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A TOPOLOGICAL APPROACH TO HULL FORM DESIGN

Abstract

The traditional approach of the design of lines of the ship is based upon sections lying in mainly orthogonal planes. Fairness and coherence was maintained and judged by a human designer, partly in a heuristic way.
Contemporary CAD methods which follow this traditional approach are inefficient, because they lack heuristics.

CAD methods which are based upon state-of-the-art mathematical formulae for surface modeling, such as B-splines or NURBS, cannot handle sections lying strictly in orthogonal planes. Due to their inflexibility they are unsuitable for production fairing. Methods based on 3D line modeling may lead to topological inconsistent models.

After a discussion of popular computer methods, the main disadvantages of these methods will be discussed, as well as some possible alternatives. Finally the new hullform modeling program "Fairway", which is based on the alternative methods, will be described and by means of some examples it is demonstrated that traditional limitations do not occur with the Fairway approach.

1. BRIEF HISTORY OF COMPUTER AIDED SHIP DESIGN

Since the dawn of the computer era many methods have been developed to define a hull form of a ship in a computer, for calculations, manipulations, drawings and logistics. In a few decades the mathematical formulations for geometrical representation have evolved considerably (see [2] for further detail):

<u>1950 - 1975</u> Polynomials and composite circular arcs

<u>abt. 1965</u> Extension of polynomials to "Bezier curves".

<u>1974</u> Extension of Bezier curves to Basis-splines, abbreviated to B-splines. When for a line in 3D space a vector function *s* is a function of parameter *u* then the B-spline representation for the line is

$$s(u) = \sum_{i=0}^{L+n-1} d_i N_i^n(u) \qquad (1)$$

where d_i are coordinates of the 3D vertices, *N* are the B-spline basis functions, and *n* is the degree. For a B-spline surface with parameters *u* and *v* the B-spline surface is defined (with basis functions *N* and *M*) by

$$s(u,v) = \sum_{j=0}^{K+n-1} \sum_{i=0}^{L+n-1} d_{i_j} N_i^n(u) M_j^n(v) \qquad (2)$$

parametrization can be choosen uniform or non-uniform, so they can be called Uniform B-Splines (abbreviated UBS) or Non-Uniform B-spline (NUBS). The most popular non-uniform parametrization is chord-length, where parameter value is more or less proportional to the line length. The most popular B-Spline is the cubic one, where degree n is 3.

abt. 1980 Implementation of an idea from the sixties: Inclusion of an additional term in the B-Spline formula. Line equation from (1) is extended to :

$$s(u) = \sum_{i=0}^{L+n-1} w_i d_i N_i^n(u) \Big/ \sum_{i=0}^{L+n-1} w_i N_i^n(u) \qquad (3)$$

where w_i is an additional weight factor. Because the ratio between numerator and denominator is governing the shape of the spline, this was baptized Rational B-Spline. It comes in two flavors: Uniform parametrized Rational B-Splines (URBS) and Non-Uniform parametrized Rational B-Splines (NURBS)

abt. 1990 Bezier curves and surfaces, B-Splines and NURBS are de facto standard in CAD.

All discussed formulae can be used 2D and 3D, implemented in line or surface methods respectively. With line methods lines of the hull surface, such as ordinates or waterlines are defined, which together form an implicit surface. The major advantage of the line method is the simple definition of existing hull forms.

With surface methods the hull surface is described by one or more regular networks of equiparametrical defining lines which extend over the complete surface. See figure 1, where the lefthand surface is defined by the righthand network. A 1:1 relationship exists between surface and network: Manipulation of the surface is performed by manipulation of the network. The main advantage of the surface method is the possibility of deriving an intersection or cross section (such as waterlines and buttocks).

