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# Mathematical description of aesthetic criteria for process planning and quality control of luxury yachts

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## Abstract

In this paper, an innovative method for an automated process planning and quality control of the coating process of luxury yachts is presented. In order to show how aesthetic quality is achieved, the current manufacturing and quality control processes are demonstrated. Furthermore, general and yacht-specific meanings of the word "aesthetics" are introduced. The derived aesthetic criteria are used to create mathematical characterisations and limitations (e.g. maximum curvature) that need to be fulfilled by an acceptable outer surface of a yacht. Finally, it is described how these requirements can be used for an automated quality control.

*Keywords:* Aesthetics; Process planning; Quality control

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## 1. Introduction

Privately owned, motorised yachts with an immense length and high costs are called mega yachts [1]. Mega yachts can be easily described as a luxury good (specialty good). In contradictions to convenience or some shopping goods (e.g. most cars or white goods), aesthetics of luxury goods are of extremely high importance for the customer. While e.g., most parts of the white goods industry centre their attention to reduction of energy- and water-consumption to increase sales, the mega yacht industry has to deliver bigger yachts, implement additional, extraordinary features and provide top-level aesthetics. Worldwide, more than 200 shipyards build yachts. In order to reduce production time and costs and remain competitive, the production processes have to be improved continuously [2].

To ensure general aesthetics on all visible surfaces an expensive coating process is required. The raw metal surface is smoothened by using different layers of primer, filler and paint. Currently, the coating process is done manually.
Moreover, the quality control depends strongly on expert knowledge. In order to improve the coating and the subsequent quality control, these processes need to be automated. Thus, reproducible adequate quality criteria are necessary. In this paper, aesthetic criteria and corresponding mathematical descriptions that enable an automatic evaluation of coated surfaces are derived.

## 2. The process chain for filling and quality control of yacht surfaces

Usually, about five years elapse between the order and the completion of a mega yacht. Welded metal sheets build the structural work of the yacht. Due to processes like transportation and handling, the surfaces of the sheets can show dents or scratches after construction. Additionally, the heat input during the welding process results in severe distortion. In order to give the yacht an aesthetic and luxury appearance, a time-consuming filling process is necessary. This process can take up to twelve months, which is about 20 % of the entire production time.

At the beginning of the process, the shell is being coated with primer (Figure 1). Afterwards the first layer of filler is applied and smoothened with tools. After the filler has dried,

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the resulting surface is sanded and coated with new primer and filler. This process is repeated in an iterative manner until the surface is smooth and shows top-level aesthetics. Finally, the surface is inspected with tools, e.g., so-called “splines” for the walls and the body shell. Splines are metre long planks that have been used in the shipbuilding industry for centuries. Fixed at some points the splines always deform in a certain way that results in smooth curves or faces. For quality control purposes, the splines are pressed onto the surfaces and it is checked if there is any gap. If this is not the case, the surface is smooth. Another example are radii that are tested with a radius gauge. Many other parts are examined even more subjectively by looking at reflections of straight lines and checking for kinks or leaps. If all surfaces are approved, the painting process starts.

During the process, rough fillers are used to smoothen large deformations while fine fillers define the resulting surface. Currently, the coating process is done manually and mainly without any assistance or guidance system.

The described process chain has some advantages. First, it has been state-of-the-art for many years and is well known. Second, it provides very good results in terms of aesthetics as the workers know exactly what steps are necessary to satisfy the customer. Furthermore, due to its low level of automation, the process is very robust against unforeseen problems or changes. For example, a worker would adapt the working path intuitively, when there is an additional dent. If the process was more automated, a small change, like a dent, would cause a total path and planning adaption and therefore increase the production time. However, the low level of automation also causes disadvantages. The long production time results in high production and personnel costs. Furthermore, the process is not repeatable and the outcome is not predictable beforehand. This causes challenges with respect to the estimation of costs and the project schedule. Finally, there is no method for an objective and easily comprehensible evaluation of the finished surface. Currently, the quality control is done manually. Thus, the results depend strongly on the experience and the skills of the worker.

Aiming to increase productivity and address the aforementioned disadvantages, a pre-planning process for the filling is developed based on the results of [3] and [4].

