

Exploring the H-rep Ship Hull Modelling Concept

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Abstract *A novel ship hull modelling method, called hybrid representation (H-rep) was proposed some years ago. The aim of the H-rep method is to make ship hull design more intuitive, and therefore faster, more accurate and more predictable. The H-rep method has been implemented in a commercial software package, so in the course of time a lot of practical experience has been gained, while also new supporting functions have been designed and implemented. This paper serves two purposes. The first one is to present and discuss the additional functions and possibilities. The second purpose is to discuss practical projects performed with the current implementation of the H-rep method. After a brief overview on hull shape modelling methods in general, a short introduction of H-rep is given, and its merits and drawbacks are discussed. Special attention is paid to shaping curved surfaces by manipulating user-defined curves, and to Boolean operations. Subsequently general aspects of importing hull shapes and surface re-engineering are discussed, as well as the role H-rep can play in these fields. One particular application of re-engineering, photogrammetric reconstruction of a ship hull, is highlighted. The projects which are presented as practical examples are a simple yacht hull, a commercial ship hull and a complex superstructure of a mega yacht. In order to demonstrate the way of operation with a H-rep implementation, not only the final results of these projects are shown, but also crucial modelling steps. Finally conclusions are drawn, and some possible future developments are proposed.*

1 Modelling methods for ship hulls

For the purpose of modelling the shape of a ship hull, many modelling methods are potentially applicable, and have been used in the course of the past decades. These models can be classified as follows :

Point-set models, where an object is formed by an unordered set of points in space, see a.o. *Rusák (2003)* and *Gerritsen (2001)*.

Curve models. With these models unconnected spatial curves are used. In naval architectural applications curve models are mainly used for engineering analysis, not for design.

Surface models, which use a single surface or multiple unconnected surfaces. Currently the vast majority of commercial and academic ship design software suits use this method, where the NURBS surface is the most common geometrical modelling method, see a.o. *Ventura et al. (1998)* and *Nowacki et al. (1995)* for an introduction.

Wireframe models, where connected spatial curves are used, see a.o. *Michelsen (1994)* and *Eida et al. (1999)*.

Solid models. For general CAD application, the most commonly used solid modelling methods are Constructive Solid Geometry (CSG), where an object is described in terms of Boolean combinations of simple shapes, and the Boundary Representation (B-rep), where an object is described in terms of the separation between 'inner' and 'outer'. For naval architectural purposes *Koelman (1999)* proposed the Hybrid Representation (H-rep), which is essentially a B-rep extended with curved curves and surfaces.

This classification is given in the order of increasing topological structure. In information-theoretical sense only the last category is topological complete, the others are topologically incomplete (see *Requicha (1980)* and *Koelman et al. (2001)* for more details on the issue of completeness).

As far as the NURBS-based surface modelling method is concerned, achievements and results have been published in great numbers, both in commercial brochures as well as in technical and

scientific papers, while some papers also make critical notes on this popular method (e.g. *Hollister (199Xb)* and *Koelman (2002)*). Because alternative methods are hardly considered in the present technical literature, it is the purpose of this paper to report on the merits and potential of the H-rep method. Currently, the only available H-rep implementation is the 'FairwayTM', module from the commercial software package 'PIASTM', so all illustrations and examples in this paper are created with the aid of this program.

2 Properties of the H-rep concept

The data structure of H-rep was presented in *Koelman et al. (2001)*. Essentially the following elements are involved :

- The topological elements of the conventional B-rep, which are the *vertex*, the *edge* and the *face*;
- the (curved) *curve*, which consists of a topologically ordered sequence of edges, and which is geometrically shaped by means of a NURBS;
- the *polycurve*, which is an ordered sequence of curves;
- the (curved) *surface*, which is topologically a collection of faces, bounded and intersected by curves. The surface derives its shape by means of transfinite interpolation of neighbouring curves.

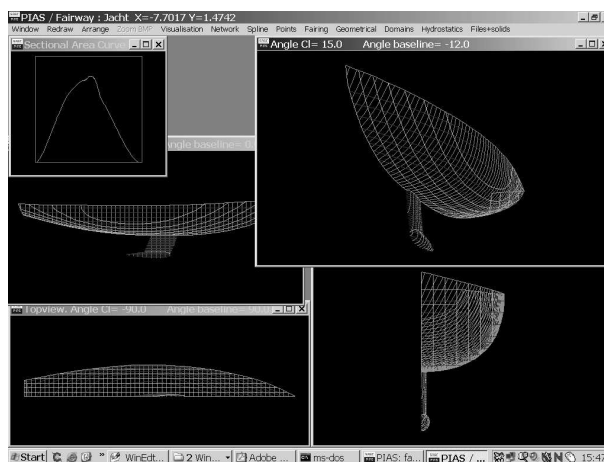


Figure 1: Curve-based User Interface

From a practical point of view it is interesting to note that the B-rep elements are only used *inside* the system, in order to maintain topological integrity. The user only sees and works with curves and surfaces, so the look-and-feel of the User Interface (UI) is rather conventional (see Figure 1). For the user the *curve* is the main modelling entity, while the *surface* automatically derives its curved shape from the curves in the vicinity. Shaping and manipulating the hull form is done by manipulating the curves, either by means of moving the curve vertices, or by shifting curve points and a subsequent fairing step. This is shown in Figure 2, which concerns a sailing yacht with a canoe body which is completely defined by eight curves: centerline contour, deck line, transom, the construction water line and four ordinates. The rightmost figure shows a distorted shape, by means of inboard bulging the foremost frame, which is translated into a dent in the entire fore ship region.

