the initial CAD repair concept developed and implemented by the authors are described in Reference [5] and are shortly repeated here for consistency. The basic CAD repair has received extra features, ensuring efficient geometrical model preparation for further analyses and conversion to the S-BREP format. The CAD repair is also tailored for the efficient usage in the ICEs as a pre-processing stage of the NCGM creation. It works in line with the concept of the abstract meshing interface [5] and can be summarized as following:

- CAD repair contains two separate interacting modules for independent (insuring global conformity of the model boundary) and dependent repair (targeting on a specific requirements of the application, in our case the S-BREP mesh generation), with the possibility of intermediate storage of the repaired model
- CAD repair is as a cyclic process involving both modules as presented in Fig. 5
- CAD repair provides an automated repair functionality, with minimal user interaction
- All operations of the CAD repair are performed on the NURBS BREP model and geometrical elements are considered equal within the given tolerance

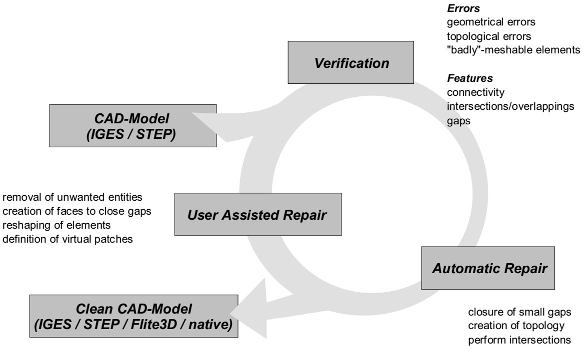


Fig. 5 CAD repair loop with interaction of independent and dependent modules

- Empirical realization of specific CAD repair features are ensured, mainly oriented on the complementary hierarchy of the parts and units of the CAD model, based on the grouping of the CAD model elements in engineering sense (see Fig. 1)
- The CAD model is accessible at any moment to the mesh generation process through the CAD/Mesh abstract interface.

The processing of the CAD-model into a form which is suitable for downstream applications is performed in three major steps (see Fig. 5):

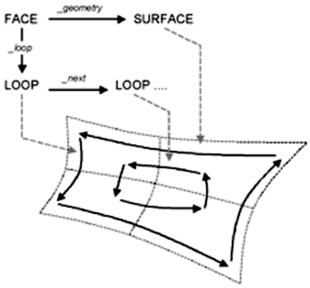
- Verification
- Repair of geometric and topological errors - independent repair
- Modification and removal of the of problematic configurations, posing difficulty for further model continuity analyses– dependent repair.

We use the cyclic workflow of the classical CAD repair in the process of model preparation for the automated S-BREP generation. As a result of CAD repair process the conformal but rather constrained in terms of possible variants of geometrical configurations NURBS BREP model is received. Typically certain geometric curve configurations are eliminated, like T-junctions of edges, thus reducing ambiguity and variations of cases for the loop edges analyses, described in section 4.2.

It is also important, that most of modern CAD engines (i.e CATIA, ACIS, Parasolid and others) are capable of creation of fully watertight CAD models. As the S-BREP model is targeted to be a generic internal geometrical format for the ICEs it is possible to upload the conformal NURBS BREP definition to the CADR module and perform only dependent part of the CAD repair. Later on the S-BREP model can be created in a straight forward manner, with further possibilities of the model export to heterogeneous components of the ICEs, such as volume mesh generation tools, surface data interpolation tools, etc.

4.2 BREP model analysis

Geometrical analysis identifies C_0 discontinuous features of a solid model. Analyses is started on the level of faces (see Fig. 1), it is based on the angle between surface normal on two sides of a co-edge, forming boundary loop of a given face (see Fig. 6, a)). The loop is traversed, loop co-edges are picked one by one (Fig. 6, b)) and an angle `F` between the faces is defined as a maximal value of angles between underlying surface normals at *n* discrete parameter positions along the edge (Fig. 6, c)) corresponding to the given co-edge. Providing an angle is higher then the user-defined threshold, the edge is marked as discontinuous C_0 feature and later on is tested for presence of consecutive edges, possibly forming a composite subdivision curve boundary for a S-BREP face.



a)

