INTEGRATION OF SHIP HULL FORM MODELING BASED ON SUBDVISION SURFACES WITH OTHER SHIP DESIGN TOOLS

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SUMMARY

The industry standard for the representation of hull forms are tensor-product B-spline surfaces. However, tensor-product B-splines are limited to four-sided surfaces. Aside of the necessity to compose hull surfaces of several patches, it makes hull form modeling and fairing inefficient. An alternative are generalized B-spline surfaces. They originate from the field of subdivision surfaces, whereas the term subdivision refers to a method that enables B-spline surfaces of arbitrary complexity.
Hull form representation based on generalized B-splines improves hull form modeling. To be employed for ship design in practice, it is essential to provide an integration with other design tools. Naturally, this is a matter of data exchange. This article describes a method to convert a generalized B-spline surface to a collection of conventional Bézier patches. These patches may be shared with other design tools using a general purpose file format such as IGES.

1. INTRODUCTION

The industry standard for the representation of hull forms are tensor-product B-spline surfaces. They have a number of characteristics that make them attractive for the representation of free-form surfaces. The most important characteristic is that they are defined with the help of a control mesh which is closely approximated by the surface. This provides a reliable method to define smooth surfaces of any shape. The result is insensitive to changes of the control mesh what simplifies fairing. Unfortunately, tensor-product B-splines are limited to four-sided surfaces and therefore most hull surfaces are composed of several patches, but this considerably increases the number of control points and yields complex dependencies of the individual control meshes. As a consequence control meshes are only rarely used for hull form modeling.

In contrast, hull form design is mostly based on the interpolation of curve networks to define hull surfaces. The complexities of the patch generation and their interdependencies are left to an interpolation algorithm, where most algorithms provide a reliable patch generation, but the result is often not satisfactory in terms of the fairness and sensitive to changes of the curves. Unfortunately, this is an intrinsic property of interpolation. Some algorithms may alleviate this issue of interpolation, but it remains difficult to fair hull surfaces based on curves.

An alternative to tensor-product B-spline surfaces are generalized B-spline surfaces. They originate from the field of subdivision surfaces. The term subdivision refers to the method that enables B-spline surfaces of arbitrary complexity. Thus, the necessity to use several patches for the representation of hull forms is avoided. The most important consequence is, however, not the ability to represent hull forms with a single surface, but the possibility to effectively utilize the control mesh for modeling.

Using the control mesh apparently improves hull design for the reasons given before. Generalized B-splines promote the utilization of control meshes for hull surface modeling, but this worth nothing when the downstream support in the ship design process is missing. This paper addresses this problem and discusses how a generalized B-spline surface could be exchanged with other design tools. Two variants are imaginable: either support for generalized B-splines is added to the relevant design tools or generalized B-splines are converted to tensor-product B-splines which are currently supported by all major design tools and data exchange formats. Although generalized B-splines are compatible to the common architecture of the geometry kernels that are used by such tools, it is unlikely that a majority of the ship design tools will adopt this surface representation in the foreseeable future. For practical purposes, this paper focuses therefore on the second variant, the conversion of a generalized B-spline surface into a collection of tensor-product B-spline patches. The result is finally exported to one of the generic file formats which are widely accepted by other design tools such as IGES.

2. RELATED WORK

The application of control meshes for hull form modeling is currently restricted by the limitation of tensor-product B-splines to regular control meshes and therefore four-sided surfaces. This limitation is addressed by a certain class of subdivision surfaces that generalize B-spline surfaces for control meshes of arbitrary topology. Examples are the generalization of biquadratic B-splines given by Doo and Sabin [1], the generalization of bicubic B-splines given by Catmull and Clark [2], and the arbitrary degree generalizations of Stam [3] and Zorin and Schröder [4].

