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Technical note

A technical note on the geometric representation of a ship hull form

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ABSTRACT

In a recent special issue on ship design of this Journal the applicability of NURBS surfaces for ship hull representation was commented upon, as part of a review of challenges. The authors rightfully point out that NURBS do have their problems when applied to ship hull modelling. The review mentions T-splines as a promising solution, and concludes that the development of applications that address the NURBS limitations remains a challenge. However, just lifting out T-splines as the only solution can be considered to be a bit meagre, because many more alternatives have been proposed in the literature over the years. In addition, applications for ship design that overcome the limitations of NURBS surfaces do exist and are being applied in the maritime industry.

As an extension to the special issue paper, in this short *technical note* the NURBS deficiencies are put into a context, and other potential solutions besides T-splines are summarized. It is illustrated that a viable alternative is offered by a hybrid representation method, comprising elements of a solid model and transfinite interpolation of an irregular network of curves, combined with curve fairing functionality. Because no single method is superb, suggestions for further research are formulated at the end of this note.

1. On the applicability of ship hull representation by means of NURBS surfaces

The 2012 special issue on applications in ship and floating structure design and analysis of this Journal contains an overview-paper, [1], where a number of key research areas are identified. Section 2.2 of that paper is about the geometric representation of a ship hull form, and here it is observed that, although NURBS surfaces are the *de facto* standard for hull shape modelling, they suffer from a number of drawbacks. These are, summarized:

- NURBS are based on rectangular patches, which are basically incompatible with the non-rectangular topology of (parts of most) ship hulls.
- In order to cope with this incompatibility, large numbers of control points are required. This causes complications regarding surface fairing and leads to high computation times, and ultimately limits the applicability of NURBS.
- For smoothing or fairing purposes the incorporation of physics-based or optimization methods would be preferable. However, this leads to high computational costs.

In general, these observations are in accordance with the daily practice of ship design. However, such conclusions have been drawn earlier. The first paper where the mentioned disadvantages are analyzed regarding ship design was published in 1997, [2], which explains the regularity[1] problem in words and pictures. This analysis was both re-iterated as well as further elaborated in [3–7]. Another and more general documentation of the shortcomings of NURBS surfaces is found in [8, Chapter 2.2] which, amongst other things, exemplifies that degenerate patches not only cause numerical challenges, but that control points in nearby columns get squeezed together, causing additional fairing problems. The disproportional density of control points in these regions, and the accuracy requirements that follow, may even strain the capabilities of physics-based frameworks and other optimization techniques. Neither are degenerate patches symmetric.

These references also identify two more practical drawbacks of NURBS, in addition to those already enumerated in [1]:

- The indirect control of the surface shape. After all, with NURBS the user does not control the actual hull surface, but, from a users' point of view, external handles which are loosely coupled to the surface.
- Rows or columns of vertices are organized in an arbitrary way over the hull surface, so the object of manipulation is not the

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[1] We prefer the word *regular* instead of *rectangular* as used in [1], because the reported problems of the NURBS are not only caused by its four-sidedness (i.e. rectangularity), but also by its property that all rows and columns of vertices have to extend over the entire patch, in other words its regularity requirement.

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familiar planar intersection, such as a waterline, ordinate or buttock, but some spatial line instead. In practice many design guidelines are related to numerical[2] or morphological[3] properties of such sections, so, consequently, they cannot be used anymore in combination with NURBS.

Despite the drawbacks of NURBS surfaces they can be successfully applied in some cases of ship hull form design, notably for hull shapes that are morphologically not too complex, as e.g. yachts or workboats can be. Also on the methodological front new options are being developed, such as the incorporation of practical developable surfaces within the NURBS framework in [9], or the parametric generation of a ship NURBS surface in [10]. However, such application-related developments do not address NURBS' core methodology, so a survey into alternative methods may be fruitful. This will be performed in the next section.

2. On the possible solutions

In the targeted paper [1], the analysis of the problem and the potential solutions are entangled; in the same enumeration of NURBS deficiencies a solution is co-suggested: T-splines. However, it would have been better to make a distinction between problem analysis and solutions, for there are more viable alternatives. For this it is beneficial to differentiate between two groups of methods:

1. approximation of a control mesh,
2. interpolation of design curves.