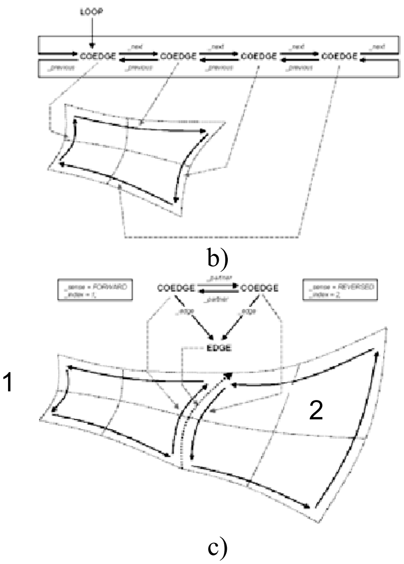


Fig. 6 The sequence of the BREP model analyses steps: a) – loop extraction on face, b) – loop transversal with co-edge extraction, c) – computation of the mean angle between normals to faces 1 and 2 along the given edge, referenced by co-edges.

For example, on Fig. 2 (right) the extracted sharp edge feature is composed from 9 segments, presented in the framework of the original NURBS model on the left. Corner nodes of the geometry are defined during analyses of the loop co-edges (Fig. 6, b)). Traversal of the co-edges is performed in physical space using automatically defined arc length parameter, which is dependent on the bounding box of the curve. During this process the NURBS curve C_0 discontinuities, related to inserted knots are also flagged as corner nodes of a subdivision curve. The corner position for a standard junction of edges is picked via normal position variation, similar to the detection of discontinuous edges as described above.

Extracting feature edges by the BREP loops traversal requires assessment of approximately 10-1000 less geometric elements, then in mesh-based volumetric element traversal, described in [8] and in surface polygon crawling algorithm in [20]. Presence of the topological tree of the BREP model permits to apply fast tree searching algorithms, further improving speed of geometry analyses. In our approach we compute the fundamental tree of the BREP topological graph and use it for the initial navigation in the search process for the geometry with multiple connected domains. Due to space limitations it is not possible to present further details of the algorithm.

4.3 Control mesh generation

The control subdivision mesh generation is performed on a watertight NURBS BREP model, obtained during the CAD repair stage of the process (Section 4.1). The MezGen advancing front surface mesh generation code [22] is used for this purpose. As obtained mesh is targeted for efficient definition of underlying subdivision surfaces, general requirements for the control mesh generation are different from the mesh generation for a generic computational application. To some extent, the control mesh of an interpolating subdivision surface defines how close the shape resembles a NURBS geometry on the initial levels of subdivision [13] (see also Fig. 4) and requires a specially tailored sizing function to control triangular element size of the control mesh.

Let us consider the following parametric surface:

$$r(u,v) = [x(u,v), y(u,v), z(u,v)] \tag{2}$$

The sizing function is related to the principal curvature of the underlying NURBS surface and can be described as follows. First we define in the standard differential geometry notation [22] the first and the second fundamental forms of (2):

$$\begin{aligned} f_1 &= Edu^2 + 2Fdudv + Gdv^2 \\ f_2 &= Ldu^2 + 2Mdudv + Ndv^2 \end{aligned} \tag{3}$$

where *E*, *F* and *G* are the first fundamental form coefficients, and *L*, *M* and *N* are the second fundamental form coefficients. The Gaussian (*K*) and the mean (*H*) curvatures are given by:

$$\begin{aligned} K &= \frac{LN - M^2}{EG - F^2} \\ H &= \frac{1}{2}\left(\frac{2FM - EN - GL}{EG - F^2}\right) \end{aligned} \tag{4}$$

The sizing function *S(u,v)* for a given point in the parametric space of a NURBS face for control mesh generation is taken as follows:

$$S(u,v) = \frac{1}{2}\left[K + C \quad H^{\frac{1}{2}}\right] \tag{5}$$

where: *C* is a constant, defined from sizing geometrical considerations, i.e. dimensions of the bounding box of the smallest face in the repaired and processed NURBS BREP model. The value of *S* is dependent on the curvature of the underlying NURBS model, ensuring smaller control mesh cells in the curved areas. Strictly speaking, this is not absolutely required for adequate definition of a subdivision face, as after a certain number of subdivision steps its shape will converge to the underlying smooth surface. However, our experience shows that using our sizing function the mesh is closer to the underlying shape just after 2 subdivision steps and this coincides with information from [13] on the influence of the initial control mesh on the shape quality after limited number of subdivisions.