There is one potential danger in this free manipulation of curves and points, which is an inconsistency between topology and geometry. As mentioned, the system maintains the topological validity of the ship model, but a user might create some freak geometrical curve whose character

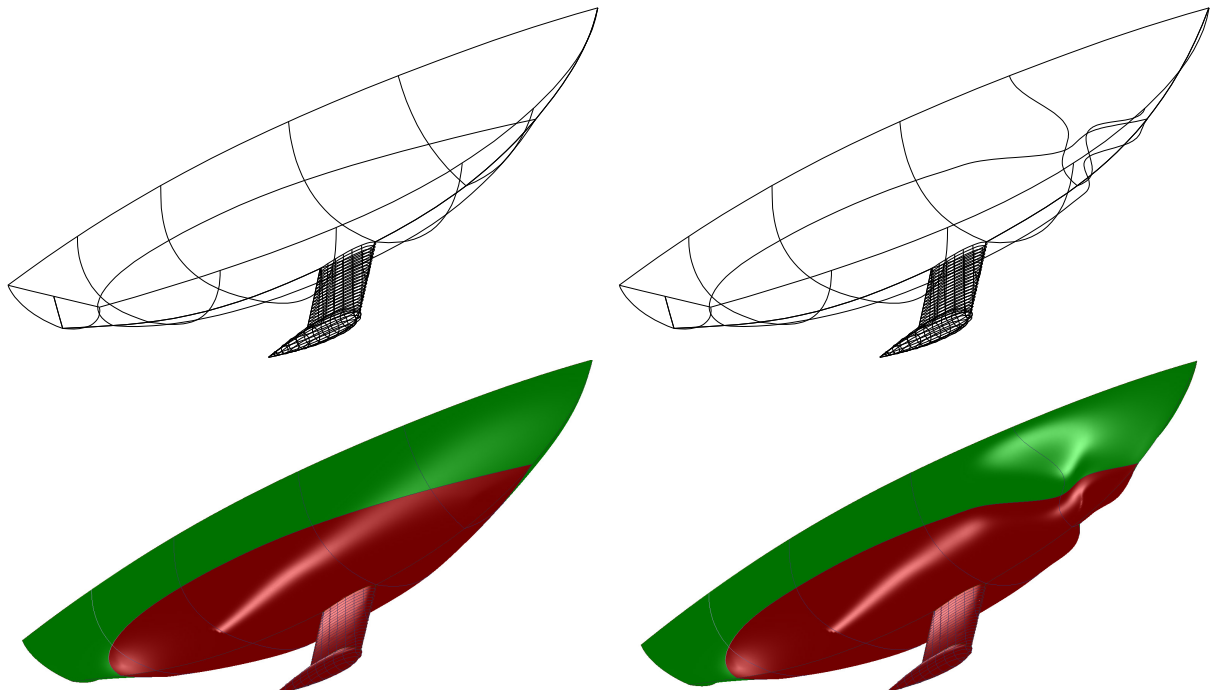


Figure 2: Original (left), and distorted (right) yacht hull, with the defining curves at the top, and the resulting surfaces at the bottom

is not matched by the topological structure, in which case the result can be undesirable. So it is the responsibility of the user that the geometrical and topological structures are compatible. Fortunately this requires less effort; the use of sufficient and well-chosen curves suffices.

2.1 Merits of the H-rep method

Compared with conventional (surface-) modelling methods, the H-rep approach offers the following advantages :

- The user can work with an irregular network of connected curves, so orientation and location of curves are completely free, while also partial curves, which are not running over the complete hull surface, can be used.
- The user can work with curve vertices, or with points on the curve itself. Because the curves coincide with the surface this implies that the user can work with points *on* the surface. Furthermore, because each curve has its own independent geometric representation, the number of (NURBS) vertices can be different for each curve.
- At any time a curved surface is available, so at any time arbitrary additional curves can be generated. It is obvious that the most frequently generated curves will be those in orthogonal planes (transverse ordinates, waterlines and buttocks), but curves in oblique planes can also be generated. Another possibility is to define a loose curve somewhere in space, and project it upon the ship hull. After this action the resulting projection line is included in the H-rep data structure.
- If a ship designer chooses to use a couple of ordinates in the initial design phase, the Sectional Area Curve (SAC) can be utilized to work goal-directed towards a desired volume or Longitudinal Center of Buoyancy (LCB).

- Curves can geometrically be dependant on other curves. An example is a sheer strake at some fixed distance below the deck edge. If the sheer strake is predefined at that particular distance from the deck edge at an early design stage, its shape will always follow the shape of the deck edge at the defined distance. This geometrical dependency is called 'master-slave relation'.
- Boolean operations can be implemented, which allow the generation of an object as the Boolean sum, difference or intersection of two other objects. Application can e.g. be the addition of a bulbous bow to a hull, creation of bow thruster tunnels, adding tunnels, flaps and other appendages to a hull, and the composition of a semi-sub from basic elements. The availability of a solid model is an advantage in this context, because Boolean operations can be performed with a single user action. If on the contrary only a surface model would be available, the intersection lines between surfaces may be determined automatically, but it would still require involvement from the user to trim the appropriate parts of the surface, and to combine resulting surfaces into the desired constellation. Based on methods from *Mäntylä (1986)* and *Hoffmann (1989)* we recently implemented an experimental Boolean functionality into Fairway, from which an example is shown in Figure 3. It is a subject of future work to extend this functionality to efficient curved-surface processing.

