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A generalized description of hydrodynamic parts based on aerodynamic profile sections

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ABSTRACT

In recent years, several unconventional propeller blade types have emerged, like endplate propellers or tip rake propellers. The tip region of such propeller blades can no longer be described in the traditional way by means of cylindrical blade sections because the blade's generator line strongly deviates from span direction. A generalized method has been conceived for the description of propeller blades and other parts designed on the base of aerodynamic contours, like rudders or ducts. The concept consists of placing a series of aerodynamic profile sections onto freely definable surfaces and lofting them in order to produce the desired part.

A flexible data structure and an open source toolbox have been developed, capable of persisting, interpreting and handling the data. Parameters are used to control the shape, position and arrangement of the sections, facilitating the design and making it easy to use in an optimization process. The combination of several parts in one arrangement allows the definition of all major ship appendages in one set-up. This will speed the design process and exclude misunderstandings, e.g. in the interpretation of strut arm angles. It is hoped that the community will make use of the toolbox, contribute to later developments and refinements.

Keywords

Design, unconventional propeller blades, hydrodynamic parts, CAD, open source

1 INTRODUCTION

According to ISO standard 3715 (2002), propeller blades are defined by a number of aerodynamic contours placed on cylindrical sections, covering the blade span from root to tip. In recent years, several unconventional propeller blade types have emerged, like endplate propellers or tip rake propellers. The tip region of such propeller blades can no longer be described by means of cylindrical blade sections because the blade's generator line strongly deviates from span direction and in some cases even points into the propeller's axial direction. The impact on the flow that results from such design features should therefore ideally relate to the definition of the shape, which will be presented in this paper. It also appears more appropriate to define the blade root section directly on the hub surface which defines the limiting flow regime, whereas the traditional approach requires several sections on cylindrical surfaces inside and outside of the hub in order to find the resulting actual root section by an intersection with the hub contour.

Based on the above considerations, a generalized method for the description of propeller blades has been conceived. The concept consists of placing a series of aerodynamic profile sections onto freely definable surfaces and lofting them in order to produce the desired part. The same concept is applicable not only for the design and description of propeller blades, but also of other, non-rotating parts, like rudders, shaft bracket arms, stabilizer fins, ducts, stator blades, pod-drive struts and gondolas or rudder bulbs.

This paper illustrates the concept in detail. It aims at the development of a corresponding flexible data structure and of an open source toolbox that is capable of persisting, interpreting and handling the data. The concept of the toolbox allows easy integration into any software-infrastructure and gives an unambiguous interpretation of the data. By this, the simultaneous handling of both, profile definitions and 3D surface lofting, becomes possible. Furthermore, the effort of interpreting the data and making it usable for a specific purpose is minimized.

Parameters are used to control the shape, position and arrangement of the sections, facilitating the design and making it easy to use in an optimization process. The combination of several parts in one arrangement allows the definition of all major ship appendages in one set-up. This will not only speed the design process, but it will also exclude misunderstandings, e.g. in the interpretation of strut arm angles.

It is hoped that the community will make use of the toolbox, contribute to later developments and refinements and thus install a kind of industry standard which might supersede in future the current ISO standard.

2 THE TRADITIONAL APPROACH: PRESENT STATE OF ISO 3715 AND ASSOCIATED DEFICIENCIES

Traditionally, propeller blades are defined by a suitable number of cylindrical section profiles, see ISO 3715 (2002) (the international standard dealing with marine propeller geometry, coordinate systems and proper vocabulary).

This approach reflects the simplifying assumption that the inflow to a section profile consists of only two components, axial and circumferential: The developed blade section in X – r*sinΘ – coordinates has much similarity with the velocity triangle $v_A - \omega * r$ or in a more refined case $(v_A + u_A) - (\omega * r + v_t - u_t)$; the local pitch angle ϕ corresponds to the local inflow angle β_i (including the induced velocities u_A, u_t) plus a certain angle of attack α. Carlton (2007) shows the coordinate transformations from profile section offsets to global 3-dimensional coordinates.