For this purpose, the pre-planning process is adjusted, shown in Figure 2. In a first step, the actual contour of the yacht is measured. For the object capturing, a kinematic terrestrial laser scanning system is used, whereby the laser scanner is continuously moved along the object (cf. [5] and [6]). Essential advantages of this technique are a direct data acquisition (cf. [7]) and an optimal angle of incidence between the laser beam and the object. A direct point cloud can be determined. Because of the continuous 3D-pose-estimation of the laser scanner by a laser tracker, all measured points are directly referenced in the coordinate system of the yacht. Afterwards, the resulting point cloud is automatically cleaned by removing points that are referring to disturbance objects like cables or framework (cf. [8]). In the next step, a

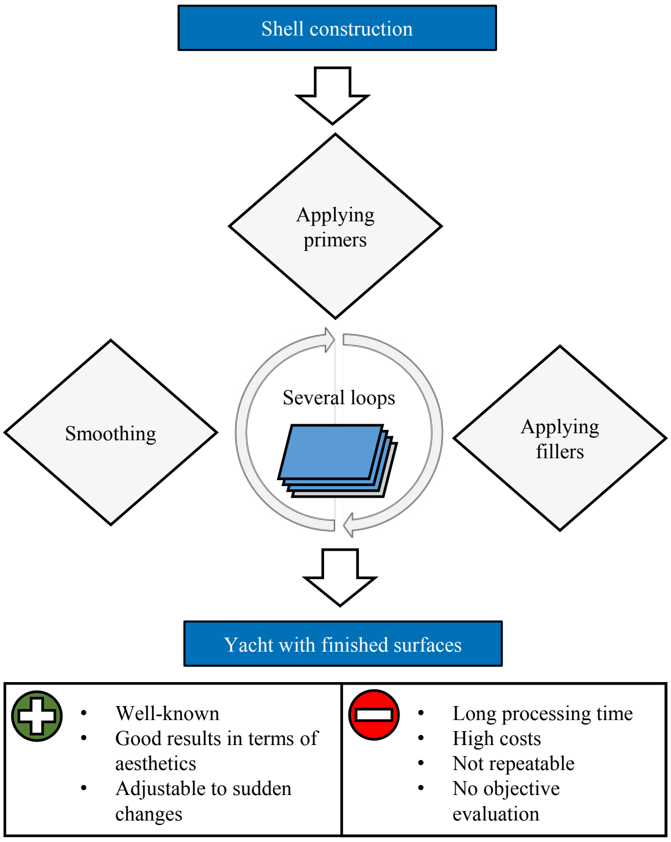


Fig. 1. Standard process for the coating process with advantages and disadvantages.