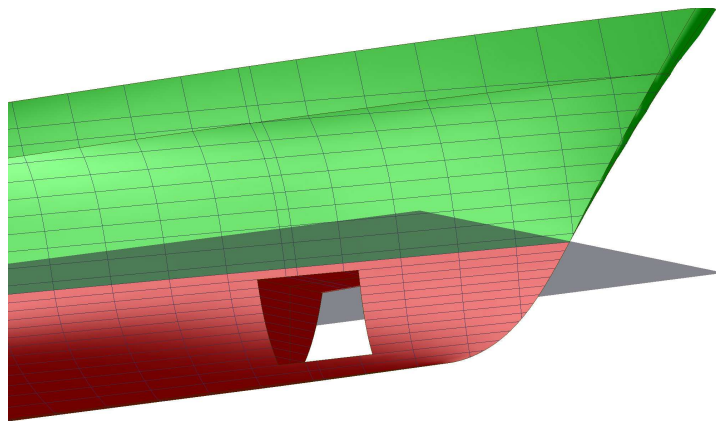


Figure 3: Boolean difference between a hull and a transverse rectangular cylinder

2.2 Drawbacks of the H-rep method

The 'Fairway' implementation of H-rep is now in use for some years with some tenths of shipyards, design offices, consultants and educational institutes. Based on the collectively gained experience also a list of drawbacks of the H-rep approach can be formulated :

- The development of a software program is an order of magnitude more complex than in case of a surface-based program. After all, for surface based software only the surface equations have to be implemented, which is rather a trivial task. On the other hand, a proper H-rep program requires implementation of topology (in the form of a genuine B-rep), curve geometry, 4-sided transfinite patches or surfaces, N-sided patches, curve fairing algorithms, plus all their interaction.
- In very early design stages the topological coherence was occasionally considered to be too rigid. The reason is that the proper topological structure is automatically maintained by the software by means of links between topological entities, but that implies that it is not possible to sketch some loose curves. And sketching of loose spatial curves gives a designer more the feeling of freedom.

Practically, this drawback can be resolved by leaving the H-rep structure out in early design stages, so the designer is completely free to sketch any curve he likes. At some stage, when more coherence is desired, a method can be employed which converts a collection of unconnected curves into a solid H-rep model. Such methods exist, and will be discussed in subsection 3.2. However, when using this procedure it is the designer responsibility that the spatial curves indeed intersect each other (within some tolerance) where needed.

- It is not really a drawback, but in some cases the H-rep method does not offer a real advantage. Particularly hull shapes which are 'simple' in a mathematical sense, such as the one of Figure 2, can just as easily be made with a H-rep program as with a program based on a surface method. In this context the notion 'simple' means a surface with (a) equally distributed curvature, (b) which fits properly in a regular mesh and (c) without chines, or with chines which extent over the complete surface.

3 Surface re-engineering and import of hull shapes

Until now we have discussed the ship *design* aspects of the H-rep. However, in many occasions some form of shape information is already available, which can be used as the basis for further design or engineering activities. The capturing and subsequent processing of that information, which may exist in the form of drawings, computer files, scale models or actual size models, is the subject of this section.

3.1 Surface re-engineering in general

With software which is based on a surface model, surface re-engineering is in general a tedious job, as experienced by the author, and as reported a.o. by *Hays et al. (1997)* and *Hollister (199Xa)*. One commonly applied approach is to force the user to choose only curves which coincide with the lines of some regular surface mesh. In this case the set of curves can, possibly after re-arrangement of some points, be converted into a NURBS surface. This method is only applicable for the simplest of shapes (i.e. those whose nature of shape fits a regular mesh).

Another approach is to show the available points or curves on screen, and let the user wrap one or more surfaces around them. In this case the hull is actually re-designed, which is time-consuming if some accuracy is required.

A third approach is to use mathematical optimisation techniques in order to automatically create a surface which fits a given set of points or curves as much as possible. A Genetic Algorithm-based version of such a technique was presented in *Birmingham et al. (1998)*. However, up to the authors present knowledge, this approach is still limited to hull forms which are 'simple' in a mathematical sense.

The H-rep, on the other hand, is potentially more suitable for re-engineering purposes, because an important constituent is the *curve*, which can more easily match the curve or point data which are available as input in the re-engineering process. However, a prerequisite for the deployment of a H-rep method in re-engineering is the availability of a method which converts from a *curve* model to a *solid* model. This aspect will be discussed in the next subsection.

3.2 Solid model generation and data acquisition

The approach to generate a solid model from the lowest modelling entity, a point-set, is rather straightforward. If higher modelling entities than a point-set are available as re-engineering subject, initial steps can be skipped:

1. We assume that a point-set is available which is *ordered* along some lines. If only a *point-cloud* is available, it must be ordered, for example by manual intervention.
2. With standard techniques curves can be generated through each set of ordered points.

3. Based on a geometric search, all intersection points between all curves are determined, and maintained in a list, so effectively a wireframe model is created. In order to compensate for round-off errors in the source data set, the curves are assumed to intersect if they pass each other within some user-supplied tolerance.
4. With a method as presented in e.g. *Inoue et al. (2001)* or *Koelman et al. (2002)* the wireframe can be converted into a B-rep solid model. As discussed in the referred papers the conversion methods have some limitations, but in the majority of practical naval architectural cases those limitations play no role or can be avoided.
5. In combination with the ordering information of the point-set the B-rep solid model can be converted into a H-rep model.

From the viewpoint of software design the conversion method is implemented in a pre-processor. Communication between the pre-processor and the actual ship design program is performed by means of a couple of ASCII files, which are called Solid eXchange File (SXF) and Curve eXchange File (CXF), whose formats have been made public. This allows the pre-processor to be fed with modelling entities which are 'higher' than an ordered point-set, such as curves, a wireframe or a solid. The system design of the pre-processor is sketched in Figure 4.