However, there might also be so-called cross flow components (i.e. in span wise direction), especially at the blade root and tip, but also at a highly swept blade leading edge. In the detail design stage, the characteristics of cylindrical blade sections cannot be adapted to those cross-flows in a direct way. A favorable pressure distribution on the blade can only be achieved by choosing suitable neighboring section characteristics. From the designer's point of view, it appears desirable to have the option of adjusting each blade defining section along the local flow direction; in that case the local pressure distribution can be controlled by the geometric characteristics of just one local blade section.

Propeller design developments in recent years have already adopted these considerations, resulting in blade geometries which can no longer be described by cylindrical blade sections. Therefore, in the opinion of these authors, ISO 3715 needs to be updated.

3 GENERALIZED CONCEPT FOR THE DEFINITION OF PROPELLER BLADE GEOMETRIES

The generalized concept for the definition of propeller blades targets two areas. The first area is to take into account the designer's knowledge or best guess of the expected flow regime that is being "seen" by the section profile and its effect on the flow while moving through the fluid. The second area, namely the mathematical representation of the geometry, is less important for the flow physics but rather for all related production and simulation-process aspects.

Design methodology of any section based component is largely based on systematic investigations of two-dimensional profile sets. The knowledge base of profile sections for lift and resistance, stall angles and induced moments are available for any designer at almost no cost, e.g. Abbott, von Doenhoff (1958). The assumption for the given characteristics of the profile sections is based on the inflow direction, a given angle of attack for the section, resistance force in flow direction and lift force normal to the incoming flow. Now, for propellers these assumptions do not fully meet reality, as we know. The flow field approaching the blade is not parallel, but curved. A first best guess for designing blades by stacking profiles on cylindrical domains –taking into account the local flow direction predicted from the rotation and the inflow velocity– is valid, as long as the incoming flow does not deviate substantially from the axial direction and the stacking is done in radial direction. Propeller induced velocities or flow changes due to the hull shape, nozzles or other appendages are not considered here. Figure 1 shows the resulting flow the section profiles would face according to the above assumptions.

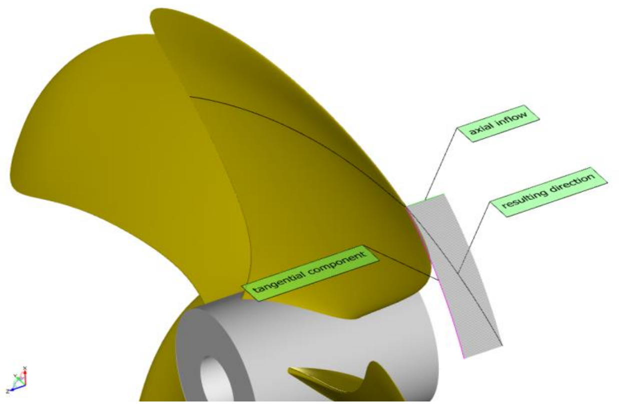

Figure 1: Assumption for inflow direction based on axial inflow

Introducing contraction of the flow to the propeller already changes that picture, see Figure 2. Profile sections that are designed on a cylindrical domain would meet the flow under a certain angle, which does not change the apparent shape dramatically, but already result in higher values of profile thickness compared to an axial inflow as in an open water prediction.