The subdivision algorithm is the core of any generalized B-spline surface as it defines the surface in the vicinity of irregular control points. It is possible to evaluate surface properties, such as points on the surface or normals, at any parameter values using the method of Stam [5], but the subdivision algorithm has to be stationary. This is the case for the previously mentioned algorithms. However, all algorithms are only generalizations of uniform B-spline surfaces. The generalization on non-uniform B-spline surfaces is covered for the low-degree case by Sederberg et al. [6,7], Müller [8,9], and for arbitrary degrees by Cashman et al. [10], but non-uniform features are only possible when the relevant part of the control mesh is regular or the subdivision algorithm is non-stationary. Therefore non-uniform generalizations of B-splines suffer from either being restrictive in the choice of the control mesh topology or Stam's method for the exact evaluation of surface properties is not applicable at irregular control points. The most important application of non-uniform B-splines is the boundary behavior of the surface. A similar behavior is, however, realizable for uniform B-splines with stationary, but topologically unrestricted, modifications of the subdivision algorithm. Therefore the uniform variants, in particular the variant of Catmull and Clark [2], are primarily used in practice.

Generalized B-splines are only rarely used for hull form modeling. An application of non-uniform bicubic B-splines, which are called T-splines, is shown by Sederberg and Sederberg [11]. Aside of the boundaries, the non-uniform features are employed to define knuckles. The presented examples reflect the complexity of typical yacht hulls and are rather simple compared to the hull forms of other vessel types. The study of Greshake and Bronsart [12] uses uniform bicubic B-splines to represent the hull form of a modern container vessel. It is shown that the fairness is improved compared to the result of conventional methods. The application of control meshes for hull form modeling is discussed by Greshake and Bronsart [13,14] for different types of vessels, likewise based on the application of uniform bicubic B-splines. While the previous work proposes to use the control mesh for hull form modeling, Lee et al. [15] present a method to generate a hull form based on a curve network in the context of generalized B-splines.

The integration of generalized B-splines into an existing CAD system is described by Antonelli et al. [16] for the uniform bicubic variant. The study reviews the typical architecture of CAD systems and shows how generalized B-splines fit into this architecture without the necessity to touch the existing concepts of the system. In contrast, once implemented, the full range of tools of the CAD system is available to modify generalized B-splines.

The conversion of a generalized B-spline surface to a collection of tensor-product patches is described by Peters [17] for the uniform bicubic variant. The algorithm generally produces one bicubic NURBS patch for each quadrilateral face of the control mesh, but next to irregular control points up to 16 patches are produced for each face. The patches join with curvature continuity except for the vicinity of irregular control points where they join only with tangent continuity. Another algorithm is given by Loop and Schaefer [18] which produces one bicubic Bézier patch for each quadrilateral face of the control mesh, even in the presence of irregular control points. Similar to the previous algorithm, the patches generally join with curvature continuity, but as a concession to the lower number of patches and the restriction to relatively simple Bézier surfaces, the patches join only with position continuity in the vicinity of irregular control points. However, it is emphasized that the patches are at least watertight, certainly not a matter of course in hull form modeling, see for example the work of Edessa et al. [19,20].

The conversion of a generalized B-spline surface to a collection of tensor-product B-spline patches represents the original surface exactly wherever the control mesh is regular, but close to irregular control points the initial surface is only approximated. The regular case is a trivial consequence of the definition of generalized B-splines which is summarized in the next section. The irregular case is, however, significantly more difficult. Given the regular patches, the construction of the remaining patches translates to the problem of filling n-sided holes smoothly with tensor-product B-splines. The complexities of this problem and possible algorithms are described for example by Piegl and Tiller [21], Ye et al. [22], Gregory and Zhou [23], or more recently by Fan and Peters [24-26]. These works indicate that constructions with simple bicubic tensor-product patches, such as Bézier patches, do not suffice to obtain a tangent continuous approximation near irregular control points. In contrast, either sophisticated constructions with multiple knots are required, patches of higher degrees have to be used, or each patch incident to the irregular control points has to be subdivided into at least nine smaller patches, see in particular Peters and Fan [25].