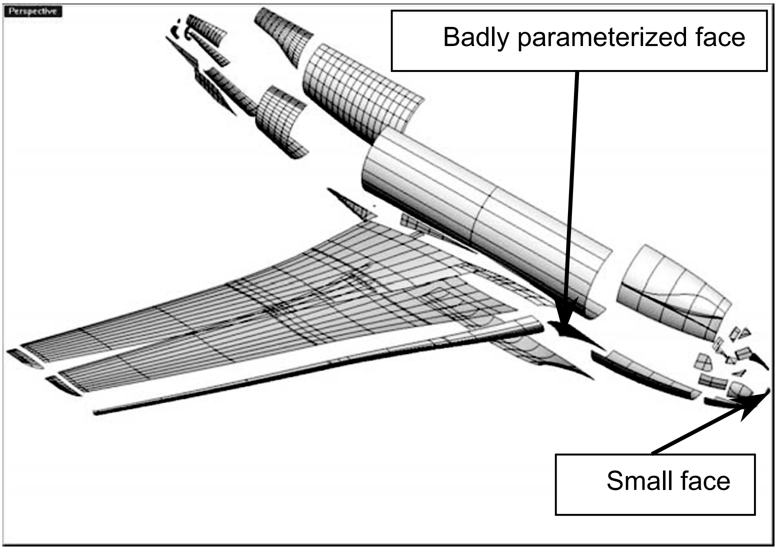
An important problem in application of subdivision surfaces for mesh generation is related to the absence of global maps for surface parameterization, therefore early applications are mostly using meshing in the physical space (see [11,12]). However, in Reference [14] Lee has developed an efficient parameterization scheme, based on an idea of the associated parametric mesh, which is basically a result of the application of the known flattening algorithms and interested readers may refer to References [24,25] for more details. Based on such a parameterization Lee has efficiently used an advancing front mesh generation scheme on subdivision surfaces geometry. Interestingly parameterization of the subdivision surface faces could be dynamic, providing more flexibility for surface mesh generation [14]. Further on, as subdivision surfaces are considered as generalization of splines to the parametric spaces of arbitrary shape [17,18] the problem of more generic parameterization appears to be possible. However, this problem is outside the scope of this paper and for the concept of the ICEs we expect direct application of the subdivision surface meshes for further generation of volumetric computational meshes and surface data interpolation.

4.4 Flagged discontinuities identification

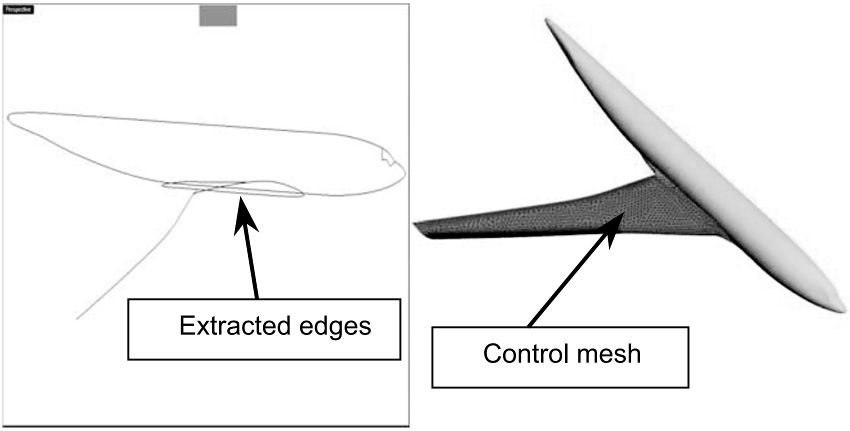
During mesh generation, nodes of a control mesh are positioned on the edges of the underlying NURBS model. Providing an edge is flagged as discontinuity, respective nodes of geometrical mesh are flagged as interior cusp node, boundary cusp node, corner node or corner cusp node similar to the tagging process, described in [13]. The main difference in our approach is in the direct analyses the underlying NURBS BREP model.