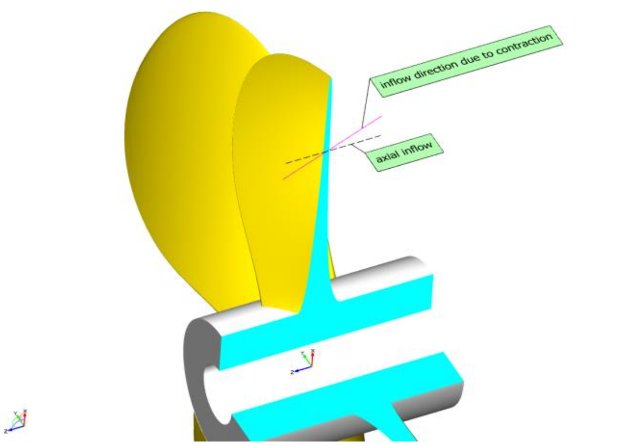

Figure 2: Non-axial inflow

If one wanted to have a particular section shape meeting the local flow regime, an option would be to model the profiles normal to a surface which can be constructed in a curved coordinate system resulting from the local inflow direction and velocity, the turn rate and a location on the blade's generator and the generator's spatial derivative in span wise direction of the blade, see Figure 5. The local coordinate for the profile is offset in normal direction from the plane that is defined through the blade's generator line swept along the assumed resulting direction of the flow, denoted *helix* in Figure 5. For the implementation of an effective angle of attack of that profile section, the desired angle of attack has to be incorporated in the value for offsetting the shape. The profile depicted in Figure 5 is set to an angle of attack of zero degree, i.e. connecting the nose-tail line lies on the assumed inflow direction.

Figure 3 and Figure 4 show profile sections near the tip, the first profile at zero degree and the second at 2 degrees angle of attack.

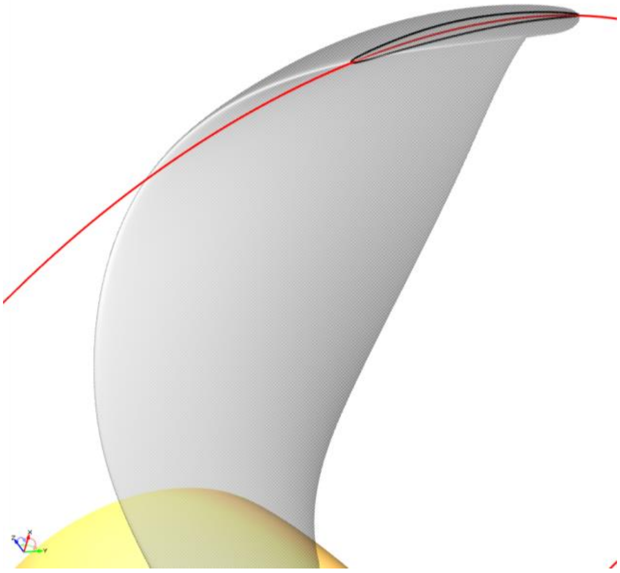

Figure 3: Profile near tip, AoA=0.0 deg, no camber

Andersen et.al. (2005) related the construction of the geometry for Kappel's propeller design in a very similar way. The approach presented in this paper adds arbitrary non-axial components of the inflow approaching the blade to the design methodology, be it due to nozzles or the contraction of the flow regime.