3. GENERALIZED B-SPLINE SURFACES

The title of the paper refers to subdivision surfaces whereas the previous text is mostly speaking of generalized B-splines what essentially reflects two complementary points of view on subdivision surfaces. The first point of view considers subdivision as method to refine polygon meshes of all kind. After a few steps of subdivision the result may look like a smooth surface, but it remains a polygon mesh. The linear nature of polygon meshes is generally not qualified for the representation of hull forms in ship design, although they are often used in the context of numerical simulations. The second point of view on subdivision provides a construction of smooth B-spline surfaces in the presence of irregular control meshes. To clarify the difference of both views, the latter is referred to as generalized B-splines. The subsequent material gives a brief introduction to the basic concepts of the generalized B-splines. The focus is laid on the relevant details for the conversion to tensor-product B-splines. For a more general introduction refer to [14] and the references specified therein.

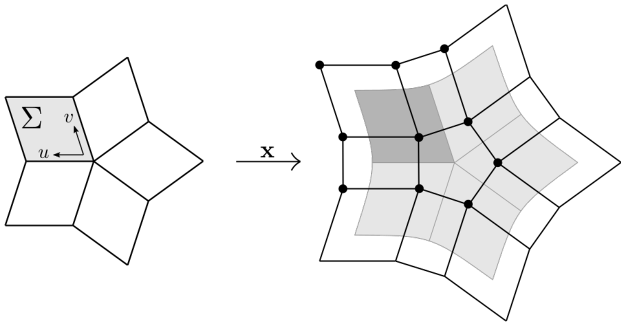


Figure 1: Definition of generalized B-spline surfaces. Left: The domain **S** is given as the composition of unit cells Σ. Right: A schematic view of the surface $\mathbf{x}(u,v,i)$ is shown in gray and the control mesh is shown in black. The surface is composed of patches according to cell layout of the domain. The black dots refer to the control points that influence the shape of the highlighted patch.

3.1 DEFINITION

A generalized B-spline surface is defined over a domain that is composed of unit cells. The restriction of the surface to a certain cell of the domain is called a patch, see Figure 1. This complies with the usual setup in hull form design to represent complex surfaces by a collection of surface patches, but they are now formally treated as a single surface. This may sound trivial at the first glance, but an essential consequence is that the surface is defined on a single control mesh what obviates the need to maintain smooth transitions between the individual patches.

Any point on a B-spline surface is only influenced by a few control points close to it. Therefore each patch is defined only on a subset of the global control mesh, refer to Figure 1 for clarification. In the presence of control meshes of arbitrary topology, this subset is either regular or irregular. Both cases are treated separately.

3.2 REGULAR PATCHES

A regular patch is defined on a regular subset of the global control mesh and can be defined in terms of a tensor-product B-spline. This is characteristic is utilized to convert generalized B-splines to a collection of tensor-product B-splines surfaces when the control mesh is locally regular.

3.3 IRREGULAR PATCHES

An irregular patch is defined on an irregular subset of the global control mesh and cannot be defined in terms of a tensor-product B-spline. The key to define irregular patches is subdivision, the refinement algorithm of meshes which is characteristic for subdivision surfaces. Applied to the control mesh, each step of subdivision introduces new control points, but it does not change the shape of the corresponding B-spline surface. As the control mesh is subdivided again and again, it is possible to define a growing portion of an irregular patch in terms of tensor-product B-splines. Once the part in question is defined in terms of a tensor-product B-spline, surface properties such as points on the surface, normals, or curvature can be computed exactly. Using the method of Stam [5], it is possible to avoid the computational expensive subdivision of the control mesh and to compute these properties directly in terms of the initial mesh.

Unfortunately, neither the recursively definition of an irregular patch, nor the direct evaluation of an irregular patch provides a construction for an equivalent tensor-product B-spline. Hence, the conversion of generalized B-splines to a collection of tensor-product B-splines requires an appropriate approximation where the control mesh is locally irregular.

4. CONVERSION ALGORITHM

The input for the conversion algorithm is a generalized B-spline surface as described in [13]. It is based on a variant of the algorithm of Catmull and Clark [2] and represents a bicubic B-spline surface with creases and corners as additional features. In [12-14] this surface is employed to represent the hull forms of various types of vessels. The conversion algorithm converts this surface to a collection of bicubic Bézier surfaces.