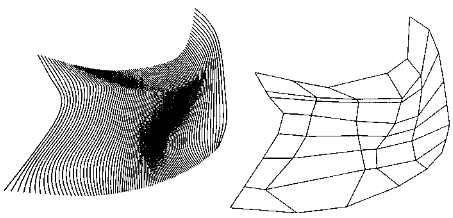


Fig. 1 Network and surface

2. EXAMPLES AND DISCUSSION OF POPULAR COMPUTER METHODS

With these methods many successful implementations of hull form systems have been made, as illustrated in the figures 2 to 4, and by most appealing examples of output with color, light sources, and rendering as can be found in leaflets and brochures. Unfortunately, to our experience, gradually complaints began to rise in the shipbuilding community about major drawbacks of the available computer methods.

2.1 ONE-WAY TRAFFIC FROM SURFACES TO LINES

Indeed it is possible to derive specific lines from surfaces, but *in general* it is not possible to generate a surface from an arbitrary composition of lines. Such a possibility is really missed, because it would enable the generation of additional lines, via the surface.

2.2 EQUI-PARAMETRICAL DEFINING LINES

The defining lines of the network are equi-parametrical: they have one parameter value in common. They are *in general* not parallel to the main orthogonal planes of the vessel. So the user must be prepared to work with more or less arbitrary 3D lines over the surface. For exact modeling (fairing!) or specific control (for example waterline entrance angles) this is cumbersome.

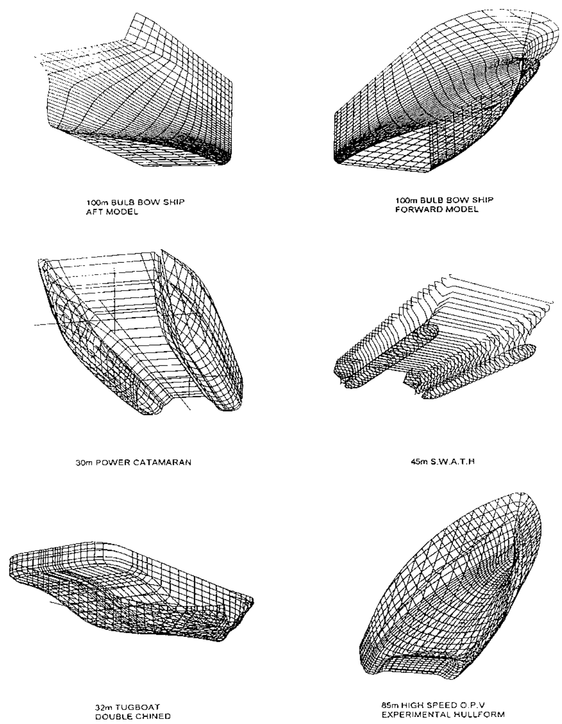


Fig. 2 Commercial brochure abt. 1990

2.3 NETWORK REGULARITY

The regular network is too rigid. As men-tioned all surface methods work with a regular equi-parametrical network, while real-life vessels can more effectively be described by a non-regular network, allowing for, for example, partial waterlines, additional local shape information, integrated stem round-offs etc.

2.4 FAIRING PROBLEM

Neither with line methods, nor with surface methods it is possible to perform production fairing, including local refinements, such as bulb shapes or specific radii in stern or stem, and taking into account that the naval architectural definition of "fairing" differs from the mathematical one, which is in general based on the continuity of higher derivatives.

For example in the midship section a naval architect likes a straight bottom line, a circular bilge, followed by a straight side, leading to discontinuities of curvature (the straight lines have zero curvature, the curvature of the bilge is 1 / bilge radius). The curvature κ of line *s(u)* is