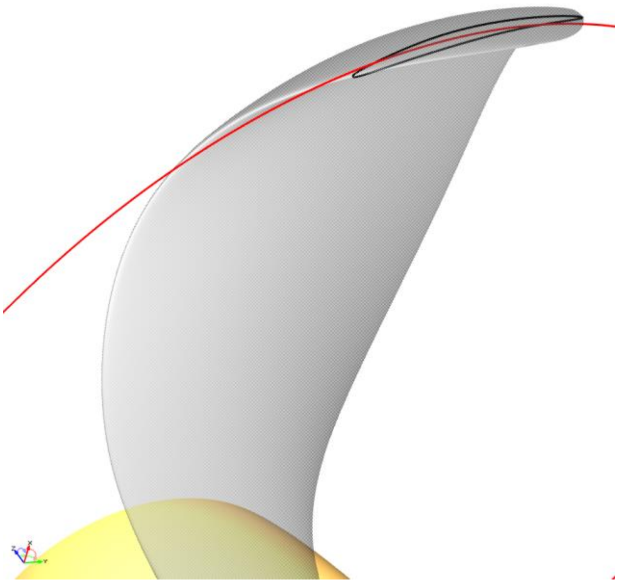

Figure 4: Profile near tip AoA=2.0 deg, no camber

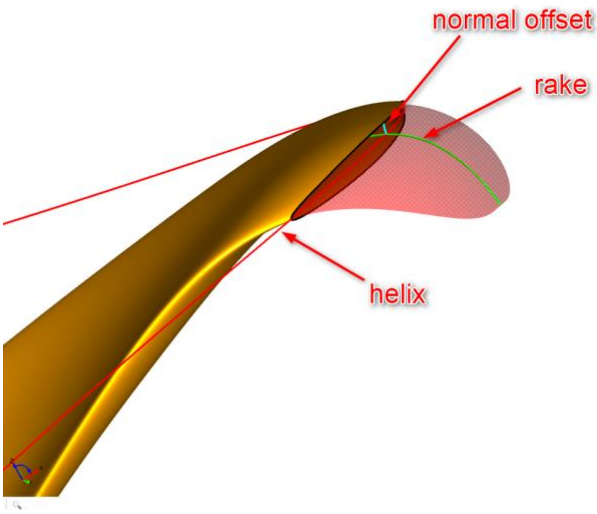

Figure 5: Construction of profiles normal to the blade's generator and assumed inflow direction

The basis for the generalized method is to envision the most accurate apparent inflow characteristic for a blade section and constructing the profile normal to the curved surface that is spanned from that inflow pattern and the span wise spatial derivative of the blade's generator line or curve.

The computer internal mathematical creation and representation process can be described as follows. Assumptions for the incoming flow represented as a mathematical surface of rotation can be made as a function of radius and axial position, e.g. an assumed contraction of the flow. A more accurate flow field, e.g. coming from a flow simulation which would also consider deviations from rotational symmetry would not add value to the design process at this stage, since the blade's geometry cannot be changed depending on the local blade angle anyway. For ducted propellers stream surfaces as an interpolation between their inner and outer boundaries, i.e. hub and shroud of the nozzle would form a suitable basis.

A spatial definition of the 3-dimensional generator's shape, either using one curve including rake and skew or a set of two 2-dimensional curves representing rake and skew individually can be chosen as the mid chord line. From the rotational speed, the assumed stream surfaces and the generator's shape, a normal offset of the sectional shape— including the desired angle of attack for the particular section – can be applied.

Parametric functions along the generator's path are defined for the section properties such as chord length, thickness, camber or other application specific characteristics, e.g. anti-singing edge. Having calculated the sections' offset locations a higher order curve creation process is selected to best represent the 3-dimensional section shape either by approximation or interpolation of the calculated offsets. Depending on the section's topology the profile may be represented by one or several curves. Busch (1990) investigated various types of splines which may be useful for the purpose. For the surface generation then a lofting procedure through the generated curves is applied, also considering the edges as rails if possible.

The tip of an open propeller always calls for special treatment and a dedicated cap surface targeted as an input for high fidelity CFD simulations featuring a tangent plane in the blade's tip is favorable.

A modeling approach for the transition between blade and hub can be realized by either defining the thickness and chord distribution towards the hub appropriately or by creating a variable radius fillet between the hub and the blade.

4 APPLICATION OF THE GENERALIZED CONCEPT TO OTHER HYDRODYNAMIC PARTS AND SHIP APPENDAGES

The estimation of the interaction of hydrodynamic devices by direct numerical calculations is an integral part of ship design. Accurate speed-power predictions or maneuvering calculations require a clear definition of all propulsion and maneuvering devices and other appendages.

During the design steps, numerous adaptations are made in order to find an optimal configuration. Decisions like flap- or standard rudders, CP- or FP-propellers or detailed design changes are carried out on a regular basis. Arranging all components to a single geometry model as shown in Figure 6 is required for model tests or direct numerical calculations.