The choice of bicubic surfaces is a natural consequence of the degree of the input surface. Bézier surfaces are the modest variant of non-uniform rational B-spline surfaces (NURBS) which are considered as the industry standard for the representation of hull surfaces.

4.1 ALGORITHM

The conversion algorithm is based on the observation that each patch of a bicubic generalized B-spline surface is associated to a face of the control mesh. The algorithm involves four steps:

Step 1: A bicubic Bézier surface is generated for each regular face of the control mesh. A regular face is four-sided, defined by only regular control points, and all incident faces are four-sided as well. However, the incident faces are allowed to be partially defined by irregular control points. The generated Bézier surfaces are an exact representation of the original surface.

Step 2: The control is mesh is once subdivided what splits each n-sided face into n four-sided faces. In the context of this section, the former is referred to as the *parent face*, the latter are called *child faces*. The effect of subdivision is twofold: the control mesh consists only of four-sided faces what is the prerequisite to obtain a collection of watertight Bézier surfaces in the presence of irregular control meshes and irregular control points are isolated because subdivision regularizes the control mesh

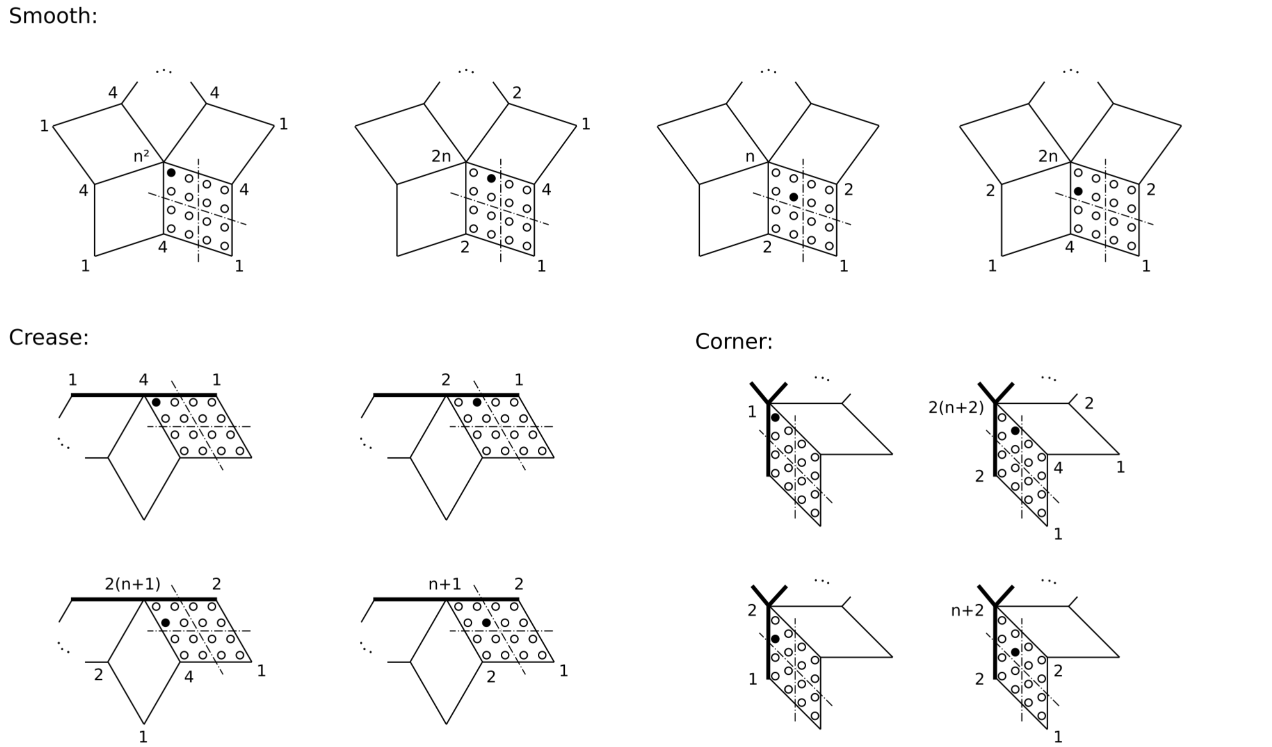


Figure 2: Rules to compute a bicubic Bézier surface which is defined by a grid of 4×4 Bézier points. The rules are specified for a single quadrant of this grid which includes a corner point, two edge points, and one interior point. The other quadrants are given by rotation of the illustrated rules. Each Bézier point is computed by the weighted average of the control points of the control mesh. The appropriate choice of the weights depends on the type of the control point at the quadrant's corner and the type of the incident edges. The illustrated cases are sorted by the control point types: smooth, crease, and corner. Crease eges are illustrated by bold lines, smooth edges are shown with thin lines. The valence of the control point at the quadrant's corner is denoted by *n*.

around them. The subdivision rules for the control mesh are summarized in [13].