$$\kappa(u) = \|\dot{s} \times \ddot{s}\| \; / \; \|\dot{s}\|^3 \qquad (4)$$

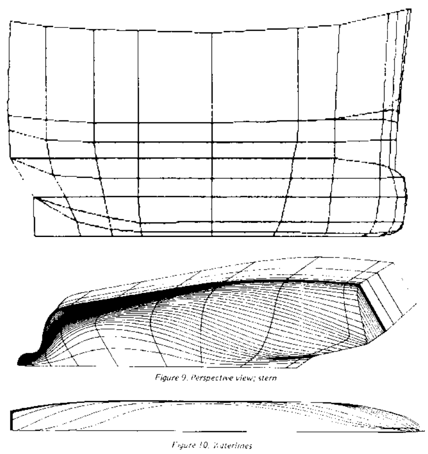


Fig. 3 Spline net and surface ([3]), 1984

Because there is tangent continuity, the curvature discontinuities must lead to a discontinuous second derivative which is in conflict with the mathematical definition of "fair", and indeed the transitions between the three segments are being smoothened out when mathematical fairing techniques are used.

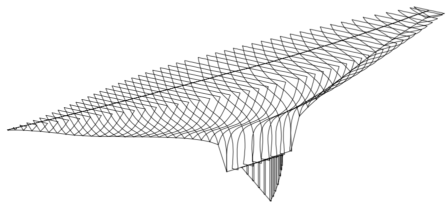


Fig. 4 PIAS Hullform generation (1988)

3. SUMMARY OF DISADVANTAGES OF CURRENT COMPUTER METHODS

The main problem of line methods is the inherent incoherence of the lines, and the main problem of surface methods lies in the rigidity of the network. Mathematicians have invented powerful surface methods based on *regular*, or *parametrical rectangular*, networks, but practically all networks in shipbuilding practice are *irregular* (Fig. 5). Of course one can try to simulate irregularity by using multiple networks, but in the first place that does not solve the basic underlying problems of regularity, and in the second place such an approach would give additional difficulties in the regions where the different networks meet.

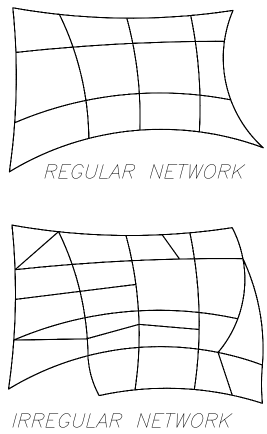


Fig. 5 Network regularity

At a closer inspection we see indeed that all examples presented sofar do have a nature where one or a few regular networks can be used to model the hull. For hull forms of a more complex nature however it is very hard, or sometimes practically impossible, to map the network(s) on the hull form. Please note in this context that all vessels of figure 2 have longitudinals, except for the SWATH vessel, where only ordinates are drawn. Apparently for the vessels with the longitudinals a surface model was used, but the SWATH was only defined by editing or digitizing simple lines: the SWATH did not fit into the net.

Or look for example at the hull of figure 6, where a regular network would not fit around the stern portion. The network lines over the skeg should stop at the aftside of the skeg, while the network lines over the bottom should continue further afterwards. Besides there is an important definition line, namely the "centerline" of the skeg, which does not need to cover the whole hull surface (preferably not !) and which makes the network irregular.

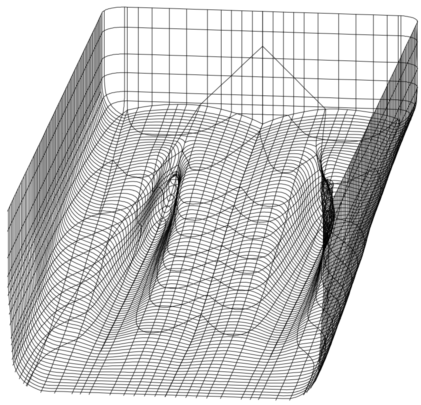


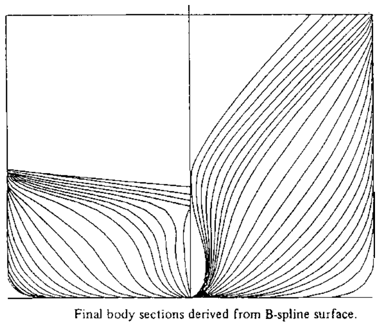
Fig. 6 Stern part showing angled skegs

Even examples can be found where the designer experienced difficulties in matching the network to the hull form, and for the sake of convenience skipped the complete bow and stern regions (Fig. 7).