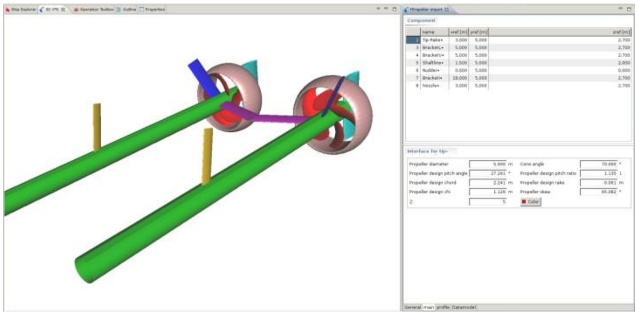

Figure 6: Example of a complex appendage configuration within a demonstrator of the data model, allowing the user to edit propeller-specific parameters within the whole composition

5 OPEN SOURCE TOOLBOX

When designing hydrodynamic devices, a certain number of conversions are usually required between "designing" the geometry and performing hydrodynamic calculations, carrying out model tests or manufacturing the final geometry. A common way is to model the geometry by lofting profiles on a defined loft curve as discussed above. The generated geometry is then e.g. exported to a (boundary-element or volume) meshing software for subsequent CFD calculations. When carrying out model tests, a simplified CAD-model is generated and for final manufacturing, a detailed CAD-model is generated, containing further details. Empirical methods (e.g. for ice class) furthermore require geometry-dependent characteristic data that has to be derived from the geometry.

A shortcoming of this procedure is that different geometries are generated in different data formats, (hopefully) containing the same information within the quality requirements. Another aspect is that later design loops or modifications (e.g. if the design pitch of a propeller changes) require that the whole process has to be repeated with the reproduction of all problem-specific data files and formats. The reason for this is that there is no data format available that can account for device-specific aspects (propeller pitch) and at the same time provide detailed data that can be used directly e.g for model tests, CFD-calculations etc.

In contrast to conventional data storage formats (e.g. IGES, STEP, STL), the concept presented in this paper is to persist both, the information about the lofted profiles and the information about the method to generate the surface, see Figure 7. The persisted information is distinct, i.e. the data model always reproduces identical data and all information is stored at only one location within the data model.

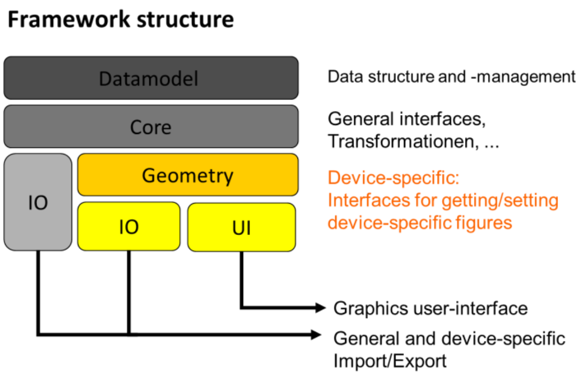

Figure 7: General structure of the open source toolbox. Device-specific software layers provide customized functionality

The concept to achieve this is to combine the data structure with an open source "toolbox" that enables the user to access all different kinds of information (like the direct surface information or the profile series identifier the lofted surface is generated with). In other words, not only a data format is defined but rather an additional software framework is being developed that takes over the interpretation of the data.

Connecting the data structure with a common software layer that is capable to interpret it allows for the definition of both, more complex and more flexible data structures – as required for the present kind of hydrodynamic devices.

Device-specific parameters (such as propeller pitch ratios or strut angles) can be handled more easily by the software layer rather than persisting it directly in the data model. This gives the freedom to define the data model in a more abstract way, which makes it more problem-independent.