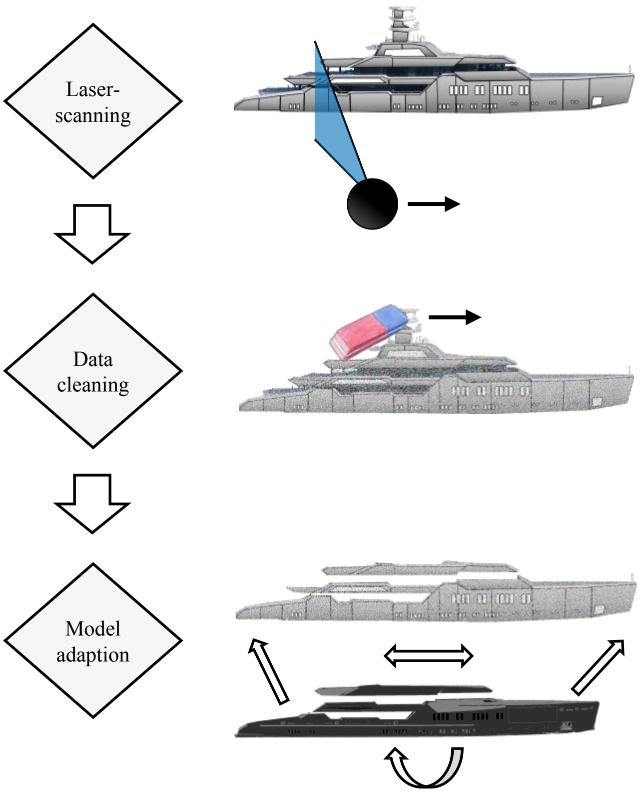


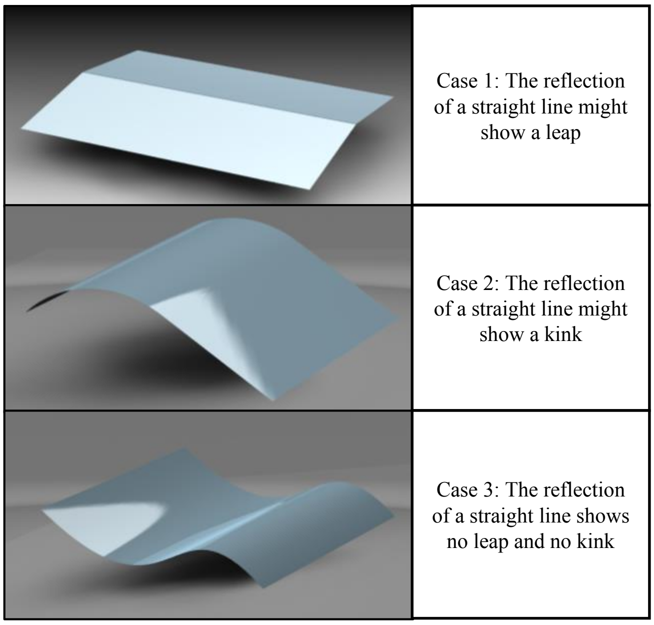
Fig. 2. New pre-planning process in the project FINISH.

“filler-map” is created, which shows how much filler has to be applied at different points along the surface. For this purpose, the design CAD-model is altered and approximated to the cleaned point cloud while maintaining aesthetic ideas and demands. A first step towards this goal is to develop an automated quality control based on aesthetic criteria and their mathematical description, which is presented in the following chapters.

## 3. Definition of aesthetics and general requirements

The word “aesthetics” derives from the Greek word “aisthanomai”, which translates to “perception by means of the senses” [9]. There are several ways to define the meaning of the word. In philosophy, aesthetics is clearly linked to the concept of taste [10] but taste is a very time- and person-dependent value. In this paper, the design component of aesthetics is in the centre of interest.

If aesthetic is really linked to taste, many factors must be considered. First, taste changes over the years as it is influenced by fashion. Second, it is strongly influenced by social and regional factors. Third, it also depends on brand preferences. Last, taste differs from person to person and is therefore very subjective. Thus, there is no aesthetic solution for every person in the world. Nevertheless, there are certain definitions that are accepted by the majority and throughout the years. To find a technical approach to a definition, the automotive sector provides some interesting ideas. This industry has a long history of researching in the area of aesthetics. In this process, different surfaces of the car are divided into classes with special requirements. According to Morello et al. classes mainly reference to the accuracy of the mathematical special requirements and therefore to the stage of the product. Until a few years ago, the outline of cars was designed with the aforementioned physical splines, which ensures a smooth surface [11]. Subsequently, a scaled model was built. After the design process is finished, a reflective film is applied to the model. With this reflective layer it is possible to evaluate the effect of the surface for a possible buyer. Hence, reflection is of essence for evaluating surfaces. In order to determine the influence of reflections on the aesthetics of surfaces, three cases need to be considered (see Figure 3). For all cases, it is the easiest to describe what happens to the reflection of a straight line. If the line is reflected on a highly mirroring and bent surface (e.g. an engine bonnet), it will look also bent. That is not preventable and still pleasing to the eye. Case 1 is a surface with a kink. A reflected straight line would have a leap in it. Of course, it can be used as a design tool to attract attention but must not occur unintentionally on smooth surfaces. The second case describes a sudden change in curvature, as for example, a straight line (curvature: 0) that is connected to a semicircle (curvature: reciprocal of radius). It looks smooth, but the reflection of a straight line would have a kink, which looks odd. In the third case, the curvature has no sudden changes. Therefore, a straight line would appear twisted but without any kinks. For the majority this looks natural and the surface consequently aesthetic.


Case 1: The reflection of a straight line might show a leap

Case 2: The reflection of a straight line might show a kink

Case 3: The reflection of a straight line shows no leap and no kink

Fig. 3. Surfaces with different aesthetic behaviour.

The general aesthetic requirements of yachts are alike, but there are some major differences that are described in the following chapter.

## 4. Aesthetics in building yachts

Regarding aesthetics, there are two notable differences between a car and a mega yacht. First, the yacht is much bigger than a car (up to 30 times in length). Second, contrary to cars, mega yachts are an individual item.

Due to the enormous size, tolerances have to be chosen way bigger as in the automotive industry. Additionally, there are multiple viewing directions. For instance, the shell of the yacht is mainly observed from the quay with an upwards viewing direction. While walking on the deck of the yacht, the viewing direction is mainly horizontal. Thus, for surfaces on the deck the aforementioned curvature continuity has higher importance in horizontal direction than in vertical direction. The large scale also leads to an inevitable low manufacturing accuracy. In combination with the production quantity of one, there is no possibility for tests and validation.