4. THE QUEST FOR A BETTER METHOD

Most appropriate for ship modeling would be a surface system based on a irregular network, with geometry formulae allowing for fairing in the naval architectural sense of the word. The reductionist paradigm has not yet been beaten, so we tried to advance by splitting up the complex problem into partial ones:

- Definition and fairing of single lines.
- Maintaining a coherent irregular network, which glues all lines together.



Final body sections derived from B-spline surface.

- Surface description, automatically derived from the single line definition.

For each of the partial problems a satisfying, be it sometimes exotic, technique was discovered in literature.

4.1 DEFINITION AND FAIRING OF SINGLE LINES

B-Splines and NURBS are quite adequate to model a variety of curved lines. We have favoured the NURBS, because in some specific forms they are the vehicle to represent arbitrary curved lines, straight lines, circles, parabolas, ellipsoid and hyperbolas, all with one formula.

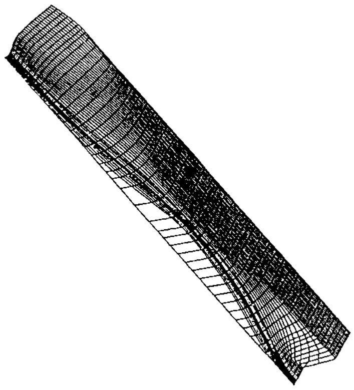


Fig. 7 From [6], 1986

The line fairing problem has been tackled by implementing an adapted least-squares algorithm. This scheme gives the user the possibility to fair a line automatically, taking into account the user-specified mean deviation between the original points and the final line. Secondly for each individual point the user may specify an individual weight factor, so that the resulting fair line is more attracted by points with a higher weight factor. This mechanism resembles the traditional batten, where the mean deviation models the (reciprocal of the) stiffness of the batten, and the weight factors model the weight of the leaden ducks.

4.2 MAINTAINING A COHERENT IRREGULAR NETWORK

A simple combination of 3D lines cannot describe an unambiguous 3D object. Take for instance the object of figure 8, where a geo-metric definition only is insufficient (left side). The geometric 3D left hand figure can be any of the three right hand real-life objects. One might question the relevance of this issue, but suppose the object is part of a vessel, then when making a horizontal section through the model (e.g. when generating a waterline), the outcome for the three cases is quite different! Additional information about connection of lines is lacking, as well as the surfaces that may exist between them, in other words: the model is topological ambiguous.

The required additional information can be delivered by the technique of the so-called "Boundary Representation" [7] or BREP, where a complete list of relations between primary objects is maintained. Those objects are points, line-segments and surfaces, or "vertices", "edges" and "faces" in BREP-parlance. Is V is the number of vertices, E the number of edges and F the number of faces, the under certain conditions the so-called "Euler formula for polyhedra" states that

$$V - E + F = 2 \tag{5}$$

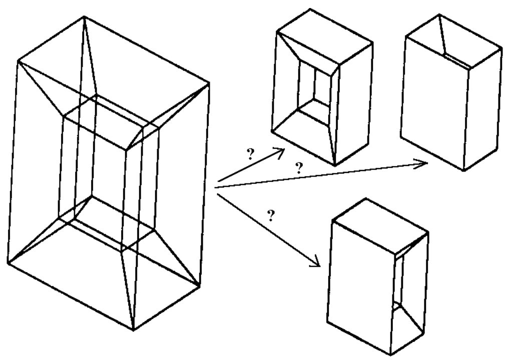


Fig. 8 Geometric definition only is ambiguous

Now a set of operators can be defined which do not violate (5), called Euler operators, for instance "Make Edge and Vertex", "Make Face and Edge" or "Kill Face and Edge". Starting with a very simple valid topological model (for instance a solid, consisting of only one vertex), the topological validity can never be violated when only Euler operators are used. It has been proven in practice that this approach eliminates topological ambiguity.

