Integrating Parametric Hull Generation into Early Stage Design

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1 Introduction

The concept and initial design phases of a ship can be highly dynamic periods where main features and dimensions are subject to frequent change in search of a good balance between often conflicting requirements. The duration of this design period varies depending on ship type and owner requirements. Specialist one-off designs may require tailored engineering solutions. The hull form affects hydrodynamics, production costs, and operation of the ship. Modern integrated ship design tools primarily focus on the analysis of hull performance rather than providing capabilities to investigate the design space. While analysis is important, designers increasingly demand better hull surface definition to allow ranges of solutions to be investigated easily before proceeding to detailed design.

Given the complex nature of the ship system, the design tools used to produce a solution must address a wide range of engineering disciplines. In addition to analysing compliance with owner and regulatory requirements, a successful tool must allow the user to investigate the design space adjacent to a solution to identify optimisations or alternative approaches which may offer better performance. As a platform supporting the entire ship system, the hull is the single most important component in any vessel. Its form affects the hydrodynamic and structural performance of the vessel during operation and the ease of construction when in production. Modern integrated ship design tools primarily focus on the analysis of hull performance rather than providing capabilities to investigate the design space. While analysis is certainly extremely important, the approaches used to assess hull performance have matured and designers now need improvements in hull surface definition to allow ranges of solutions to be investigated easily before committing to the detailed design phases.

2 Mathematics in Hull Form Representation and Design

While the mathematical representation of hull surfaces can be traced as far back as *Chapman (1760)*, designers preferred to use practical methods, battens and weights, to control the shape of hull surfaces until the introduction of desktop computers and CAD software tools became affordable and effective to use in a commercial environment. The use of mathematical representations of hull surfaces was initially driven by the needs of analysis techniques, particularly hydrodynamics, rather than designers. *Taylor (1915)* developed use a polynomial approach which assisted in the development of a series of hull forms based on an initial parent that could be used to investigate the effect of different form parameters on resistance. *Benson (1940)* extended this technique so that it could be quickly used to generate waterline and section curves for use in the design office.

High-degree polynomials require many offset data points to produce acceptable shapes and introduce complexity in manipulation. For analysis such as seakeeping, an alternative hull representation based on conformal mapping techniques was developed. These approximate the hull sections by simpler geometric forms permitting quasi-analytic hydrodynamic solutions. *Von Kerczek (1969)* developed one of the first computer based hull design systems based on this technique where the user could use a light pen to manipulate point offsets which would change the shape of the hull surface.

With a mathematical relationship between hull shape and performance, it was not long before attempts were being made to develop techniques which would produce the hull form geometry based on parameters governing geometric and performance characteristics. *Kuiper (1970)* introduced a technique loosely based on Benson's approach which – rather than base the hull representation on offset data – used initial parameters describing hull characteristics used to generate longitudinal form curves (waterline, profile, section area curve) or influence functions used to generate individual section

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geometry. This approach was rather successful and used by many subsequent techniques. However, there were still limitations in the mathematical functions used to represent the hull surface itself in that they were just not flexible enough to represent the range of hull surface shapes. *Reed and Nowacki (1974)* combined the use of the conformal mapping technique below the waterline and polynomial functions above to make a small improvement and allow flare, but limitations still remained.

While these developments were taking place, computer systems became affordable for large commercial organisations and research centres. Investigation into using these systems for both design and manufacturing began with particular interest from the automotive industry. New freeform parametric curves like Bezier curves, *Bezier (1972)*, and B-Splines, *Riesenfeld (1972)*, were significantly more flexible and easier to work with than either conformal mapping or pure polynomial techniques. Hull surface design techniques were adapted to work with these new representations, *Creutz and Schubert (1978)*, *Munchmeyer et al. (1979)* greatly improving the results. However, with the introduction of parametric surface counterparts of the curves, particularly NURBS, many users found that the representations alone could be used for hull surface design without any supporting technology. It was good enough to manipulate the surface definition point until an acceptable surface is obtained in an iterative process analogous to using batten and weights.

3 Computer Aided Hull Design in Ship Design Tools

When cheap personal computing became available in the 1980s, the effectiveness of hull design software took a great step forward when combined with parametric surface representation techniques such as NURBS. Prior to this, computer aided hull design tools had been no more than functional electronic versions of the paper lines plan. The introduction of windowed graphical user interfaces and interactive peripherals, such as the mouse, allowed developers to produce CAD tools that could operate consistently across a wide range of low cost computing hardware. As a result, NURBS surfaces have become the most popular technique for describing the shape of hull. The surface definition (control vertices) can be interactive manipulated using the mouse and programmers with even novice experience can easily develop the algorithms required to produce the representation.

Before intuitive interactive design became one of the most important advantages of parametric surface representations, the initial benefit from the introduction of techniques such as NURBS was the ease and accuracy that could be achieved in production activities. The mathematical descriptions of component parts could be used to directly control tools such as cutting machines from a centralised design database rather than have this control information generated separately by reviewing the many drawings produced for the ship. Production is the most labour-intensive activity in shipbuilding. Therefore ship design tools have concentrated on providing the best solution for the detailed stages of design, seeing there the greatest potential savings in initial cost. However, although production is the most labour intensive activity, it is during early design phases where the designer has the most influence on the through life costs of a vessel.

Today, while many shipyards still rely on 2D methods, the main focus of ship design tool development is in the use of database or PDM (Product Data Model) technologies as a centralised data repository for all design definition and associated analysis results. On projects which require many concurrently working engineers, the design needs to be kept updated by allowing changes to automatically propagate across all affected components and for any infringements to be flagged up. For example, a change in the location of a bulkhead must lead to an update to the definition of the adjacent compartments which will subsequently lead to changes in the damage stability, etc. To achieve this, the design database must retain the topological relationships between different components as well as geometrical definition. While almost all geometric components in a model can be updated because their individual influence on the design is small and definition simple, the shape of the hull cannot be updated so easily as existing design tools do not possess the ability to topologically describe how hull form shape changes, preventing even the simplest of hull surface definitions from being updated.