Different software layers can provide device-specific interfaces. E.g. a propeller-layer will enable the user to edit the pitch ratios of each profile section, whereas a rudder-layer will provide rudder-specific modification methods.

The device-specific layers will be provided in separate libraries. This will ensure a downwards compatibility in case of future changes: A modification in the propeller layer will not affect the core or the data model layer.

The core layer will provide general functionality (e.g. export to other standard geometry formats) and will also allow the modification of all data in a more abstract way.

E.g. instead of editing the propeller pitch via the propeller layer, it is also possible to change that value by modifying the local coordinate system definition of the profile (which defines the local pitch of the profile) within the core layer.

A simplified data structure that is capable to handle all various device types is shown in form of an UML (Universal Markup Language) diagram in Figure 8. A global object (called ‘HComposition’) represents the whole arrangement of hydrodynamic parts, e.g. all ship appendages. It contains a list of all parts, named ‘HComponent’. Each component again holds a loft path and a list of loft elements containing the profile data.

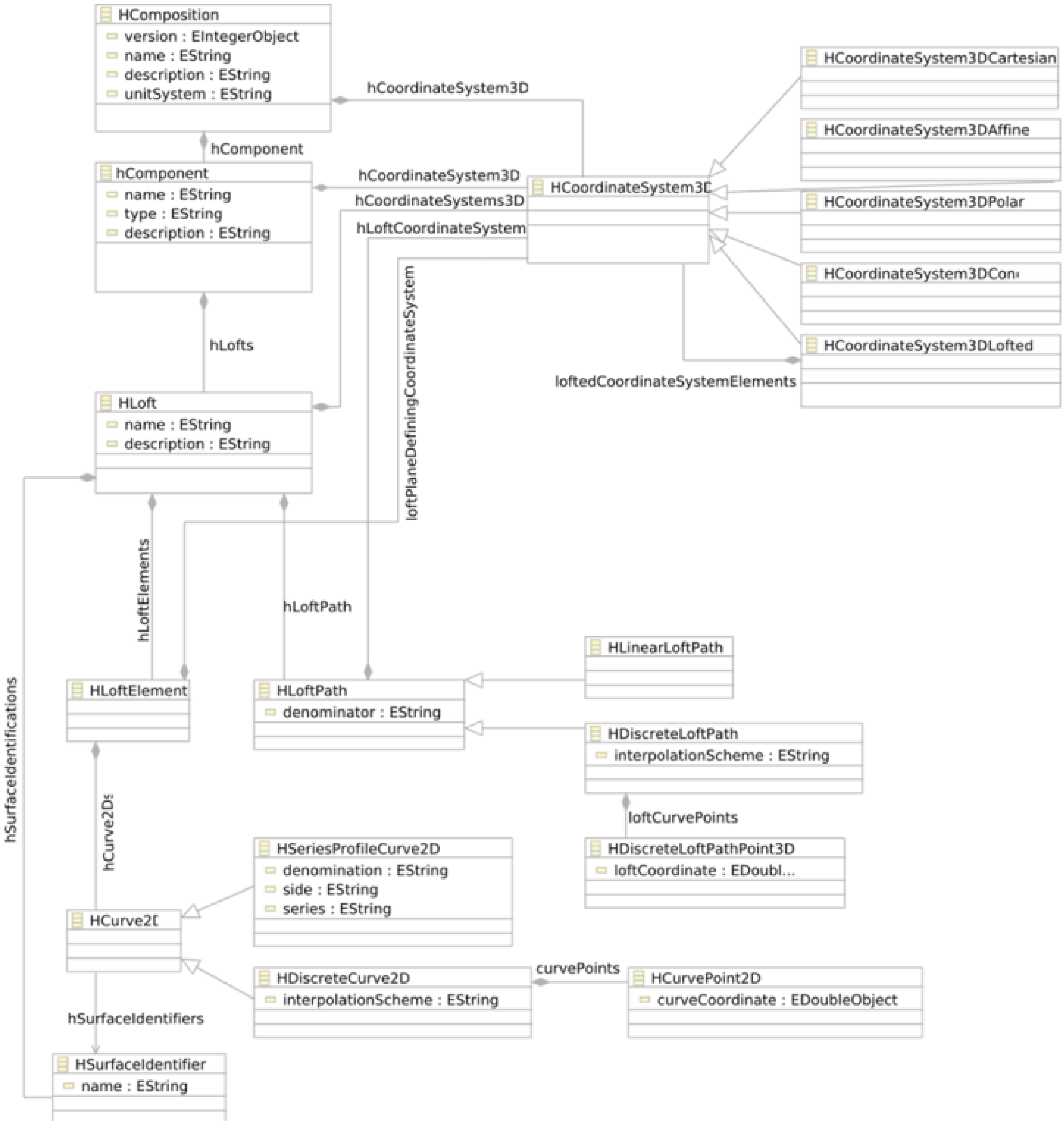

Figure 8: A simplified UML diagram of the data model for lofted surfaces

Profile data can either be persisted in the form of offset points or as a profile identification, e.g. the name of a series profile. Most of the classes shown in the diagram also contain a reference to a coordinate system. The concatenation of these coordinate systems defines the transformation from local (profile-) coordinates to global coordinates and vice-versa. By providing various kinds of coordinate systems, any kind of lofted geometry becomes representable.

The integration of the framework into a specific software environment (e.g. as a DLL, Dynamic Link Library) allows the user to access (read/write) all different kinds of hydrodynamic geometries in an easy way.

Another benefit of this concept is that the interpretation of the data model is distinct even if used in different software architectures and it is also very easy to integrate the libraries into a particular software environment.