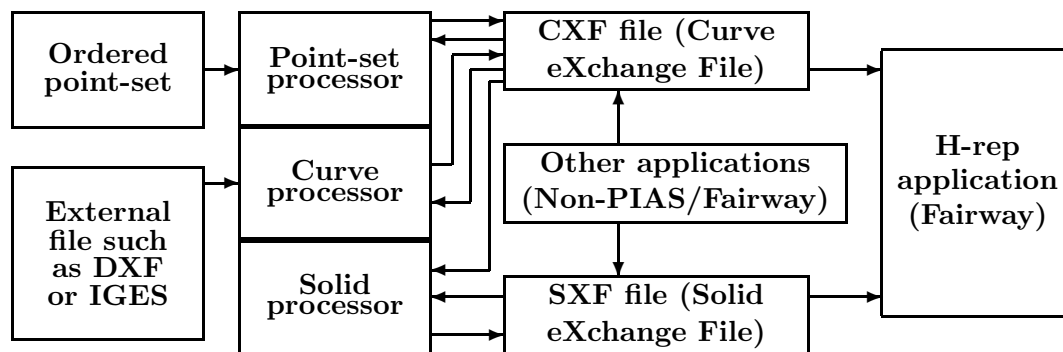


Figure 4: Pre-processor system design

3.2.1 File import

Based on the methodology as discussed in the previous paragraph, import facilities have been implemented for DXF 3D curves (subtypes line, polyline and NURBS), IGES 3D curves (subtype NURBS) and IGES surfaces (subtypes NURBS and parametric surface). Figure 5 shows an example of import from a DXF file which contains polylines, and conversion to a solid model.

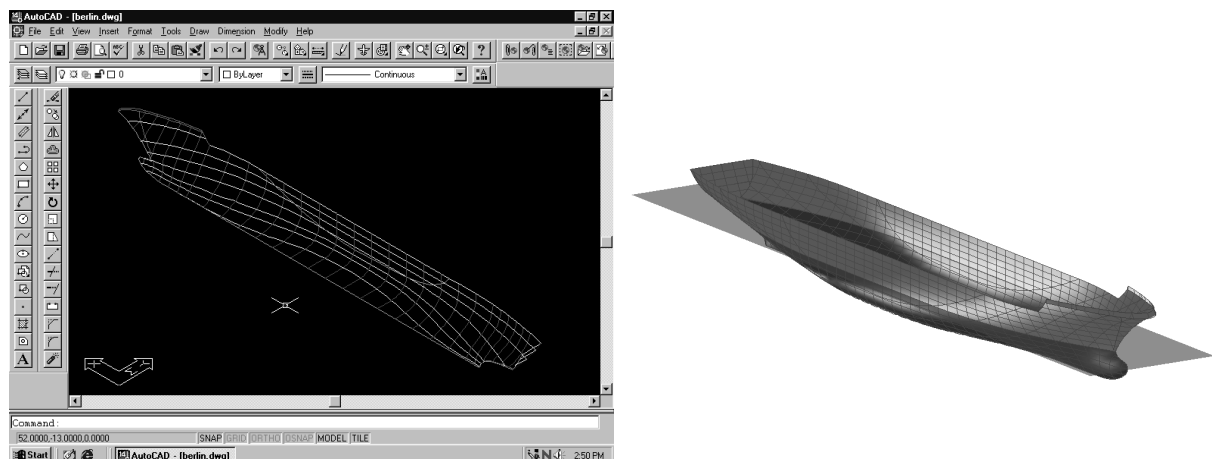


Figure 5: Source DXF-file (left), and resulting H-rep model (right)

3.2.2 Photogrammetric measurement of a ship hull

The possibility to convert an ordered point-set into a H-rep, and to process it further with H-rep software opens the door to capture data from scale models or real vessels by means of a data-collection method like photogrammetry. Basically, with photogrammetry multiple photos or stereo photos from an object are taken, and based on classical projection theory the three-dimensional co-ordinates of those points which occur on more than one photo are determined. Photogrammetry was first applied in the field of aerial and terrestrial surveillance, but later on it has been found useful also in close-range applications for the measurement of medical, archeological, architectural and industrial objects, see e.g. *Kraus (2000)* for more details.

In order to be able to measure real ships, we have equipped our software with a module for photogrammetry, which in short works as follows :

1. Markers are placed on the hull. A variety of markers can be used, such as stickers, magnets and paint dots. Naturally distinguishable points, such as corners or joints between welds, can also be used as markers.
2. For a limited number of markers (e.g. 4 - 10) the world co-ordinates must be established by some conventional method.
3. Photos are taken from different positions, where each marker must be visible on at least two photos. For taking the photos a regular camera can be used, but in order to achieve a high accuracy, we used a special, so-called 'metric', camera which possesses no or only a minor lens distortion.
4. Each photo is shown on screen, and each marker on each photo must be pointed to with the cursor, so the processing software is able to determine the co-ordinates (in the co-ordinate system of the photo) of that point. Should a sticker with a unique pattern be applied as a marker, a pattern recognition technique may be used to identify the markers automatically.
5. With appropriate techniques, see e.g. *Kraus (2000)* and *Atkinson (2001)* for details, the 3D positions of the camera and the markers are calculated.