By focusing on the management of the complete design model, the development of these integrated tools has focused on the detailed phases of design to the detriment of early stage design capabilities where a coarse definition of the ship is preferable. However, as most of the analysis techniques are just as applicable at the early design stage these tools cannot be disregarded, being one of the reasons why many of these tools are used throughout the whole process. Therefore, in order to improve the hull design process, the best approach is to adapt existing hull surface definition techniques allowing them to respond to changes commonly found in integrated design tools. Moreover, this needs to be achieved without dictating only a detailed level of design. In fact, the hull definition technique needs to be able to respond to a greater range of changes at global and medium levels as well as at detailed scale. As a result, integrated design tools should become more amenable to early stage design allowing a single platform to support the whole design process.

4 Current Hull Design Techniques

There are several different approaches used to interact with the hull surface depending on whether an acceptable definition exists or on what type of design process is to be employed.

4.1 Manual Development of New Hull Surface Definitions

To develop a new hull form, the data defining the surface representation must be built up and this is normally achieved using an iterative process where the definition is manually modified until the surface is fair and it fits the design requirements. Depending on the scale of the design there are two approaches that can be used:

- Direct Manipulation of Surface Definition Data

For small vessels with relatively simple surface, it is possible to manipulate the raw surface definition (control polygon) directly. This approach is most favoured in popular low cost design tools as the algorithms used to generate the hull surface are simple to implement and control of the definition data is intuitive. However, as the scale of the design increases, the time required to develop the hull surface increases more significantly and the process becomes very tedious. Furthermore, without expert knowledge, specific features cannot be accurately introduced into the surface. Despite being the easiest and most artistic technique, its flexibility makes it the least productive. Examples of commercially available tools which allow the user to manipulate the surface directly are Autoship and Maxsurf.

- Structured Hull Definition Techniques

Rather than control the mathematical surface definition, tools used to develop more complex hull forms often generate the surface definition from a set of curves. The curves are used to create a net which the design tool interpolates to generate the hull surface. In addition to definition locations which the surface will interpolate, curves can include attribute information used to constrain the surface, by applying specific tangent along an edge or by creating a corner (knuckle) along the curve for example. Detailed features can be easily constructed within the hull without affecting other areas of the surface by using irregular curve networks. Although this approach is much more productive, development of good curve networks requires experience and it can be difficult to change hull shape if the structure of the curve network must be changed. This is not necessarily the fault of the technique as improvements in the user interface can greatly enhance the designer's experience. Examples of commercially available tools with structure hull surface definition are NAPA, PIAS, EzHull, *Lee et al. (2001)*, and to some extent Multisurf, *Letcher et al. (1995)*.

4.2 Transforming Existing Hull Surfaces for New Designs

As the process of developing a new hull form definition can be lengthy and tedious, designers are often reluctant to modify the surface, particularly if the design has been proven or has had extensive

analysis. In this situation, hull transformations allow the surface to be consistently altered minimising the need for further fairing. The origins of these transformation can be traced back well into the Lines Plan era where time spent on addition fairing could be costly. Basic affine transformation can be used to change the overall dimensions of the hull surface while functions more specific to hull design can be used to change the volume distribution, *Lackenby (1950)*. Due to their relative simplicity, these functions are unable to respect the shape of many surface features and can introduce undesirable distortions if transformed significantly from the original design. Despite this, these functions are considered core tools for any practical ship designer as they offer a relative cheap way of reusing existing hull forms and are generally available in most hull surface design tools.

4.3 Automatic Generation of Hull Surface Definition from Form Parameters

Neither direct surface manipulation nor hull form transformation are particularly efficient tools. The designer spends a considerable time to continually check the quality of the surface and remove undesirable features. Hull surface generation offers an alternative by aiming to construct a fair surface from a predefined set of characteristics. Parametric hull generation techniques were popular developments until the introduction of parametric freeform surfaces like NURBS which allowed the same hull representation from concept to production design. More recently, increased pressure to faster turnaround design proposals and the potential for automatic optimisation of the hull surfaces has rekindled interest in these techniques. Parametric freeform surface representations have matured. NURBS have become the industry standard of modelling CAD surfaces. These representations can now be wholly embraced and incorporated into modern parametric hull generation tools. The Friendship modeller, *Harries (1998)*, is an excellent example of a tool based on form curves but ultimately producing a NURBS hull surface. In combination with hydrodynamic analysis and optimisation tools; it produces hull surfaces with particular performance characteristics.

There are other recent examples of parametric hull generation techniques not using freeform parametric surfaces. *Jorde (1997)* developed a hull generation technique based on Microsoft Excel demonstrating that anyone who wants to develop their own technique has access to tools which can support the functions required. *Lowe (2005)* updated work by *Bloor (1990)* combining resistance optimisation through the use of genetic algorithms based on a hull form defined by partial differential equations (PDE). Of the many different parametric hull generation techniques, few are used in actual ship design. In order to have a greater understanding of the limitations, two different hull generation techniques were developed as precursors to the work here:

- YachtLINES is a single cubic B-Spline surface yacht hull generator based on 19 geometric parameters. It follows the basic approach taken by many previous techniques using longitudinal form curves from which section shape is generated. Form curves are defined using B-Spline curves and an iterative approach is employed to modify control vertices until the desired hull properties are reached. A final NURBS hull surface representation is generated by performing a longitudinal fit to the control polygons of each section. Recent updates to this technique to constrain input parameters to ranges capable of being produced by the technique and the addition of bracketing of the iteration procedures have resulted in very robust performance, Fig.1.
- ShipLINES, Fig.2, produces a B-Spline surface of a single-screw cargo ship hull form with and without bulb based on 25 geometric parameters. Most of these are used to define local appendages such as the bulb and shaped skeg. The control polygon of the hull surface is specified directly around the areas of the stem, midship section, transom and skeg. The rows of the surface are blended in between taking account of the parallel middle body. Unfortunately, this construction technique and the requirement to produce both bulb and skeg in the surface place a significant constraint on the surface definition such that it is no longer possible to control the hydrostatic properties independently of the other input parameters. Despite this, the surfaces produced by this technique are reasonably good as the effect of the high level of constraint results only in a reduction in the range of hull shapes that can be produced.