Regarding aesthetic demands, a yacht can be divided into three main classes: Major surfaces at the shell (henceforth-called Surfaces 1), major surfaces in the deck area (Surfaces 2) and minor surfaces with special requirements (Surfaces 3). For Surfaces 1 the requirements are similar to the class A surfaces (cf. chapter 3) even though there are some alterations and additions. As mentioned before, the curvature continuity in horizontal and vertical direction are of essence. The design idea has to be fulfilled. Thus, a deviation of the finished surface to the design model is possible but limited. On the outer surfaces design ideas are mainly the planned curvature as well as some design elements like edges. As the Surfaces 1 are very large, waves can be acceptable, but must not be visible for the human eye. During construction, a so-called water line is determined. Most Surfaces 1 touch the waterline. Hence, the aesthetic criteria only apply until about one meter below the waterline. Surfaces 2 have similar requirements as Surfaces 1 with some important differences. In the deck area, most surfaces are plane walls. As a perfect plane is hard to archive, some additional requirements have to be made. As against inwards bent surfaces, an outwards bent surface is acceptable for plane walls. If there is a small curvature, the reflection of a straight line would look slightly curved but it would not look irritating. Opposed to this, the requirement for the existence of waves are even higher. Primary, the waves in horizontal direction must not occur. As the main viewing direction is along the wall, these waves are highly visible and appear extremely irritating.

Surfaces 1 and 2 represent large connected parts of the yacht, while Surfaces 3 are smaller and more diverse. In this paper, three exemplary surfaces are discussed, as there is a great amount of objects and related requirements. Example 1 is an anchor pocket, example 2 concerns protecting ribs and example 3 covers openings.

The anchor pocket of example 1 is the metal frame that protects the yacht from damage in the anchor area. It is fixed to the metal plates, but with an offset. Consequently, the surrounding surfaces must be filled and connected to the anchor pocket. To make the transition between metal and filler aesthetic, the height between the edge of the anchor pocket and the filler must be equal along the perimeter. Additionally, the length of the transition into the surrounding surface should be alike and neither too harsh nor too wide.

Example 2 covers the filling of protecting rib that protects the yacht mainly during the anchoring in the harbour. These ribs are usually on both sides of the yacht and about 70% the length of the whole yacht. These ribs must obtain the intended form while the length it protrudes from the surrounding surfaces should be constant. Additionally, the length of transition should be smooth. The last example concerns the filling of openings or holes (for drainage, windows, etc.). To make these holes look aesthetic, the opening must have a shape tolerance, especially when there are similar openings nearby. The shape can differ from the intended design, but must not differ too much from the neighbouring openings, as this would appear irritating. This leads to another necessary definition, the position tolerance. If there is just one opening it is not too important that position is very accurate. However, if there is a group of openings, slight position variations are extremely visible. Furthermore, the orientation of the openings is of high importance. Even if it were an independent opening, a tilt would look unpleasing, especially if there are lines visible that should be parallel.

To summarize, for an automated quality control of filled yacht surfaces there are many criteria to take into account. While some necessities are almost universal, many parts of a yacht need additional requirements. To use requirements for an automated quality control, a mathematical description is necessary, which is presented in the following chapter.

## 5. Aesthetics Mathematical description of aesthetic criteria

To make aesthetic criteria usable for automatic processing, it is necessary to understand what these criteria mean from a mathematical point of view. In the previous chapter, a criterion was mentioned that reflections of straight lines must not be edged or disrupted. These unpleasant deformations correspond to a leap in curvature. Mathematically speaking, it means that a curve in viewing direction is not two times continuously differentiable (this is called “C2-continuity”). Thus, one universal mathematical demand for surfaces is at least a C2-continuity. In practise, this means that the curvature in two adjacent points must not differ more than a tolerance value that depends on the distance of these points and the surrounding curvature. The curvature of a point on a surface can be described in several ways. The two main curvatures are the minimum (k1) and maximum (k2) curvature and their corresponding directions. For instance, the direction of maximum curvature describes the plane, which intersection curve with the surface has the highest curvature. The directions of minimum and maximum curvature are always orthogonal to each other. Based on these curvatures two more essential curvatures can be calculated: First, the Gaussian curvature that is the product of both main curvatures. Second, the mean curvature, which is the arithmetic mean of the main curvatures. As described, the viewing direction is a crucial factor in the aesthetic evaluation of yacht surfaces. To find the curvature in a certain direction, the angle to the maximum curvature (θ) is calculated and Euler’s formula is used:

$$k_x = k_1 \cdot \cos^2(\theta) + k_2 \cdot \sin^2(\theta) \qquad (1)$$

With this calculation, it is possible to investigate every curvature-dependent requirement. For instance, as described in the previous chapter, waves must not occur on yacht surfaces. Mathematically speaking, waves on surfaces are a sequence of two or more local maxima followed by local minimum points. As extrema are dependent on the orientation towards an outer coordinate system, they are not suitable to recognise waves on surfaces automatically. Between a maximum and a minimum is always a change of the direction of curvature, called point of inflection. To define what is acceptable, the ratio between wavelength and amplitude must be determined. In practise, the wavelength is calculated by determining the distance between two points of inflection while the amplitude is the maximum distance orthogonal to a line between the two points of inflection.