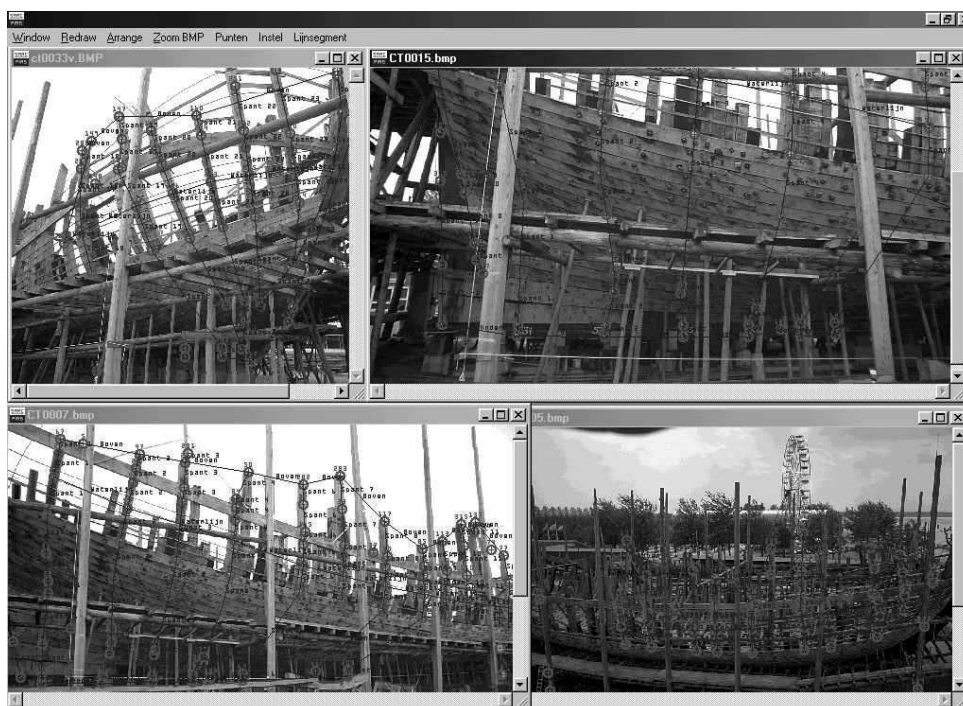


Figure 6: Photos, markers and connections of the '7 Provinciën' reconstruction

6. Besides identifying the markers, in the fourth step the sequences of markers along (arbitrary) lines have been indicated by the operator. This implies that an ordered point-set is available, which can be converted into a H-rep model with the algorithms as described in subsection 3.2.
7. If desired some post-processing, such as smoothing or generating additional curves, can be applied within the standard design environment of the H-rep implementation.

As a practical example we present the measurement of a the ‘7 Provinciën’. This is an actual-size reconstruction of a Ship of the Line, which was originally built in 1665, and measures (LxBxH) 46.14x12.14x4.74 m. The ship can be visited in Lelystad, The Netherlands, and more information can be found at website www.bataviawerf.nl.

Figure 6 shows a constellation of photos, plus the already identified markers and the connections between the markers, while Figure 7 shows the resulting H-rep model.

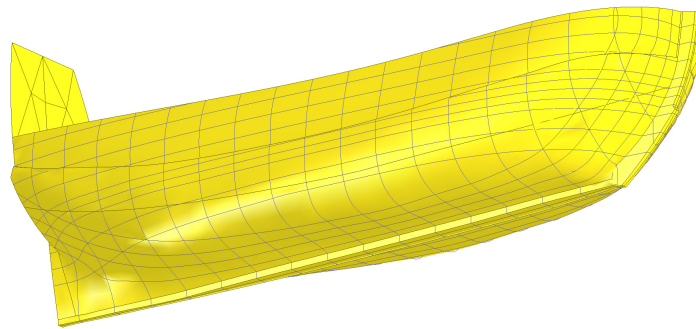


Figure 7: CAD model of the ‘7 Provinciën’, as obtained by photogrammetry

3.3 Shape re-use

Until now we have discussed re-engineering and data acquisition, but also another use of the collected shape data can be made, which is re-use or re-design. Of course all available design actions can be performed once the ship model is available in a H-rep environment, but it can also be appropriate to convert the data into an other model, where manipulation actions can be applied. An example is explored in a current research project, where the goal is to extend the available geometrical and topological information with some kind of meaningful *semantical* information. The idea is that with the aid of the semantical layer design modifications can be applied very effectively. More details are discussed in *Koelman et al. (2003)* from which Figure 8 was extracted, which shows an experimental point-set model.

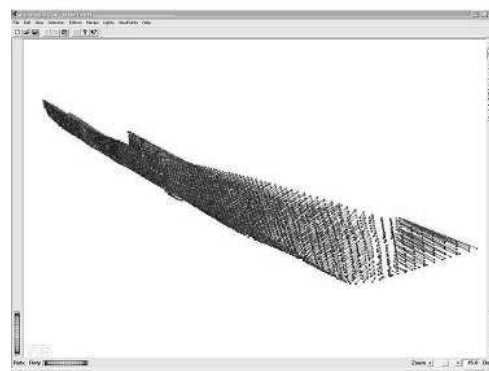


Figure 8: Point-set representation of a frigate-like hull form

4 Example projects

In order to demonstrate the practical potential of the H-rep approach, in this section we present two actual design projects which have recently been performed with H-rep-based software. The first example concerns a high-speed monohull, which is presented to demonstrate steps in the design process of a conventional hull. The second example concerns the superstructure of a mega yacht, which is shown to demonstrate that application of the H-rep model is not necessarily limited to ship hulls, but also extends towards unconventional shapes.