Fig.1: Three examples of hulls generated YachtLINES

Fig.2: Two hull forms generated by ShipLINES; courtesy of SMIT Singapore

The primary aim of hull surface generation techniques is the production of a fair form from a set of numerical parameters providing the user with an almost instantaneous way of creating a new design with the correct characteristics. However, as both these hull generation prototypes demonstrate, hull forms can have many different characteristics and it is very difficult to find a mathematical formulation which will accurately produce appropriate surfaces with even a small range of variation. The dilemma faced in developing these tools is either to produce a wide range of generic hull forms which must be modified manually once generated or produce detailed surface definitions with similar characteristics and limited variation. Specifying a hull form using numerical parameters is not always easy. Parameters such as dimensions and volumetric coefficients are obvious inclusions but additional parameters are required to complete the definition and allow some variation in the range of hull forms that can be generated. Often, numerical parameters must be used to define characteristics which may be difficult to describe and may control features where it is more intuitive to interact directly with the surface definition. Furthermore, detailed features such as bulbs or shaped skegs may require many parameters dominating the definition making the technique difficult to use. An appropriate solution would be to integrate hull surface generation technique into a tool that also allows interactive manipulation. However, as it is very difficult to design a mathematical surface generation function which can also adapt to interactive user customisation of the hull surface, the change from a generated surface to one which can be manually modified is both unacceptable and irreversible. Consequently, designers have found hull generation technique difficult to integrate into their approach and opt to use the other hull design techniques.

All three hull surface design techniques have scope for improvement. But rather than address the disadvantages through separate technical improvements and retain the existing techniques, an alternative approach will be taken to identify the capabilities required by the designer allowing the investigation of innovative engineering solutions with minimal overhead resulting from the operation of the design tool.

5 Approaching the Problem from the Designer's Perspective

Research to improve hull surface design techniques is still active, as the methodology behind many accepted tools has not changed for some time. Unfortunately, most new developments do hardly consider the needs or opinion of the users. We take here an alternative approach to formulate a framework for future hull surface design platforms by considering:

- the process used by designers to synthesize new hull forms
- the capability of existing surface representation techniques
- the limitations enforced by current working practice (data exchange, capabilities of other CAD tools, etc.)

A designer will have a good mental picture of the hull surface when developing a new design to the extent that, even without the assistance of a CAD system, a representative sketch, Fig.3, can be readily produced. Of course, the sketch will not have any accuracy but it may illustrate key characteristics of the design such as knuckle lines, flat areas, bulbs and propulsion arrangements etc. Consequently, the designer associates most closely with the "features" of the hull surface more than any other characteristic of the hull form, Fig.4. Looking more closely at the contents of the sketch, the arrangement of hull features forms a topology of surface shapes and could assist in the design process making it more manageable by effectively dividing the surface into separate parts which have some independence from each other. Furthermore, there are only a limited variety of different types of hull form and the shapes within the topology can be easily described. This offers the possibility that for a given topology, the design tool could develop much of the shape of the surface representation automatically.

Fig.3: Basic hand sketch of a ship hull form

Fig.4: Hand sketch with rendering and text descriptions of surface shape

Numerical control of principle hull form characteristics has always been an attractive concept and has resulted in continued interest into parametric hull generation. However, as these methods require all characteristics to be defined numerically, description and control of shape has always been unsatisfactory. Ultimately, the designer wants to be able to control dimensions numerically but still be able to control shape through interactive manual manipulation. With an underlying topological representation of the hull form, there is an opportunity to use numerical control to change dimensions of the hull form with the reassurance that the topological definition will maintain consistency between the features of the surface.

One of the underlying limitations of current hull definition techniques is control of detail. Direct definition of the surface representation requires high resolution information about local details while parametric hull generation techniques often ignore important local features completely. Consequently,

there are often problems when moving through the design process requiring the hull surface to be redefined. Definition of the hull form topology could potentially assist this process as it records the underlying structure of the surface. The surface within a particular zone could be refined using the previous definition without affecting other areas of the surface. Furthermore, if some areas had been originally defined using generation techniques then as the definition progressed through subsequently more detailed design phase these areas could be converted to geometric definition to provide the designer with more local flexibility. As a result, the technique is capable of adapting its resolution to the required level of detail for a particular point in the design process.

An understanding of the common hull form surface shapes and control of geometric definition and numerical parameters appears to be primary requirements which would enable a hull design tool to be used in an early stage ship design environment, while at the same time having the flexibility to produce a range of different designs by providing the designer with artistic control of shape which does not require any significant fairing. Having formulated the concept of a hull design tool which solves some of the limitations of existing techniques and aims to fit the needs of the design process more closely, the next stage is to look at the technical aspects behind the implementation of a tool which follows this philosophy.

6 Technical Considerations for a New Hull Surface Design Tool

Just as it is important to review the hull design process when developing a new technique, it is equally important to consider the practical aspects of the technology used within any new methods and the environment in which the tool will be used:

- Mathematical surface representation: There are many different mathematical surface techniques used throughout the CAD industry although NURBS is by far the best supported both as an intuitive surface design tool and for transferring data between different systems.
- Access to the surface flexibility: Experience from parametric hull generation demonstrates that closed approaches, where there is limited practical opportunity to change the way the surface is constructed, greatly constrain the designer. A preferable alternative is to employ an open technique by providing tools which can be optionally used to constrain the surface. These constraints may be initially applied by the tool to attain the correct surface shape according to the defined topology but may be later removed by the designer when access to the full extent of the surface representation's flexibility is required.
- User familiarity: Traditional techniques to control surface shape allow users of existing tools to use the new approach with a minimum of training. The user interface allows the designer to control the hull surface ab initio by providing intuitive tools for flexibly controlling and accurately positioning geometry. Ideally, curves should be used to control the hull form as they provide clearer feedback of shape. Surface control polygons, while familiar to most designers, often become distorted and can require a good level of interpretation to understand how an individual control point affects surface shape. Numerical parameters should be clearly labelled so the designer understands exactly what it controls.
- Procedure and sequence: In addition to good technical capability, the most effective tools emphasize a preferred procedure that should be followed when assembling a surface definition. While subtle, a procedure makes the process of creating a surface definition more deterministic as the designer always knows what steps are still to be taken and the implications of modifying a particular aspect of the surface.
- Integration with other tools: While there are many tools which provide "integrated" solutions it is common for many different tools to be used during the design process. Therefore, any hull surface design tool should allow data to be exchanged between other systems using commonly

supported representations and with a high degree of accuracy. In practical terms, this means supporting bi-directional exchange of data through file formats such as IGES and DXF, with consideration for future developments of STEP and XML based formats when they mature.