4.3 SURFACE DESCRIPTION

On top of the network of lines lies a surface description. Techniques have been developed which recognize regular sub-surfaces. These regular sub-surfaces are modeled by Gordon patches ([4]) or Coons patches ([1]). After mapping the main surfaces this way some small non-rectangular surfaces remain (triangles, pentagons, hexagons), which are mapped with methods of [5]. The constructed surfaces are of help when making cross sections, and are needed for visualisation purposes (light sources, shading etc.).
It must be emphasized that the complete process of recognizing, mapping and modeling of the surfaces is performed fully automatically. No user interaction is required, or even possible.

5. FUNCTIONS OF FAIRWAY

The new approach described above has been implemented in a new software module, baptized "Fairway". Fairway is part of SARC's PIAS suite of naval architectural programs for hull design and numerous design calculations, such as hydrostatics, intact and (probabilistic) damage stability, longitudinal strength, weight estimation and resistance and propulsion. PIAS is used by nearly a hundred organizations.
Based on the analysis as discussed, Fairway offers the following functionality :

- A coherent irregular network, based on a full-blown BREP.
- 3D graphical manipulation in Windows (not necessarily Microsoft), where each window gives a view on the one and only underlying 3D model. In other words: When the model is updated by an action in one of the windows, all other views, in other windows, are instantaneously updated.
- Automatic fairing, with the aid of *mean deviation* and individual weight factors as described in 4.1.
- Multiple line definitions: Generally curved (NURBS), exact circular, parabolic, ellipsoid, hyperbolical and straight.
- Line shape of the generally curved lines can be manipulated by means of the vertices, or by tangents at the line ends.
- Line segments *can* be connected by means of a master/slave relation. With this mechanism the tangent of one line end can be declared equal to the tangent of the end of the connected line segment. For example, this mechanism can be used for waterline round-offs, where after the proper definition the round-off will be modified automatically, after any waterline modification.
- Addional surface methods, such as generally developable, extrusion, cone and cylinder and doubly curved
- Calculation of simple upright hydrostatics, such as volume, coefficients, metacentric height etc.
- Hull form transformation, according to different methods, such as linear scaling, Lackenby frame shifting, and inflation / deflation of ordinates.
- Support for Sectional Area Curve (SAC). By means of the SAC the user can work straightforward towards a desired block coefficient and LCB.
- Composition of a lines plan, on users specification.
- Conversion of the 3D model to Autocad (DXF, 2D as well as 3D), IGES (NURBS lines as well as surfaces), Dawson (MARIN's potential flow software), Eagle, NUPAS and FEM software.
- Shell plate expansion.
- The so-called "hull-server", where a direct link between Fairway and a drafting package is established. With the hull-server the drafting packa-

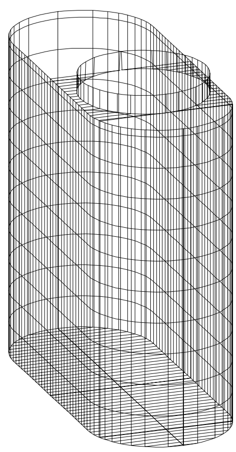


Fig. 9 Tank hatch

ge can obtain any cross section from Fairway and treat it as if it was created by the drafting package itself. To the user Fairway remains invisible. The only interaction is with the drafting package.

With Fairway it is possible to design simple elements (fig. 9), but also complex ships, such as the reefer (fig. 10) from which, by the way, a previous "PIAS hullform generation" version decorates the announcements of this HYDRONAV conference.