2.1. Approximating methods

Approximating methods continue using the same paradigm as traditional NURBS surfaces, in which the surface shape is derived from distinct control points positioned in the vicinity of the surface. Solutions include:

- Indeed, T-splines [11]. Contrary to what [1] suggests, T-splines are available to the naval architect already [12]. This solution might provide a feasible alternative to NURBS, however, we note that
  - T-splines, like NURBS, allow no variations in knot spacing across faces and T-joints,
  - the polynomial degree of T-splines is generally fixed at three (although recent research defines a subset of T-splines of arbitrary degree [13], at the cost of topological restrictions on the T-mesh),
  - being a superset of cubic NURBS, T-splines are in theory able to describe algebraic surfaces. But how well algebraic regions can be embedded in a larger T-spline surface seems to be undocumented. Something as simple as defining a parallel mid body with circular bilge radius and smooth transitions to fore and aft ship may still not be straightforward, if practically possible.

  It will be interesting to see the implications of these properties for practical ship hull modelling.
- NURBS with extraordinary points [14]. This is another generalization of NURBS, supporting higher (but odd) degree surfaces.
- Subdivision surfaces (see e.g. [15]). Methods for direct evaluation of shape and curvature exist [16], as well as solutions against impurities around extraordinary points [17]. Again, subdivision surfaces have been commercially available in MCAD systems for half a decade [18].
- Manifold surfaces. This is another approach to modelling free-form surfaces of arbitrary topology based on the concept of overlapping charts [19]. The method was further elaborated in many more recent publications, resulting in very high quality surfaces well suited for various kinds of numerical analysis.
- Stick with NURBS surfaces, while trying to overcome the fundamental problems with user-interface wizardry. For example: n-sided holes can be filled with n smaller NURBS patches [20].

All these approximating solutions retain the following disadvantages:

- Indirect control over the ship hull surface.
- Parameter lines generally do not align with waterlines, frames and buttocks, which are the lines that are important to the naval architect.
- The placement of extraordinary points needs planning.
- Adding surface features that do not align with the control mesh requires remodelling, with or without refinement.

2.2. Interpolating methods

The limitations of NURBS surfaces, including the retained problems mentioned above, can be circumvented with a paradigm shift. Solutions include:

- A network of curves where the meshes are 'filled in' with surface patches, as can be obtained by transfinite interpolation. Such a solution was proposed in [21,22]. Furthermore, work on the smoothness of a network of curves and the continuity of derivatives along the edges and at the corners of the surface patches is reported in [23–25]. An alternative with the meshes filled in with G^1 Bézier patches is given in [26].
- Extend the wireframe from the previous method with a *solid model* in order to ensure topological consistency. This solution was first proposed in [27], while the first application in ship hull modelling has been reported in already referred Refs. [2–7, amongst others], where it was baptized the *hybrid representation*. The *hybrid representation* allows continuous curves to run along the hull in arbitrary fashion, while a B-rep solid model maintains the topological consistency of the curves and their intersections. The resulting n-sided meshes are transfinitely interpolated to produce a G^1 continuous surface. This representation is well suited to be combined with curve fairing methods, which produces an effective system for the production of complex ship hull forms, at and beyond production accuracy.

The method above has been elaborated and implemented in a commercial software package for the design of ship hull forms, see [28] as well as Fig. 1. This product, which has recently undergone an extensive rewrite and modernization [29], shows that the *hybrid representation* method is viable and practically useful; it is in fact frequently used to correct deficiencies in models produced by NURBS surface-based hull modellers. Nevertheless, there is sufficient room for enhancements, some of which will be discussed in the next section.

We emphasize that the *hybrid representation* method explicitly supports the requirements of space and volume as stated in [1, Section 2.2], and that the curves that are important for design and for production are directly under the control of the naval architect. There are no limitations on the degree or parametrization of curves, nor on the topology of the network except that curves must start and end on other curves. Curves can even be defined as an arithmetic combination of other curves, in a master/slave relationship. In addition, the system is capable of computing high-precision plate expansions, and the use of developable surfaces is explicitly supported, which is important for cost-effective production. The shape in developable areas is governed by the classical

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[2] Such as the required *ordinate* area (as derived from the desired sectional area curve) or the *waterline* entrance angle.

[3] Such as the degree of U or V-shapedness of an *ordinate*, or the notion that hollow *waterlines* should be avoided.