7 Realisation: Combining Functional Aspirations with the Technical Reality

In existing hull design solutions, the software has a static role in the design process providing an instance of the surface representation. The user controls shape by manipulating the representation definition structure taking on the sole responsibility to ensure that the surface is correct. However, a tool which assists the designer in the surface development process as well as supporting all the technical requirements of a hull surface design tool requires a more innovative solution. Certain functions will require the tool to analyse the surface representation to assess the best way to modify the definition to the users' demands. By introducing a framework that interfaces between the user and the resulting surface definition, the software can control what aspects of the surface can be manipulated and introduce specific features needed in the hull design process. Curves offer the best means of controlling hull form shape for the following reasons:

- Can be used to define the topology of the surface, marking the boundaries between the different features of the hull form
- More intuitive control and representation of shapes within the hull form
- Functions used to modify the shape of the hull form will be the least complex when implemented for curves
- Tools that constrain curve shape are understood by users more easily than if implemented directly on the surface definition

7.1 Simplifying surface definition and reducing modification

In order to speed up hull form definition and to allow the surface to be modified consistently methods of reducing the amount of definition and controlling surface shape with respect to the topology need to be introduced into the framework. Rather than relying on the user to correctly position all curves, a collection of tools which impose geometrical constraints on curve definition can be used to produce shapes commonly found in hull forms. These constraints will maintain shape relationships between control points and between curves forming a hierarchy based on the underlying topology of the surface. Consequently, changes to individual curves will need to propagate to others maintaining the correct hull form topology.

7.2 Addressing Parametric Control of the Hull Surface

Using the topology of the hull form and the hierarchy of constraints, introducing parametric control to a geometrically defined surface is now easier. In traditional parametric hull generation techniques, the topology of the hull form is encoded in the complex mathematical formulae used to produce the surface making it very difficult to change how the hull is shaped. Having topologically represented hull form shapes, these mathematical procedures no longer have to consider the implications of changing shape, as this is maintained by the applied constraints, and they have only to identify which aspects of the hull form to transform, which can be achieved by interrogating the topology. Parametric control can now be introduced to the framework as an additional set of tools. Individual parameters can be measured from locations in the surface definition identified by analysing the topology. Subsequently, a transformation function can be invoked when a parameter is changed by a user, which modifies specific characteristics of the hull definition.

7.3 Introducing Independently Defined Local Features to the Hull Surface

The introduction of local features to the hull surface, such as bulbs or propeller skegs, often requires increased definition in the area of interest to allow the feature to be modelled. However, this may only be achieved by increasing the level of detail in definition across greater parts surface making further modifications to the hull form difficult, as much more data must be kept fair. As the framework is effectively managing the surface definition, an alternative approach can be introduced which allows features of the hull surface to be added sequentially by refining only the generated surface definition. By handling the introduction of hull features separately, the definition of the initial hull surface and subsequent features remains independent so the surface is always just as easy to modify and the designer can add, remove or change the shape of any features of the hull without having to make any irreversible changes to a unique surface definition.

8 Implementation of a Concept Demonstrator - IntelliHull

IntelliHull, *Bole (2002)*, was developed as a simple demonstrator of some of the proposed functions using a single NURBS surface and focusing on ship hull forms with and without bulbs. IntelliHull implements each aspect of the design tool discussed in the previous section as follows:

8.1 Framework

One of the difficulties faced when representing a ship hull form using a single NURBS surface is the large number of vertices in the control polygon which each have three independent parameters (coordinate components) that must be specified to produce the surface. While some techniques have used goal seeking techniques which manipulate each individual vertex, *Sanderski (1998)*, a more effective approach is to construct a geometric framework based on selected hull characteristics which can be used to determine the location of the surface control polygon vertices using a predefined set of rules. The ShipLINES prototype illustrated that a fair (i.e. smooth from the mathematical perspective) hull could be generated by blending the vertices of the control polygon between the bow, parallel middle body and transom if local features and appendages were ignored. This perhaps invokes the idea that a fair control polygon will produce a fair hull.

The framework for IntelliHull is based on the idea of three separate areas or panels of the hull surface representing the entrance, parallel middle body and run of the hull. In many ways this format is similar to the arrangement used in both Tribon FORM and FORAN FORMG although neither of these two techniques was originally designed to produce a NURBS surface. Each row of the hull surface control polygon is associated with a B-Spline curve used to blend the shape of the hull, Fig.6. In order to produce a fair hull surface, the curves must behave as a family with similar arrangements of control points and discontinuities. A series of transverse definition curves are used to control the blending curves. The vertices on each transverse curve define the location of an equivalent vertex on each blending curve producing a coarser equivalent of the control polygon.

By arranging the transverse curves to form discontinuities in the shape of the longitudinal blending curves with respect to the key characteristics of B-Splines, *Rogers (2000)*, the three panels of the hull surface can be exposed allowing full control of the panel boundaries, tangents and fullness in the centre of each panel. To form a hull surface with entrance, parallel middle body and run, the definition of many transverse curves are geometrically related to other curves in the definition. For example, within the parallel middle body panel and associated tangent curves, equivalent vertices on each curve must lie on the same line in the X coordinate direction to form the prismatic shape of the hull. By constructing the framework entirely based on B-Spline curves, rules based on the key characteristic can be defined and used to constrain and relate separate definition curves together to form a ship hull surface. Consequently, in addition to manipulating the vertices of each definition curve, the tool can provide a set of tools used to constrain definition curves producing the desired hull form shape. It is possible to take this concept further. For example, if the characteristics of the hull surface can be defined within the tool with some topological description, it can generate much of the hull surface

definition itself leaving the user to manipulate definition which controls the characteristic shape of the hull surface.

To form a ship surface, IntelliHull needs between eleven and fifteen curves depending on what characteristic features are desired in the hull surface. A Ro-Ro type hull, for example, requires thirteen curves, Fig.5. Seven of these can be automatically generated from the definition of other curves and further user assigned constraint tools can be used to simplify the definition of other curves by assigning specific shapes to the definition creating, for example, the bilge radius.

Fig.5: Curves representing Ro-Ro hull

Fig.6: Blending functions at entrance region

8.2 Control Curves and Constraints

Control curves were highlighted as one of the methods designers associate best with for controlling hull surface shape. The framework exposes definition curves but to generate an accurate ship hull form the curves need to be placed in certain geometric relationships with respect to each other to produce the discontinuities and tangents forming the panels. Such a system is not intuitive to use and requires the designer to understand the theories behind B-Spline representations. Rather than rely on the designer to place the definition accurately, the tool can provide features which assign these rules to the hull definition in the form of constraints. IntelliHull provides a range of different constraints which assist in the development of transverse definition curves.