Step 3: A bicubic Bézier surface is generated for each child face with an irregular parent face. Irregular parent faces are omitted in the first step of the algorithm. Thus, the third step of the algorithm generates the missing surfaces. Curved surfaces are only an approximation of the original surface, but flat surfaces coincide with the original surface. This is an important characteristic in the context of hull form regions such as the flat side, flat bottom, or flat transom.

Step 4: All generated Bézier surfaces are written to a file for data exchange with other design tools. The authors employ the widely accepted IGES file format, but any other file format which handles B-spline surfaces could be used.

4.2 BÉZIER POINTS

The core of the conversion algorithm is the construction of the Bézier surfaces. A surface is constructed for a face of the control mesh. The surface is defined by a grid of 4×4 Bézier points which are computed based on the control points of the control mesh in the local neighborhood of the face.

The rules proposed by Loop and Schaefer [18] are employed to compute the Bézier points. The rules are reproduced in Figure 2 for a number cases, where each case illustrates the computation of a single point of the grid of 4×4 Bézier points. Only a single quadrant of this grid is covered in the figure because the other quadrants are given by rotation of the illustrated cases. A quadrant includes a corner point, two edge points and one interior point of the grid.

The additional features of the input surface are realized with tags that are applied to the elements of the control mesh. Control points are by default smooth, but can be tagged as creases or corners. Edges are by default smooth or tagged as creases. Each Bézier point is computed as the weighted average of the control points in local neighborhood of the face the Bézier surface is associated to. The appropriate choice of the weights depends on the tag of the control point at the quadrant's corner and the tags of the incident edges. The illustrated cases are sorted by the control point type:

- **Smooth:** The corner point depends on the control points of the incident faces. No incident crease edges are allowed for smooth control points.

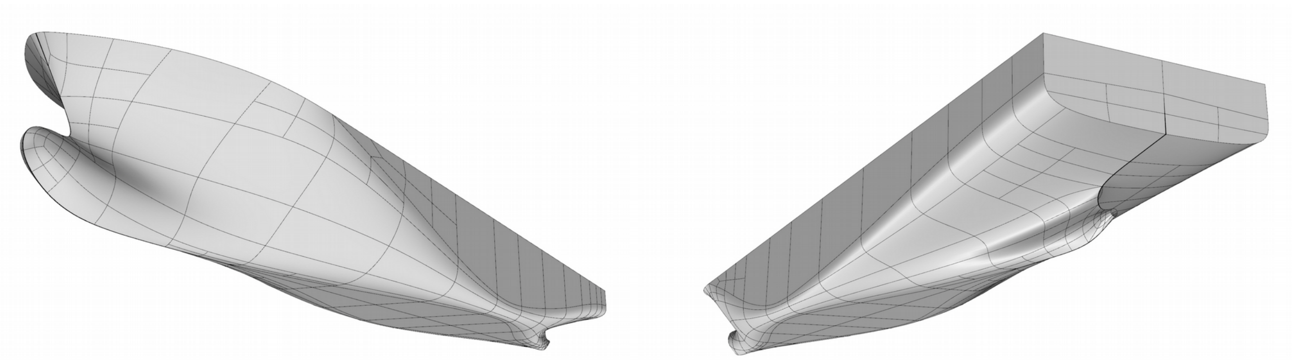


Figure 3: Bézier patches generated for the Generalized B-spline Container Carrier (GCC). In total 189 patches are created to represent the original hull surface. No degenerated patches are generated, what avoids discontinuities in the curved regions of the hull form, but yields a needlessly high number of patches at the forward end of the flat side.