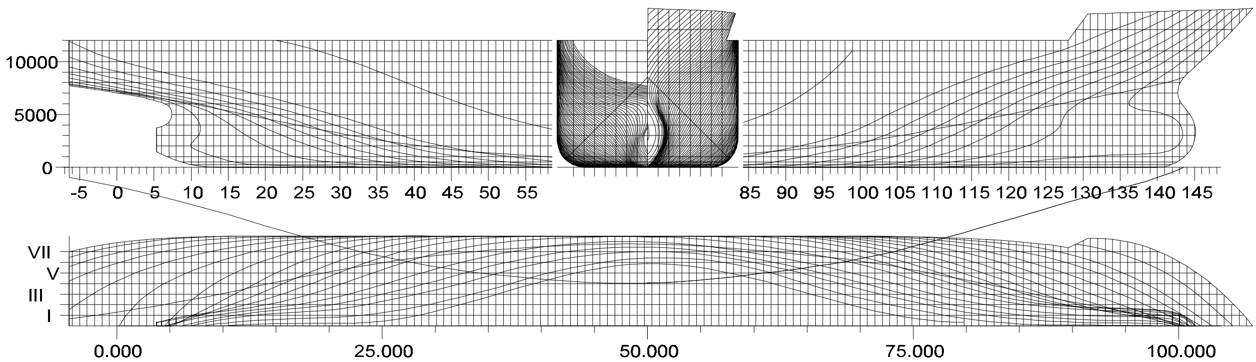


Fig. 10 Reefer vessel

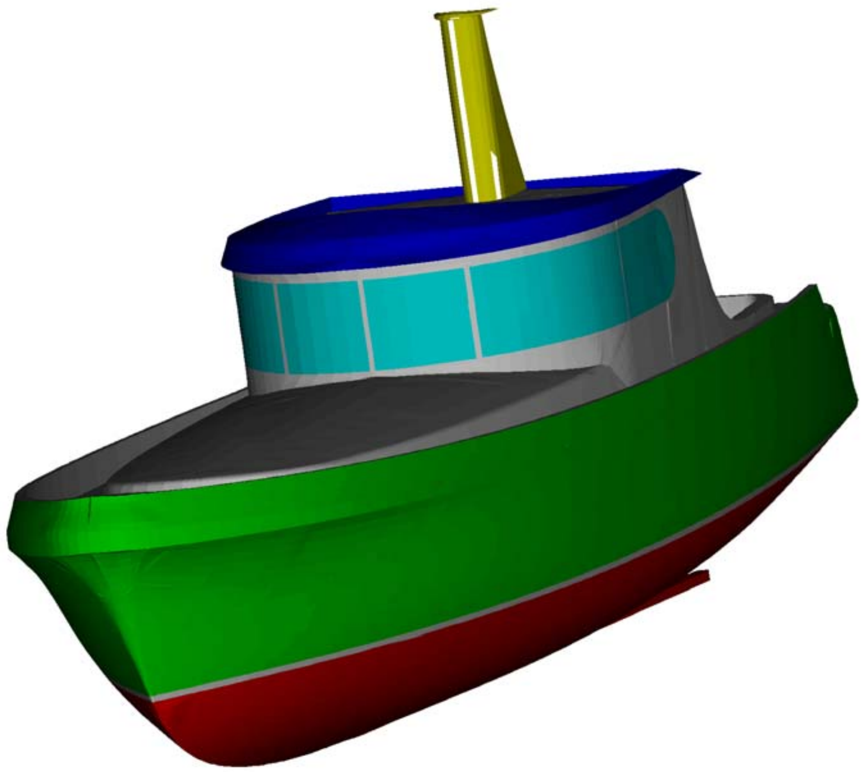


Fig. 11 Complete model of hull, deckhouses and mast in Fairway

Conclusion

The traditional B-Spline or NURBS surface methods are inflexible due to the rigidity of the parametrical rectangular network, so when used for hull design the designer must spent much time and energy to try to work around the limitations; the designer must split his attention between the design process itself, and the caprices of the CAD system.
The presented combination of techniques, implemented in Fairway, overcomes the traditional limitations and alway leads to a consistent, topological valid 3D ship model.

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