Another requirement is to persist various kinds of hydrodynamic geometries (e.g. propeller, rudder, nozzle). However, it will also be possible to describe newly developed geometries in the future without the necessity to adopt the software structure or data model. This is achieved by the use of an "abstraction layer" that converts all geometries into an abstract lofting that is independent of the kind of device that it represents. Component-specific characteristics (such as the design pitch for a propeller, a rudder angle or the orientation angle of a shaft bracket) can be provided by an additional software layer that takes over the interpretation of the abstract data in both directions.

The idea is to establish a standard geometry interface that can be used by the maritime industry and that is capable of handling complex and innovative geometric data. The benefit would be an easy exchange of complex hydrodynamic data at a high level of quality. At the same time, modifications and optimizations can be easily performed in an intuitive way since all profile information and component-specific data is still available in the way the designer has foreseen it.

More information about the open source toolbox can be found on www.hykops.sva-potsdam.de or by contacting the authors.

The toolbox is published under the LGPL3 license, allowing free distribution and integration even into commercial software. All software is written in C++. A C-interface allows accessing the toolbox in any other (common) programming language and on most platforms.

CONCLUSIONS AND FUTURE WORK

A digital data model and the associated open source toolbox have been developed which allows modeling virtually any part which is designed on the base of aerodynamic profile sections. While the primary focus was laid on unconventional propeller blade geometries, the method is also applicable to nozzles, rudders and other ship appendages. Separate parts can be combined in a complete set of ship appendages, thus allowing for scale model manufacturing or CFD analysis of completely appended ships. Parameterization will make this software a valuable tool for design studies and optimizations. It is hoped that the community will make use of the toolbox, contribute to later developments and refinements and thus install a kind of industry standard.

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DISCUSSION

Question from Norbert Bulten

Will Parasolid format (*.x_t) become available?

Author's closure

The project partners have not yet finally decided which export formats will be available. STL will certainly be the first one due to its simplicity; others like STEP, IGES or X_T might follow. Even if it won't be available at the end of the current project, the idea of the open source toolbox consists of continuous improvements and extensions according to upcoming needs and demands, to be implemented by a hopefully growing and active user community.