- **Crease:** The corner point depends only on the control points along the two incident crease edges. The computation of the edge points differentiates crease edges (top right) and smooth edges (bottom left).

- **Corner:** The corner point interpolates the control point at the quadrant's corner. The computation of the edge points differentiates crease edges (top right) and smooth edges (bottom left).

5. RESULTS

The conversion algorithm is applied to convert the hull form of a container vessel, which is represented by a single generalized B-spline surface, to a collection of Bézier surfaces. As the individual Bézier surfaces are considered as parts of the hull surface, they are referred to as patches in the following text.

5.1 PATCHES

The vessel is called the Generalized B-spline Container Carrier (GCC). It is a modern container vessel and closely imitates the design of the Duisburg Test Case (DTC) [27]. The main characteristics of the hull form are summarized in Table 1.

The generated Bézier patches are shown in Figure 3. In total 189 patches are created. The algorithm does not create any degenerated patches, where one edge of the patch is set to zero length. On the one hand, this is advisable to avoid discontinuities in curved regions of the hull form, but on the other hand flat regions of the hull form may be represented by a needlessly high number of patches. For example seven patches are generated to represent the forward end of the flat side. As all patches are flat, a single degenerated patch at the tip and an ordinary patch next to it would suffice to represent this part of the hull form properly. The hull form of the GCC includes a flat bar to consider production requirements. Upon conversion this yields a layer of Bézier patches with high aspect ratios next to the center plane, see Figure 5 for clarification. Although

	GCC	DTC	Δ
L_{PP} [m]	355.0	355.0	
B [m]	51.0	51.0	
T [m]	14.5	14.5	
C_B [-]	0.661	0.658	-0.46%
C_M [-]	0.987	0.989	+0.20%
C_P [-]	0.669	0.665	-0.66%
C_{WP} [-]	0.846	0.845	-0.11%
LCB [%]	-0.967	-1.038	-0.15%

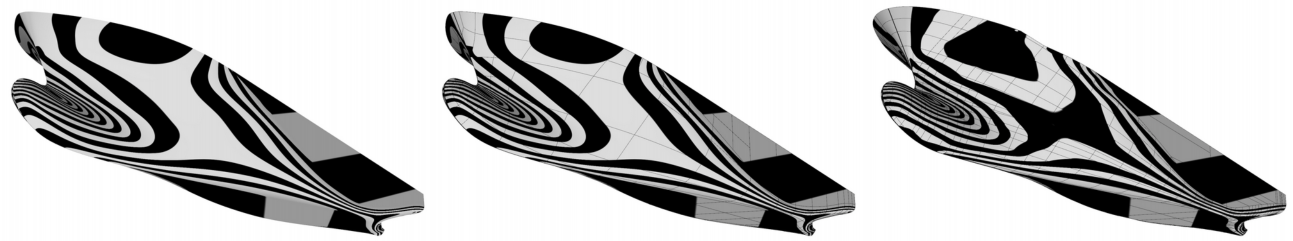
Table 1: Main dimensions of the Generalized B-spline Container Carrier (GCC). The vessel reflects the design of the Duisburg Test Case (DTC).

there is a potential to further minimize the number of generated Bézier patches, the total number agrees with the result of state-of-the-art modeling systems which mostly employ a curve network to construct the surface patches. The hull form of the DTC is for example modeled with this method and the hull surface is composed of even 660 B-spline patches. However, the authors believe that this number could be at least halved without sacrificing the precision of the hull surface definition.