8.2.1 Vertex Level Constraints

These are the simplest of constraints and provide the designer with the ability to create certain shapes within an individual curve by assigning rules to a contiguous set of control points. The rules constrain the internal vertices of the selection using the known properties of B-Spline curves. The variations available are:

- Straight: Internal control points are constrained to lie linearly and at uniform intervals between the two end points, Fig.7. This constraint is used for developing flat of side and flat of bottom in the midship section or for constructing straight sections in the stem or transom. It can be used generically in all control curves.

Fig.7: Straight segments

- Blend: Internal control points are constrained to lie at uniform intervals on a cubic spline formed from tangent information determined at the end points of the selected range of control points, Fig.8. The tangents are determined from neighbouring constraints or from adjacent vertices if there is no other information. The blend is tuned so that for direction changes of 90° will result as close as possible to a circular arc. The blend can be used to form the bilge radius in the midship section or to form curved shapes in the stem and transom.

Fig.8: Blended curve segments

- Knuckle: According to the known properties of B-Spline curves, a cusp can be formed in a cubic B-Spline by collocating three adjacent points. Knuckle constrains two vertices adjacent to lie at the location of the selected vertex, Fig.9.

Fig.9: Knuckle constraint

8.2.2 Curve Level Constraints

Curve level constraints assign rules which apply to all the vertices on a single curve, and subsequently all of the blending curves at that location along the hull. The two examples implemented in IntelliHull are:

- Plane: The plane constraint forces all the vertices on a curve to lie on a plane, Fig.10. This is useful for simplifying the definition, and hence manipulation, of planar curves such as the midship section and stem. It can also be useful for defining inclined transoms. The benefit of assigning this constraint is that the curve can be manipulated by changing the definition of the constraint rule by modifying, for example, the location of the plane (to move the midship section) or by changing inclination (to vary a transom).

Fig.10: Plane constraint

Fig.11: Offset constraint

- Offset: Offset constrains certain coordinates of each vertex on the curve to be the same as the corresponding vertex on a referenced curve. Consequently, it appears as though each vertex is fixed to a line through its equivalent on the referenced curve although the user is free to modify how far along the line the vertex is located, Fig.11. The constraint supports relationships functioning in each of the three primary coordinate directions or can extract the vector between

the initial points of both curves. All curves which form the parallel middle body can use this constraint so that they acquire the same transverse shape as the midship section. Their shape is updated as the midship section shape is modified.

8.2.3 Automatically Generated Curves

Certain definition curves affect the shape of the surface strongly. Examples are curves that form tangents and control blending in the middle of panels affecting prismatic coefficient. In most cases it is easier to control these curves using geometric rules and numerical parameters rather than user manipulated control points. Consequently, these definition curves can be automatically assigned to the hull definition by the design tool, but later manually customised by the user. IntelliHull implements the following three curves which are generated parametrically.

– Tangent Control Curve

The direction and magnitude of tangents in B-Splines is determined by the arrangement between the outer two control vertices of the control polygon or vertices on either side of a discontinuity. In the framework, tangents in the hull surface at the bow and transom are controlled by the relationship between the curve at the panel boundary and adjacent curve. The vertex and curve constraints can be used to define this relationship but the longitudinal blending curves need to reflect this information and allow the surface to blend into the tangent. This is achieved by assigning the same tangent direction and magnitude to the blending curves but using the user tangent definition curve rather than the boundary curve as the origin of the tangent, Fig.12.

Fig.12: The tangent control curve adds tangency into each blending curve based on the user curves defining the end of a panel in the surface.

Left: Control points from each transverse definition used defining end of blending curve.

Right: The arrangement is repeated for each blending curve

– Flat Control Curves

At each end of the parallel middle body, the direction of the blending curve tangents are known (they lie in line with the parallel middle body) as indicated by the topology of the hull form. Thus it should not be necessary for the user to explicitly add this information. The approach used for the tangent control curve is extended by generating both the curves which control the tangency in the hull surface and the tangency in the blending curves. The vertices of both curves lie on lines extended through the vertices of the midship section. The only thing left to be determined is the magnitude of the tangent. While experimenting with the definition, the most aesthetically pleasing effect was achieved if the distance between the boundary curve and tangent control curves was equivalent to a uniform distance normal to the panel boundary, Fig.13. The construct has to be translated into control vertex positions on lines formed through the corresponding vertices on the midship section definition using an equivalent operation to offsetting in CAD tools. The offset is exposed to the user as a controllable numerical parameter

as a percentage of the length of the entrance or run panels depending on which end of the parallel middle body is being controlled.

Fig.13: Controlling magnitude of tangent at ends of parallel middle body

– Volume Control Curves

The framework allows for control of panel shape between boundaries. The user can add further additional control curves. If none is provided the system will introduce an automatically generated curve which can be used to control the volume and centroid of the underwater hull surface. The goal of the volume control curve is to expose a single parameter which can be used to control the shape of the panel so that it can exhibit the maximum and minimum volumetric fullness given the shape of the hull at the boundaries. Volume control curves have a geometric framework, Fig.14, of their own to allow the control of shape based on the following specification:

- A control parameter for each vertex on the curve is introduced and based on the interval $[0,1]$ representing the minimum to maximum range of fullness.
- The longitudinal location of each vertex is halfway between the corresponding vertices on the adjacent tangent control curves at each end of the panel.
- At maximum fullness, the transverse location of the vertex (y, z) is the same as the corresponding vertex on the tangent control curve at the boundary to the parallel middle body.
- At minimum fullness the transverse location of the vertex is the same as the corresponding vertex on the tangent control curve at the applicable bow or stern boundary.
- The location of the vertex varies linearly with the control parameter between these two positions.

Fig.14: Volume control curve

A schedule mechanism determines the control parameter of each vertex which varies the fullness of the hull at the keel while keeping the shape at the deck constant, *Bole (2002)*. Additional

complexities are introduced when considering the different shapes associated with flat of side and flat of bottom.

Constraints are applied so that parts of the definition will conform to certain rules leaving other parts for the designer to modify. All of the constraints are applied as active rules so that if any part of the definition is changed the constraints are applied and the surface regenerated. This requires the generation process to work in an ordered way. Constraints associated with a particular curve are managed and owned by that curve. The curve executes each type of constraint based on a predetermined order. Once all user defined curves have been updated the generated curves can be recalculated again based on a predetermined order. If one generated curve references another, the referenced curve will update first. Obviously, no circular dependencies are allowed and the user is not provided with any options that would allow this to happen.