4.1 High-speed monohull

The first example we present is a high-speed 20.72 x 4.40 x 2.80 m monohull, equipped with a propeller tunnel. This vessel is currently under construction at 'Engelaer Scheepsbouw' of Beneden-Leeuwen, The Netherlands. This example is shown to demonstrate the flexibility of the H-rep model, because each design step is purely driven by notions and desires of the ship designer; not a single action had to be executed because the software insisted to do so. The design stages are presented in Figure 9

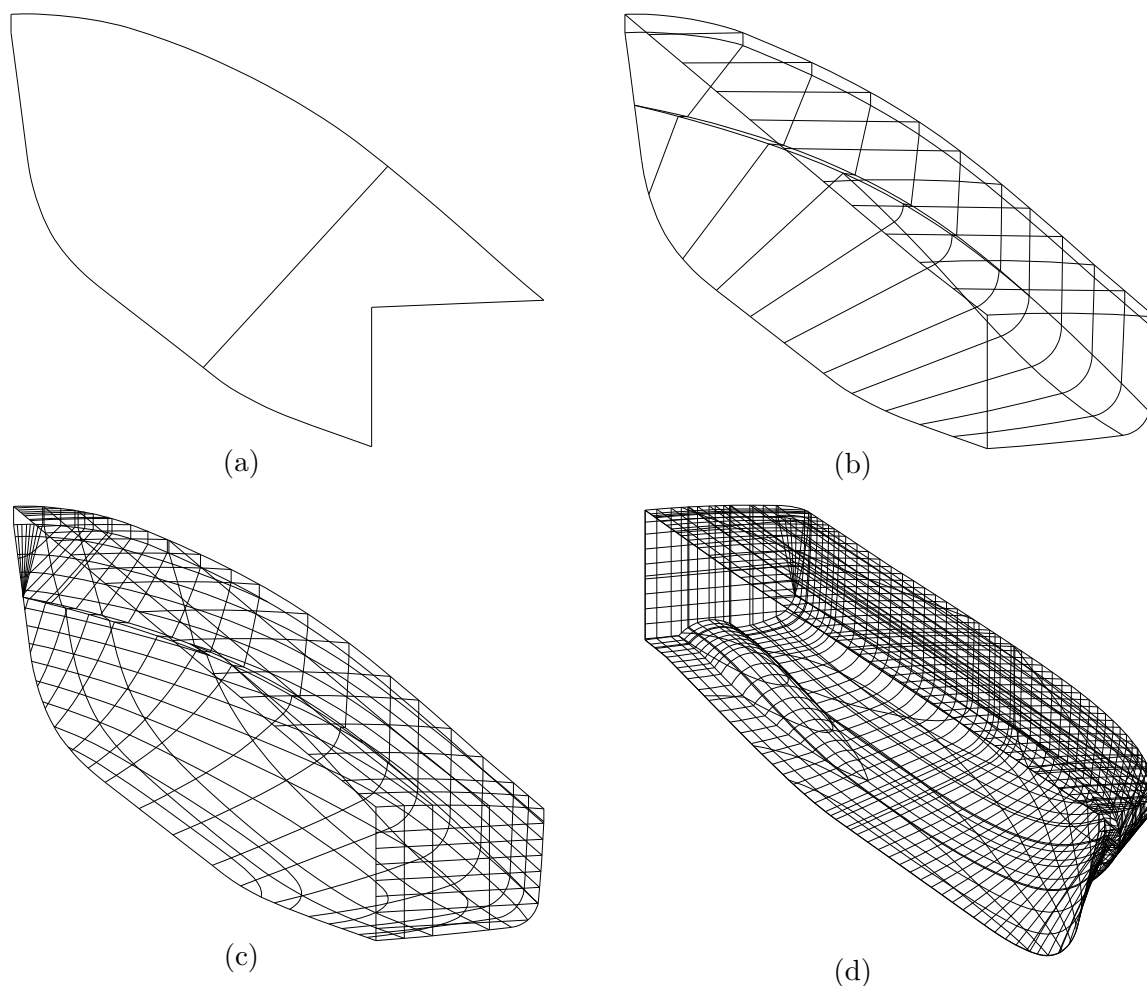


Figure 9: Design stages of high-speed monohull

The initial design information consisted of a hand-made sketch of a lines plan with a couple of ordinates (with an idea of the propeller tunnel) and the required volume and LCB. The first step (a) was to measure the centerline contour and the deckline from the sketch, define them in the software and fair those curves. It is important to fair all curves up to full production accuracy; because so few curves are available at this design stage it is very easy to do, while in

a later design stage one will benefit from the fact that these curves are already completed. The straight line at abt. $L_{pp}/2$ is a dummy ordinate, it will be shaped at a later stage. Subsequently a few points on ordinates of the design sketches have been measured or digitized and defined in the computer model. Knuckle points have been marked as such, and the sprayrail chines have been defined, just by pointing at the knuckle points in the subsequent ordinates. The same applies to the chine just below the deck edge. This stage is shown in Figure (b), which also shows that at this early stage the deck has already been included in the model. The reason is that a requirement for this vessel was a deck camber of $1/50^{th}$ of the vessel's breadth, combined with a pre-defined deck shape at CL. To model this, the deck at side and at CL have been defined to have a 'master-slave' relation (which was discussed in subsection 2.1), with the deck at CL being the master and the deck at side being the slave. So the geometrical relation between deck at side and at CL was integrally taken into account, and the height of the deck at side is permanently derived from the deck at CL.

Figure (c) shows a more mature stage, already with the cone-segment as stem-plate. However, it does still not have a propeller tunnel.

It was a design requirement that the propeller tunnel should be circularly shaped at cross section, with a specified but non-constant radius. In order to model this, the topline of the tunnel was projected on the tunnelless hull, and was given the desired shape by means of interactive manipulation. Subsequently, circular arcs have been generated and intersected with the existing bottom. Finally, the operator connected all intersection points between bottom and arcs, thus forming the tunnel chine. The result is shown in Figure (d), and the resulting lines plan in Figure 10, where it is interesting to note the curves resulting from intersection with angled planes (e.g. at a longitudinal location of abt. 18 m). Those curves have not been included for design purposes, but as aids for the engineering process, which had already commenced when the finishing touches were put to the design. Figure 11 shows the hull surface.