5.2 QUALITY

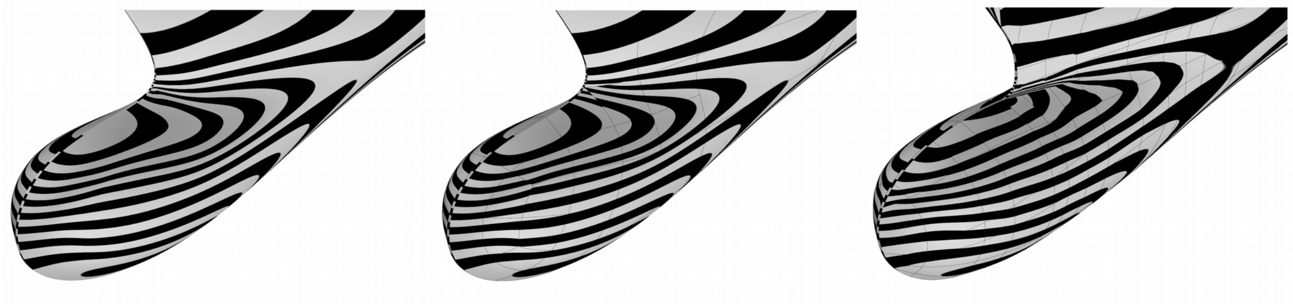
A previous study [12] shows that using a generalized B-spline surface to represent a hull form improves the quality of the hull representation. The study compares the GCC to the DTC, what brings up the question whether this still applies after the conversion to a collection of Bézier patches using the algorithm given in Section 4.

The first observation is that the Bézier patches generated for the GCC are watertight as opposed to the patches of the DTC. The patches next the flat of side and flat of bottom of the DTC are not connected to each other, what supposedly results from an inappropriate manual definition of the flat patches after the curved patches are generated from the curve network. The result are gaps



(a) Generalized B-spline surface (b) Conversion to Bézier patches (c) Duisburg Test Case (DTC)

Figure 4: Quality analysis of the generated Bézier patches. Smooth reflection lines show curvature contiuity, straight reflection lines indicate fairness of the hull surface. Left: GCC represented by a single generalized B-spline surface. Middle: GCC converted to a collection of Bézier patches. The overall quality of the original surface is mainted. Right: The patches of the DTC show a lack of smoothness compared to the two other cases.



(a) Generalized B-spline surface (b) Conversion to Bézier patches (c) Duisburg Test Case (DTC)

Figure 5: Detailed quality analysis of the bulbous bow. Left: GCC represented by a single generalized B-spline surface. Left: The conversion to a collection of Bézier patches introduces continuity errors between a few of the patches. Right: The hull surface of the DTC also also affected by discontinuities. The overall situation is even worse.

and overlaps between adjacent patches. These kind of issues occur frequently in practice and require substantial effort to be handled in downstream analysis methods.

More technically, the former characteristic is referred to as zero-order continuity of the patches. The second component of the quality assessment covers the high-order continuity. The bicubic generalized B-spline surface which is used to represent the GCC is curvature continuous (G^2) everywhere except for a few irregular points where it is only normal continuous (G^1). Across features, such as knuckles, the continuity characteristics of the surface are intentionally different. Ideally, the generated Bézier patches inherit the continuity properties of the original surface. Figure 4a shows the reflection lines of the GCC which are smooth as supposed for curvature continuity, Figure 4b shows the reflection lines for the generated Bézier patches. Figure 4c shows the reflection lines for the DTC as reference of the state-of-the-art. The reflection lines of the DTC are clearly not as smooth as the reflection lines of the GCC. The superior quality of the GCC is mostly maintained by the generated Bézier patches and still better than the DTC. However, the Bézier surfaces are less smooth than the original model as the detailed analysis of the bulbous bow in Figure 5 reveals. Again, the original hull surface of the GCC is compared to the generated Bézier surfaces and the patches of the DTC. In Figure 5b, a mismatch of the reflection lines across some of the patch boundaries indicates discontinuities of the normals. The respective patches form a knuckle along the common boundary which is difficult to spot based on the surface shading, but easily seen by the mismatch of reflection lines. The relevant Bézier surfaces are considered as irregular and the Bézier point computation given in Section 4.2 yields only position continuous surfaces. However, the patches of the DTC suffer from the same discontinuities and the overall situation shown in Figure 5c is even worse.

5.3 ACCURACY

The last analysis covers the accuracy of the generated Bézier patches. The geometrical deviation of the original surface and the generated Bézier patches is illustrated in Figure 6.