8.3 Parametric Control and Transformation of the Definition

One of the drawbacks of directly manipulating the mathematical surface definition is the number of times individual vertices must be moved to achieve a fair surface after a change. Constraints minimise this activity because the assigned rules can automatically update many vertices in one operation. For specific changes to the hull surface, parametric modification can be used for changing measurable characteristics of the hull surface. This can be implemented by using focused transformations which modify specific parts of the hull definition and propagate throughout by the assigned constraints. Values of adjustable parameters are measured directly from the hull definition and changes made by invoking specific transformation routines. IntelliHull could be described as being an indirect approach to parametric hull generation as it leaves the user free to manipulate geometry and create shapes which may be difficult to describe numerically.

Fig.15: Primary parameters used to transform the hull definition

8.3.1 Geometric Transformations

All geometric transformations can be described as either translation or scale operations, or combinations of the two. Both translation and scale operations can be applied to the entire definition of a curve or to a selected range of vertices where one of the vertices will form an origin in the case of the scale operation. Operations involving combinations of both scaling and translation can be used to minimise distortion which may occur if a single transformation was used allowing sections, for example, to retain the same bilge radius.

– Midship Section Transformation

Parametrically changing the depth or breadth of the hull form invokes transformations which primarily focus on the midship section but are applied to the other user defined curves. The

two transformations are designed to minimise the distortion that would occur if a single scale operation was applied by combining translate and scale operations together, Fig.16. Before the transformation is performed, the section geometry is checked to identify the vertices that should be moved and those that should be scaled. For changing breadth, the vertex at the bottom of the bilge radius is identified. Vertices inboard of this location are scaled while vertices outboard are translated ensuring that the shape of the bilge radius is retained. For changing depth, the vertex at the top of the bilge radius is identified and vertices above this location are scaled. Both these transformations assume that no constraints are applied to the midship section and try to retain the original shape. Any applied constraints update after the transformation to bring the section definition in line with the rules assigned by the user.

Fig.16: Midship section changed with a combination of scaling and translation

– Parallel Middle Body and Deck Transformations

Transformations on the extent of the parallel middle body and deck work in a similar fashion to those used to change the midship section except that only scale operations are used. IntelliHull extracts the length of the parallel middle body and deck from the definition, but also provides additional parameters which describe the longitudinal locations of where these measurements were taken, i.e. the curves defining the forward and aft boundary of the parallel middle body panel.

Measurement	Symbols	
	Parallel Middle Body	Parallel Deck
Extent	PMB	PD
Forward Location	PMBF	PDF
Aft Location	PMBA	PDA

The curves are only transformed when the specific parametric measurement relating to the particular curve are changed. For example, the curve defining the forward end of the parallel middle body can only respond to changes in the values of the PMBF and PDF parameters. When the user makes a change to either the extent of parallel middle body or deck, the change is distributed between the location parameters at the forward and aft end by the ratio of the location of midship section curve within the parallel middle body. The transformation of the actual curves takes the form of a scale operation about selected vertices, Fig.17. To change the end of the parallel deck, the vertex on the deck edge is shifted to the desired location and

then the vertices between it and the vertex closest to the midship section are shifted by scaling longitudinal location by the ratio of vertical vertex locations in the flat of side. A change to the parallel middle body is achieved similarly. The vertex closest to the midship section is shifted by the desired amount and vertices either side are shifted by scaling longitudinal position by the ratio of the vertex location in the flat of side or flat of bottom whichever is appropriate. Again, if any constraints have been applied to these curves, vertex locations will be updated after the transformation has been applied.

Fig.17: Transformation of PDF (left) and PMBF (right) by selective longitudinal scaling

– Length Modifications

Changes in length are implemented as translations or scale transformations applied to the individual curves. Before any geometry is changed, the hull definition is first checked to identify if the hull has an extent parallel middle body. Depending on whether the hull is being increased or reduced in length the transformation will change the length of the parallel middle body before performing any scaling transformations to avoid introducing distortions. Consequently, if the hull is being reduced in length but there is not enough parallel middle body to absorb the change, the transformation process will first translate all curves, from the midship section to the stem, aft until the extent of parallel middle body is zero. Subsequent further reduction will be introduced by scaling the definition about the origin (Aft Perpendicular). While this technique could be described as being arbitrary, it does not matter to the hull generation process how geometry is changed as the technique is not dependant on the implementation of individual transformations and could work with any designed to make an appropriate parametric change.

Fig.18: Length changed by changing just parallel middle body (left) or whole definition (right)

8.3.2 Hydrostatic Transformations

One of the primary objectives of almost all parametric hull generation techniques is to produce a hull surface with particular hydrostatic characteristics. ShipLINES demonstrated that if too much attention was focused on the geometric aspects of hull shape, the ability to control hydrostatic characteristics is lost. The hydrostatic transformations used in IntelliHull work in conjunction with the automatically generated volume control curves defined in 8.2.3 and allow the volumetric characteristics to be changed independently of any curves the user may have defined. Most parametric hull generation techniques produce the hull surface by using a model of the hydrostatic characteristics. However, the hull surface already exists in IntelliHull when hydrostatics transformations are invoked and mean that the response of the definition to any changes must be used to guide the transformation process.

The transformations need to be applied iteratively because the only accurate model of the hull characteristics is the actual surface definition and far too complex to make any attempt at solving directly. YachtLINES uses iterations to manipulate B-Spline curve definition and demonstrates the

feasibility of the approach. However, the iterative techniques used were naïve and the results were slow and far from robust. (YachtLINES has since been updated to incorporate the improved iterative technique used in IntelliHull and is now much faster and significantly more robust.). IntelliHull uses several approaches to improve performance. Firstly, the parameters that drive the shape of the volume control curves are bracketed to the range $[0,1]$. Consequently, if control values outside this range are encountered it is immediately obvious that this is outside the capability of the curves. The second improvement is the introduction of a simple model of the volumetric distribution of hull forms in order to reduce interdependency between control parameters affecting the fullness of the hull forward and aft and the goal parameters of volume displacement and longitudinal centre of buoyancy (LCB). A simplistic block "barge" model of a section area curve is used to represent the fixed volume (analogous to the volume in the parallel middle body) and the variable volume in the entrance and run of the hull, Fig.19. The equivalent mathematical model is:

$$\Delta_T = C_F \Delta_F + \Delta_M + C_A \Delta_A \quad (1)$$

$$\Delta_T x_T = C_F \Delta_F x_F + \Delta_M x_M + C_A \Delta_A x_A \quad (2)$$

Δ denotes the displacement, X the longitudinal centre of buoyancy (LCB), and subscripts T , F , M , A , refer to the Total, Forebody, Midship and Afterbody volumes, respectively.