5. Examples of the S-BREP geometry

Due to space limitations, current section provides only two example of the S-BREP geometry, automatically generated from the NURBS BREP model using the algorithm outlined in section 4.



a)



b)

Fig. 7 a) A blow-off of CAD faces in the original NURBS BREP model (41 faces) b) automatically extracted curves (left) and the S-BREP model, containing 5 subdivision faces, corresponding to the wing, fuselage, belly, window and rear fuselage tip.

In the first example (Fig. 7) a simplified wing-body aerospace configuration has been analysed for extraction of sharp features. The configuration contains 41 NURBS faces with different parameterisation and size (Fig. 7 a) gives a blow-up of the faces, a number of small and badly parameterised faces could be observed). Minimisation of the number of faces requires definition of bigger entities; in a standard NURBS definition that implies matching of the knot vectors for a number of faces and results in splines with complex parameterisation negatively influencing parametric meshing process. An automatic definition of sharp feature edges in (Fig. 7 b) left) is performed and just 5 subdivision faces permit to simplify CAD model significantly. Note, that Fig. 7 b) on the right shows the control mesh on the S-BREP face corresponding to the wing and insertion of the cusp curve at the trailing edge permits to avoid smoothing of the geometry. Should provided subdivision mesh quality will not be acceptable for certain applications, the model on different subdivision levels could be used for surface meshing, applying for example the method described in [14].

As compared to published in [8] and [20] algorithms of feature edges extraction, presented topological tree based method appears to be rather effective. For configuration, shown on Fig. 6, meshed internally with tetrahedral mesh (112321 elements), feature extraction with our implementation of skinning algorithm, published in [8] takes approximately 18 sec., while our approach takes approximately 0.78 sec with the same edges result, shown in Fig. 6 b), left. However, it should be mentioned, that automatic CAD repair process timing is not included in the test.

In our second example (Fig. 8) the original NURBS BREP geometry is defined by the 427 trimmed NURBS surfaces. After the sharp features extraction and further generation of the control mesh (Fig. 8, left) the obtained NCGM consists of only three subdivision faces, corresponding to the vertical tail plane (Face 1), the rare fuselage (Face 2) and the front vertical tail plane (Face 3) sections of the geometry. Flexibility of the automatic S-BREP creation approach is also demonstrated by the operator-driven definition of the Face 3 (Fig. 8), when a certain group of faces could be assigned to a separate SE group, i.e. having different boundary conditions or physical properties for the downstream FEM solver. Apparently, there is no sharp feature on the boundary of the Faces 1 and 3 and a separation is enforced due to the requirements of the simulations. The colour scheme in Fig. 8 gives the value of pressure provided by CFD computation on the surface of the geometry. The concept of the Butterfly interpolation of scalar/vector variables permits to use geometrical model directly for the CFD or other relevant aerodynamic data storage. The colour scheme of Face 3 is taken different for visualisation purposes.

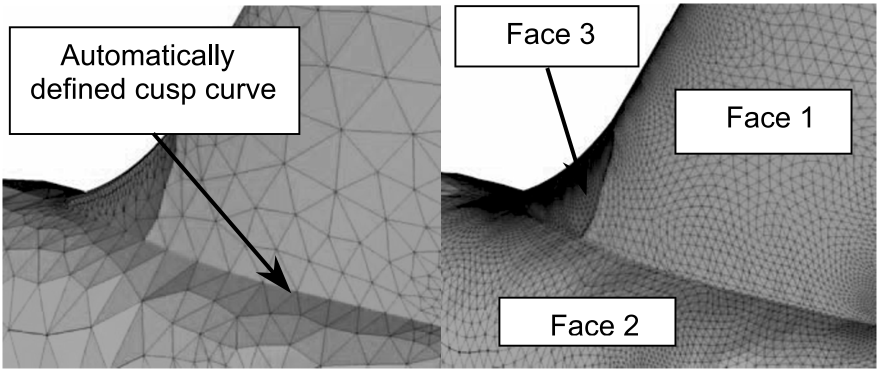


Fig. 8 The rear fuselage and vertical tail plane sections of the NURBS CAD model (427 faces). The S-BREP geometry is represented by just 3 faces on initial and second subdivision levels. C_0 internal cusp curve is automatically defined on step 2 of the NURBS CAD analyses. Face 3 is operator-defined entity, reflecting requirements of the FEM model.