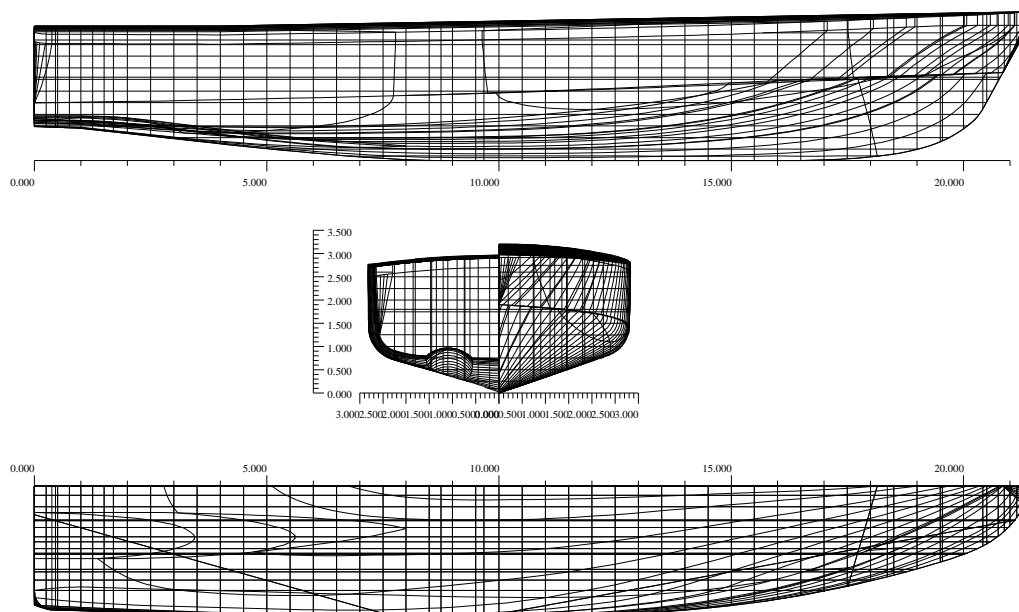


Figure 10: Lines plan of high-speed monohull

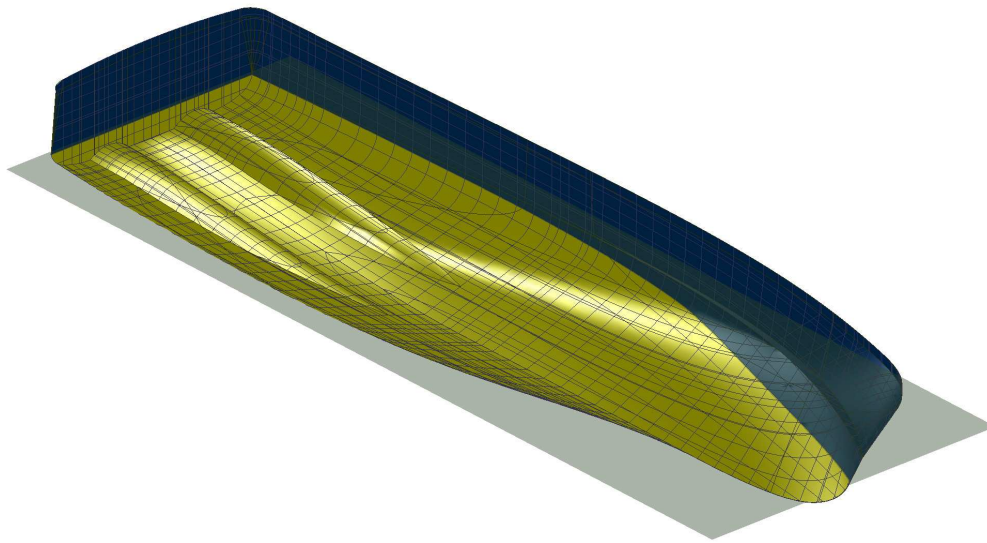


Figure 11: View on shell of the high-speed monohull

4.2 Superstructure of a mega yacht

Our H-rep application is more or less designed to work with curves, because they match the naval architectural notions of ordinates, waterlines and buttocks so well. However, also other complex sculptured objects than ship hulls may be handled well with an H-rep application, especially if many local constraints apply, such as prescribed diameters, steps, knuckles, round-offs or notches. As an example we present the superstructure of a 76 x 12.80 m motor yacht, which was recently engineered by the company 'Ankerbeer' of Veendam, Groningen, The Netherlands. Because the superstructure is asymmetrical, first the SB part was modelled, and copied to PS. For the symmetrical parts the PS curves inherited their shape from the SB curves by means of master-slave relations. Only the actual asymmetrical parts have been modelled by distinct curves on SB and PS.

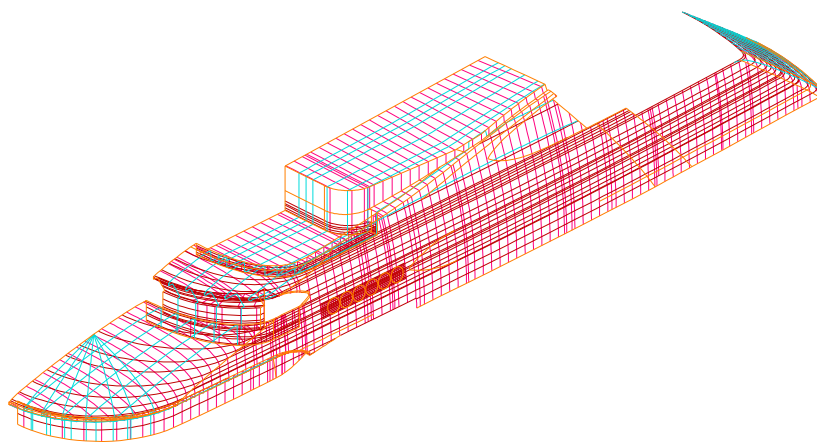


Figure 12: Wireframe representation of mega yacht superstructure

The purpose of modelling this superstructure was twofold. In the first place it was required to serve as a shape database for subsequent engineering application, and secondly shell plate expansions have been derived on the basis of this model. In order to fulfill these requirements a tolerance of less than 0.5 mm was necessary.