As explained in Section 4, the algorithm generates one surface for each face of the control mesh and differentiates between regular and irregular faces. Similarly, the generated Bézier patches may be classified as regular or irregular. Regular Bézier patches are an exact representation of the original surface. As well-behaved control meshes for hull forms are mostly regular for the reasons given in [14], most Bézier patches are regular and consequently large parts of the hull surface of the GCC are exactly represented by the Bézier patches. In contrast, irregular Bézier patches are only an approximation of the original surface. Irregular interior patches do not show any significant deviation, but the boundary patches deviate up to 0.05m from the original surface.

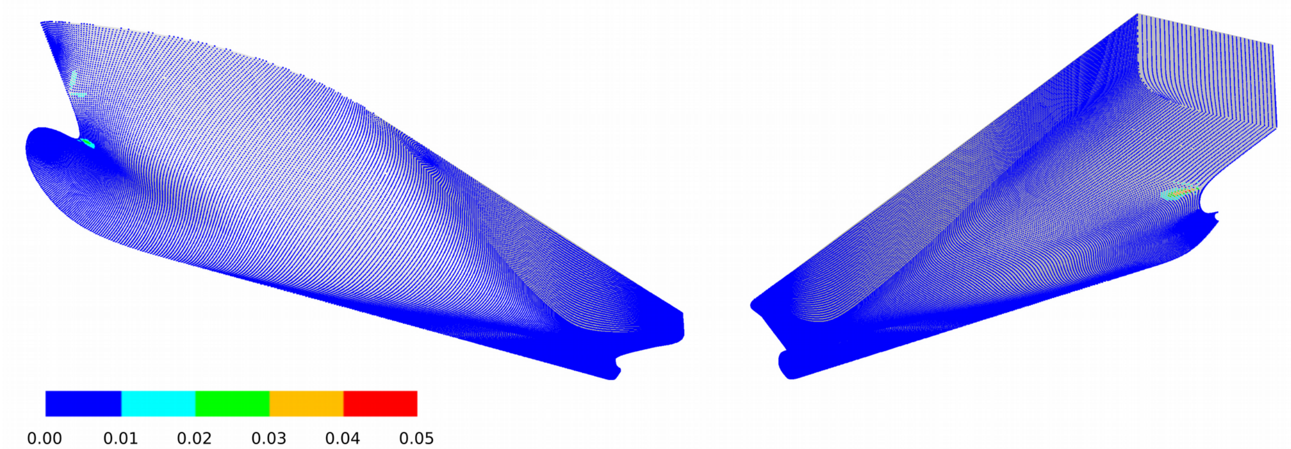


Figure 6: Geometrical deviation of the generated Bézier patches to the original surface. Large parts of the hull surface are exactly represented by the Bézier patches so the deviation is zero. In the vicinity of irregularties the original surface is only approximated by the Bézier patches. In the interior this is neglible, but on the boundary the Bézier patches deviate up to 0.05 m form the original surface (L_{PP} = 355.0 m).

6. CONCLUSION

Tensor-product B-spline surfaces are the industry standard for the representation of hull forms, but they suffer from their limitation to four-sided surfaces. Generalized B-splines originate from the field of subdivision surfaces and allow to define B-spline surfaces of any complexity.

A practical integration generalized B-splines into the ship design process is the conversion to collection of tensor-product B-splines which can be shared with other design tools that do not support this surface representation. This study presents an algorithm to generate a collection of Bézier surfaces, the simplest variant of tensor-product B-splines. The number of generated Bézier patches is similar to the usual number of patches used to represent hull forms. The generated Bézier patches are always watertight and the superior quality of the generalized B-spline surface is mostly maintained. Only at a few irregular spots the quality is less. The same holds for the accuracy of the Bézier patches as most parts of the original hull surface are exactly represented, but in the vicinity of irregularities the original surface is only approximated.

The approximation error is negligible in the interior of the surface, but may be notable at the boundary and other surface features such as knuckles. Therefore future work should address the surface construction for these cases. In addition, there is a potential identified to further reduce the number of patches generated for flat regions of the hull form.

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