The interpolation idea is to apply equation (1) for computation of scalars/vectors on the S-BREP geometry on new levels of subdivision. For example, pressure could be efficiently represented on the NCGM model using firstly control mesh of the subdivision surface and respectively interpolated values on different levels of subdivision directly using interpolation rules of the Butterfly subdivision scheme. Though certain smoothing effect could be observed on the data, subdivision interpolation could be directly used for storing the data on the geometry without fitting or extra processing. Original nodal values of the CFD aerodynamic data are obtained by projection of subdivision surface control mesh on the underlying CFD surface grid. Detailed discussion of the data storage using subdivision interpolation is outside the scope of the current paper.

The main motivation of the new model development has been the robust exchange of geometrical data and it has been tested for input to undisclosed Reynolds Averaged Navier-Stokes solver, aero elasticity and virtual reality modules. Using traditional CAD exchange format, input of the CAD model to individual component of the ICE required automated CAD repair process, which contained a number of user-driven operations. Each CAD repair cycle takes 0.3 – 2.7 person hours and overall production cycle within the ICE has not satisfied technical requirements for time. After introduction of the new model repeated CAD repair process has been excluded from the cycle due to stability of geometry exchange. Surface mesh, used in the S-BREP model has been directly used for volumetric CFD computational mesh generation, while discrete geometry has provided robust input for structural mesh generation and rendering in virtual reality applications.

In general, the proposed S-BREP model is extremely efficient for visualisation in the virtual reality environments, providing *a priori* tessellated surfaces for virtual reality engine. For example, the initial loading and rendering of the model on the 4th level of subdivision takes only 0.27 seconds for 57960 triangles with the Visualisation Toolkit (VTK) engine. Initial loading and rendering of the same geometry in the NURBS BREP with approximately 50000 surface triangles on the same workstation requires approximately 1.89 seconds.

6. Implementation issues

Current version of the S-BREP geometrical model is implemented in an object-oriented framework, similar to the coding paradigm of the MezGen mesh generator [22]. Subdivision BREP object is derived from the base virtual class mtkMesh [22] and in its topological structure coincides with the ACIS 8.0 BREP model. The S-BREP model is directly integrated to the CAD repair module [5], developed in collaboration with Dr. Thomas Woehler, Fraunhofer Institute for Production Systems and Design Technology – IPK, and works in the workflow of the ICE. The S-BREP here is an extension of the traditional NURBS model, combining full topological information with robust transfer and direct surface meshing capabilities. In our opinion there is no need for alternative surface meshing algorithms to be applied on the S-BREP as initial and subsequent subdivision surface tessellations are adequate for most downstream computational applications. Insuring optimal geometrical and computational mesh quality, the MezGen mesh generator applies a number of especially designed cosmetics operation on the generated control mesh, i.e. edge swapping and removal of triangles, as described in [22].

7. Conclusions

We have proposed a generic highly automatic method for complex geometry definition using Subdivision Surfaces based on the BREP data structure of the underlying NURBS model. Due to robustness of the mesh-like geometry transfer, proposed model combines fidelity of CAD, based on parametric surfaces with stability of discrete mesh-based geometry exchange. A set of extensions is proposed for the existing CAD repair process to enforce subdivision-compliant structure of the repaired model. Developed method of geometry definition directly uses the repaired NURBS BREP model for fully automatic extraction and flagging of the discontinuous geometrical features, thus providing complex C_1 in the limit free form CAD models with C_0 discontinuous features utilizing a new concept of the S-BREP faces. A heuristically defined curvature-based sizing function is proposed for an optimal definition of the control meshes for the S-BREP faces of the new model. A set of cosmetics operations, related to the optimal connectivity pattern of the generated control mesh is introduced in the MezGen surface mesh generation code.

The developed S-BREP NCGM model has been effectively tested on a set of complex CATIA and ACIS BREP input geometries with thousands of trimmed faces and has proved to be stable, efficient for direct surface data interpolation and capable of variable global/local resolution of the surface meshes.

Provided generalization of the S-BREP generation forms the main contribution of the paper together with the idea of subdivision interpolation of variables directly on the subdivision mesh using subdivision rules.

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