The wireframe representation, which shows all curves which have actually been fixed or manipulated in the design process, is shown in Figure 12, while the resulting surface is shown in Figure 13.

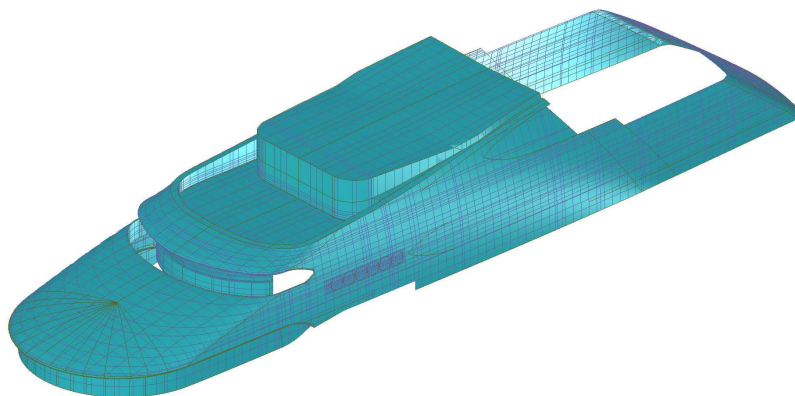


Figure 13: Surface representation of mega yacht superstructure

An interesting aspect of this project is the data exchange method between the shape repository (which is the H-rep application) and the engineering application, where all construction elements such as girders, stiffeners and pillars are modelled. Conventionally, the shape data are transferred to the engineering application by means of some kind of data file, but that approach might have two disadvantages. In the first place the transferred data are static, so modified shape data are not automatically processed in the engineering application. Secondly, in case the engineering application is curve-based, it is almost impossible to anticipate on the amount and location of all curves that might be necessary in the engineering process. A practical example is a longitudinal engine girder, whose location can not be foreseen in an early design stage. At the time the location is finally known, additional work is required to transfer the shape at that particular location from the shape repository, with a data file as a carrier, to the engineering application.

In order to improve this procedure, we have developed the so-called ‘hull-server’. Essentially, the hull-server is an instance of the PIAS/Fairway program, without the standard UI. Instead it is equipped with a (Windows-based) communication protocol which allows any external program to request the shape at a particular section or location. In no time the hull-server replies with that requested shape.

Of course this approach is only useful if the engineering application is equipped with a ‘hull-client’, which can interact with our hull-server. Fortunately, quite recently the ‘NUPASTM’ engineering program, by ‘Numeriek Centrum’ of Groningen, The Netherlands, has been equipped with such a hull-client, and because the superstructure under consideration was both defined in PIAS/Fairway and engineered with NUPAS, this mechanism could be applied successfully for this project. Figure 14 shows NUPAS’ construction model, based on Fairway’s shape, as communicated over the hull-server \Leftrightarrow hull-client interface.

5 Conclusions and future developments

In this paper we have summarized the potential of the H-rep approach, in the field of modelling of objects ranging from conventional ship hulls to complex sculptured compositions. It was demonstrated that for every activity in the design and engineering phase the H-rep structure can offer benefits. Of course each method can be enhanced with additional functions, and currently the following extensions are under consideration :

- As motivated in subsection 2.1, at this moment Boolean operations are implemented, but

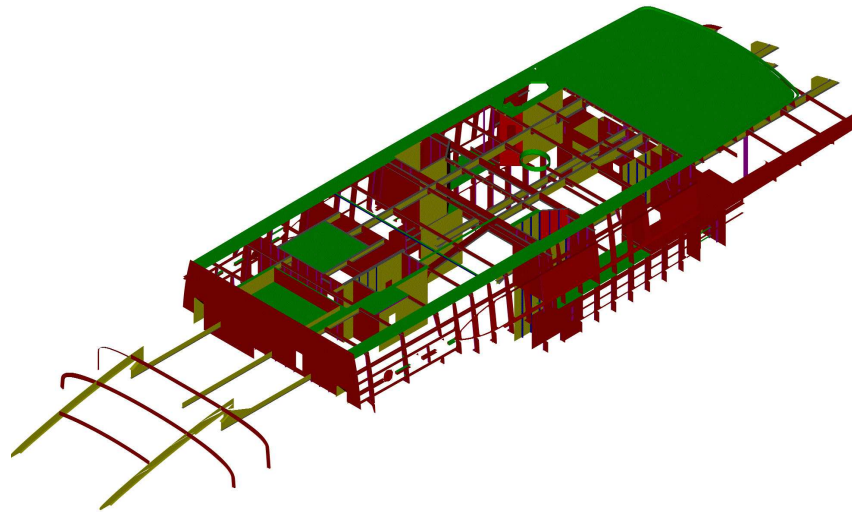


Figure 14: Construction model of the mega yacht superstructure

it would speed up the ship design process if those operations would be more efficient in a curved-surface environment. Implementing of fast Boolean operations is on our list.

- The region of modification is implicitly fixed with the present H-rep model. Modification of one curve does change the surfaces in the neighbourhood of that curve, so the curve spacings ultimately determine the extent of the modification. It could be desirable to explicitly specify the modification region, and currently we are preliminary investigating methods which may provide such a function.
- Extend the software with a pre-processor which generates an initial hullform, either automatically, or by means of user commands in some sort. The method as discussed in subchapter 3.3 is a candidate for such a function.

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