Fig.19: Simplified section area curve model used to represent fixed and variable hull characteristics

The model can be rearranged so that the value of the control parameters can be found in terms of the target displacement and LCB:

$$C_F = \frac{\Delta_T X_T - \Delta_M X_M - X_A (\Delta_T - \Delta_M)}{\Delta_F (X_F - X_A)} \quad (3)$$

$$C_A = \frac{\Delta_T - C_F \Delta_F - \Delta_M}{\Delta_A} \quad (4)$$

The coefficients of the model are determined by exploring the minimum and maximum limits of the control variables. The iterative process subsequently determines the exact values of the control parameters by considering the error between the simple model and calculated hydrostatics of the hull surface. This technique has been found to very successful, capable of working with hull forms without parallel middle body (e.g. YachtLINES) and is easily adapted to finding partial solutions when one of the target parameters cannot be achieved.

8.4 Local Surface Modification

The details of the technique described so far develop a hull surface by blending between the different transverse definition curves. This process depends on the definition of the longitudinal blending curves which must clearly define a family of shapes for the hull form to be fair. This framework does not allow for local features such as appendages to be introduced, as this prevents the longitudinal blending curves from being controlled as a family.

Hull surface manipulation is an iterative process and it is often difficult to see whether a single change makes a positive or negative step towards producing a fair form. The manipulation process is made somewhat more difficult by the standard "stack" approach used to implement undo/redo because the user may have to undo desirable changes to reach the undo information for earlier undesirable changes made elsewhere in the surface. As a result, there has been little impetus to introduce additional modelling tools that assists by modifying larger portions of the surface because, although the operation itself can be directly undone, in relation to the other changes that the user may subsequently make, it may be detrimental to the hull surface design process as a whole.

This problem does not exist in IntelliHull as the hull generation process consists of a series of operations that are reversible if necessary. Once an initial hull surface has been generated, tools that make local modifications to the surface can be applied independently introducing features, such as a bulb and other appendages, without affecting any preceding definition information. (The hull surface is generated from the transverse definition curves which would not be affected by any subsequent modelling operations applied directly to the hull representation).

Piegl and Tiller (1995) present several techniques for introducing locally shaped features into a B-Spline curve or surface. These techniques operate by refining the curve or surface definition in the area where the feature will be introduced by adding knots. Subsequently, the control points are blended between their original location and the introduced shape. IntelliHull implements a variant of the warping process to introduce a parametric bulb into the hull surface. Rather than modify the hull representation by blending between the two shapes, as in *Piegl and Tiller (1995)*, the definition of the hull surface is refined allowing the control vertices from the hull surface to be moved to the same location as control points defining the bulb surface. The details of the operation are as follows:

1. The bulb surface definition is orientated so that U/V directions are compatible with the main hull surface.
2. Bulb surface control vertices which lie outside of the main hull surface are identified establishing a selection of vertices to be introduced into the main hull surface definition, Fig.20a.
3. Hull surface control vertices lying inside of the bulb surface control polygon are identified establishing the equivalent selection of vertices that will be moved onto the bulb surface.
4. Knots are introduced into either surface until the selection of vertices on each surface has the same number of vertices, Fig.20b.
5. The selected control vertices of the main hull surface definition are moved to the location of the equivalent selected control vertex in the bulb surface.
6. As the bulb surface is defined by discrete points, unlike the continuous mathematical functions used to modify surface shape in *Piegl and Tiller's* examples, blending must be explicitly applied around the boundary of the modified area.

Fig.20: Procedure to introduce a bulb into a hull surface control polygon

Although the shape of main surface does not exactly match the originating surface of the bulb feature, the result is more than accurate enough for surface generation. This technique can be used for introducing other appendages into the surface although this has not been investigated. However, potential problems have been identified if the grid orientation of the control polygon of each surface is not closely orthogonal to each other. In these cases, it may be better to follow the examples presented by *Piegl and Tiller (1995)* more closely.

9 Examples of IntelliHull Definitions

9.1 Implementation

The IntelliHull technique is implemented in PolyCAD, a tool that provides a range of entities from pure curve and surface definitions such as B-Splines to the proprietary hull generation techniques including YachtLINES and ShipLINES. The user interface is optimised for hull surface design and aims to provide all the basic tools a designer expects such as control point manipulation and hydrostatic calculations as well specific features such as allowing the user to actively control one and two dimensional manipulation while viewing in three dimensions, snapping to other entities and analyse curvature of both curves and surfaces. The PolyCAD implementation of IntelliHull takes advantage of the editing features available to all interactive entities provided within the system. Two IntelliHull entities are exposed to the user, the IntelliCurve and the IntelliHull itself.

Fig.21: Process to develop hull form

9.2 Generating a New Hull

The following section demonstrates some of the technique's capabilities for creating hull surface definitions. The first example shows the main steps used to build up a new hull surface. The user

starts by sketching a curve, then applies two straight and one blend constraint to form a generic ship type midship section curve. The midship section curve is twice copied to form the forward and aft limits of the parallel middle body. The constraints are removed and an extrusion (offset) constraint applied so that both curves have the same shape in section as the midship curve. Further copies are made to form the basis for definition curves at the bow and stern. The bow tangent curve is defined in a similar way to the parallel middle body, extruded in 'Y' from the bow curve to ensure that the hull surface is perpendicular to the centre plane along the stem. The hull surface is formed by blending it through the shape of each curve. Additional attribute information is used to constrain the surface by imposing specific tangent effects at the divisions of the parallel middle body and at the bow. Finally, a parametrically defined bulbous is added by applying the local surface modification technique described previously, Fig.21.

9.3 Using IntelliHull to Copy Surfaces

An ability to create surfaces based on existing hull forms is an essential feature. Fig.22 compares a surface generated from the bow of a Ro-Ro hull form omitting the shape of the bulb. The resulting surface is a fairly close match and differs along the stem where the original hull has more strength in the tangent and along the forward flat of bottom curve. A comparison of hydrostatics shows that the generated hull form was generally within 0.3% of displacement and within 2% of LCB. Fig.23 compares the aft end of a bulk carrier hull with a generated surface. In this example, the surface has more difficulty in matching the original surface as the demonstrator does not have sufficient control of the surface and requires additional trimming tools to produce the transom. Correspondingly, the hydrostatics calculations indicate that the generated hull is within 10% of displacement and an error in LCB of 30%. The second example illustrates that the single surface demonstrator has limitations for hulls with local areas of high curvature which are not part of a specific feature or appendage. Despite this, the resulting surface is reasonably fair and could be used as part of a new concept design.

Fig.22: Matching to bow of Ro-Ro hull except the bulb
IntelliHull contours are dashed

Fig.23: Matching to the stern post of bulk carrier; stern needs to be trimmed to form transom.
IntelliHull contours are dashed

10 IntelliHull in an Integrated Ship Design Tool

While many of the parametric hull generation techniques discussed here have limitations, even the simplest techniques can be used to generate good hull forms for particular design scenarios. However, one of the main failings is that these techniques are generally pushed to the fringes of hull form design by having very little connectivity to other tools used in ship design process. They are, e.g., implemented as separate pieces of software within suites of larger design tools or implemented as special features hidden away behind the larger features of integrated design tools. Consequently, it is difficult for

the designer to immediately see the potential benefits that can be obtained when these techniques are introduced into the design process and prefer to remain with the tried and tested technique of manually manipulating the surface definition. IntelliHull is implemented within Paramarine, an integrated ship and submarine design tool which supports parametric connectivity between all parts of the tool. The technique is now being actively used for developing hull forms for conceptual and exploratory ship design.

10.1 Paramarine

Paramarine is an integrated ship and submarine design environment developed by embracing the full capabilities of modern object-orientated software development. The tool itself features an object-orientated design framework which allows the parametric connection of all aspects of both the product model and analysis elements together. The system supports analysis disciplines in common to most ship design tools such as stability, powering and structural analysis, which when combined with parametric connectivity, allow designers to build up complex designs using all of the features of the solid modelling kernel provided by the industry standard Parasolid tool set. In addition, Paramarine features several unique modules specifically orientated towards the development of concept designs where the role of the vessel may require the designer to explore innovative solutions.

Objects make up the individual definition elements of a design usually with a set of corresponding attributes which may be numerical values, other objects or references. The design itself will consist of a collection of simpler objects assembled together to form a more complicated design. Therefore, the topological aspects are modelled as accurately as the geometric aspects.

One of the key objectives of Paramarine is the management of the design configuration. In essence, the system will attempt to maintain every aspect of the design in a correct and updated state by responding to user changes. This not only means that out of date elements are recalculated but also that any connections (references) are legitimate, e.g., ensuring that a connection points to the right kind of object (type-checking) or that the dimensional units of a formula equate correctly taking into account the input parameters and the expected outcome. With fairly limited experience any user can quickly define and arrange a set of objects which can be used to investigate various characteristics of a design.

10.2 Paramarine Early Stage Design Module

The Early Stage Design provides the designer with an alternative method of exploring ideas without being forced to follow the traditional approach of defining hull form, subdivision etc. Based on the University College London (UCL) Functional Building Block methodology, *Andrews and Pawling (2003)*, the framework consists of a hierarchy of objects called building blocks used to represent the different functional aspects of the design. The module provides the designer with a "free space" to construct solutions to requirements and determine the overall form of the vessel. While the methodology can be considered abstract when compared with the traditional approach, the process is much more rigorous as it forces the designer to define exactly how the solution will function. Consequently, decisions are addressed earlier reducing the amount of time it takes to deliver a design.

Building blocks in the design are associated with attributes which encapsulate the geometric, functional and topological characteristics to clearly define the role of a block. Characteristics (Weight, Space, Buoyancy, Consumable, Manning, etc.) can be used to define both requirements and solutions in the style of supply or demand. In many cases a block providing a solution to a particular problem may introduce further requirements which must be subsequently addressed. By working through this design process all of the requirements associated with a design can be captured and solutions to requirements defined. The Early Stage Design module collates information from within the building blocks hierarchy and compares related characteristics together, a simple example being a comparison between the buoyancy and weight characteristics to see if the design will float. Ultimately, the designer aims to develop a balanced design by making decisions based on information extracted from the building block hierarchy. The geometrical definition of individual building blocks is initially coarse to

minimise the level of detail. The design is likely to go through several stages of refinement starting with a coarse definition to allow the primary design decisions to be evaluated moving to finer models, as the details of the solution are worked through, Fig.24.

Fig.24: The impact different design solutions can be flexibly investigated e.g. machinery arrangement (left) and (centre) before adding more detail to the design for deeper analysis (right).

11 Continuing Work

While IntelliHull successfully demonstrates the concepts behind the design tool, the implementation exhibits limitations as it is applied to detailed design scenarios. Two key limitations are that the transverse control curves provide the designer with very limited control over longitudinal shapes particularly for fine hull forms and the application of successive local surface modification creates a surface which, while accurate and fair, has too many control point and non-uniform knot vectors making it difficult to modify the definition in any other tool.

Surfaces defined by multiple patches offer a much more suitable platform for this technique as local features can be defined in greater resolution independently of other parts of the surface. Furthermore, as these techniques are usually driven by a grid of curves, hull form topology can be defined more clearly than in the demonstrator allowing the transformation functions to be implemented as implicit features of the definition. Based on experience using IntelliHull, the curves will not directly expose the user to the underlying NURBS representation but will instead construct the control polygon based on the users point data and constraints allowing straight sections, knuckles, blends or cubic splines to be again produced. The surface itself will be generated by forming patches between each face of the manifold network of curves using subdivision to accurately extract each edge as a NURBS curve.

Work to develop this solution has been progressing steadily for some time and the greatest proportion involves the development of a technique which can create surfaces from an irregular network of curves, an operation which several existing tools already offer. At this time, despite being unable to produce a complete surface for complex hull ship forms, simpler hull forms such as yachts can be defined and some basic topological transformation capability can be demonstrated, Fig.25.

a) Curve network for yacht constructed from linked B-Spline curves

b) Surface resulting from (a)

c) Ship surface; holes are faces with more than 4 sides, a configuration not yet implemented

Fig.25: Surfaces produced by the IntelliHull technique

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