The mathematical requirement concerning walls in the deck area is to have a positive (respectively negative) Gaussian curvature throughout the surface. Additionally, dependent on the dimensions, the magnitude of the mean curvature has to be very small. Regarding the previous described examples for the category Surface 3, additional mathematical descriptions have to be made. As mentioned, the height between the upper edge of the anchor pocket and the filler has to be equal, which is already a mathematical description. With respect to the transition, the tangents should face orthogonal from the edges of the anchor. The tangents should also be the same direction as the surrounding surface after 10 cm. The mathematical requirements for the protecting rib is similar. The tangent in direction of maximum curvature should face orthogonal to the length of the rib and be similar to the surrounding surface after not more than 10 cm. Further tolerances, like position and orientation are mathematical per se. The application of the derived mathematical criteria is described in the following chapter.

## 6. Application of the mathematical descriptions for an automated quality control

The previous chapters show and mathematically describe some exemplary aesthetic criteria. This chapter explains how these requirements can be utilized for an automated quality control approach to evaluate the surface finish of mega yachts. A point cloud of the filled surfaces forms the base on which a surface reconstruction is performed to obtain a model of the finished state of the skin.

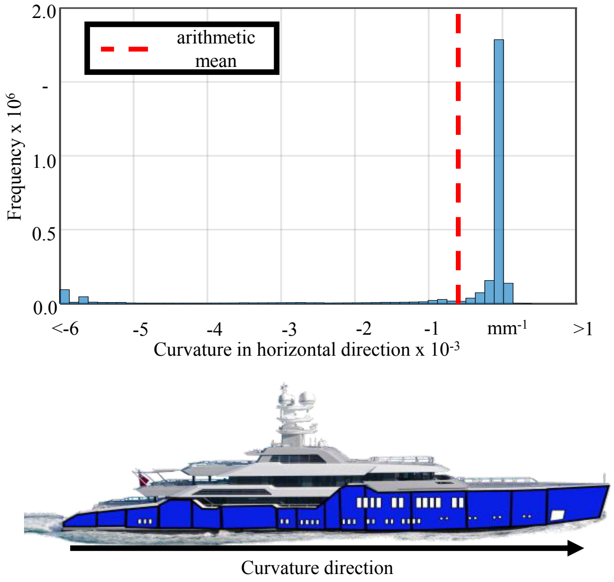


Fig. 4 Histogram of curvature in horizontal direction.

In the next step, the shape of the intended yacht surface (design model) is analysed. Figure 4 shows an exemplary analysis.

The parts (about 860 m² of surface) were analysed in 2.6 million points. The exemplary design model represents the inner surface of single metal sheets. As NURBS faces are always defined in a rectangular interval in $R^2$, for the representation of openings, these surfaces are trimmed. The analysis uses a completely untrimmed surface. As shown, most parts of the yacht have a very small curvature in horizontal direction. As a yacht is usually narrow at the bow, then getting wider in the middle part and narrow again at the stern, a similar curvature distribution can be expected for most yachts. Additionally, parts with a very low curvature are visible. These parts are mainly in the front part, where the two sides of the ship meet. These or similar analysis of the planned surface become even more useful when combined with an analysis of the actual surface.

As described previously, a universal demand for the surface is the similarity between intended and finished surface. Some changes are acceptable and even necessary for optimisation, but a large deviation is most likely an indicator for an unacceptable surface. For walls in the deck area, an analysis of the horizontal curvature of the filled surfaces is necessary, as this is the main viewing direction. The evaluation of the continuity of the filled surface is challenging, as the analysis is discrete. Even with a very high density of points, there is no certainty that the continuity is safely determined. Therefore, another approach is needed. Most surfaces can be described using NURBS-surfaces (Non-Uniform-Rational-B-Spline). In this paper, the practical aspects of NURBS are shown. Splines were first investigated by Schoenberg [e.g. [12]) and are still part of many research projects (e.g. [13]). NURBS-surfaces are described by:

- the control points,
- the polynomial degree,
- the knot vector,
- the weights of each control point.

With these factors an accurate mathematical description of a surface is given. To represent larger areas, usually multiple NURBS-surfaces are connected to a group of patches.

Thus, by differentiating the surface the continuity can be determined continuously.

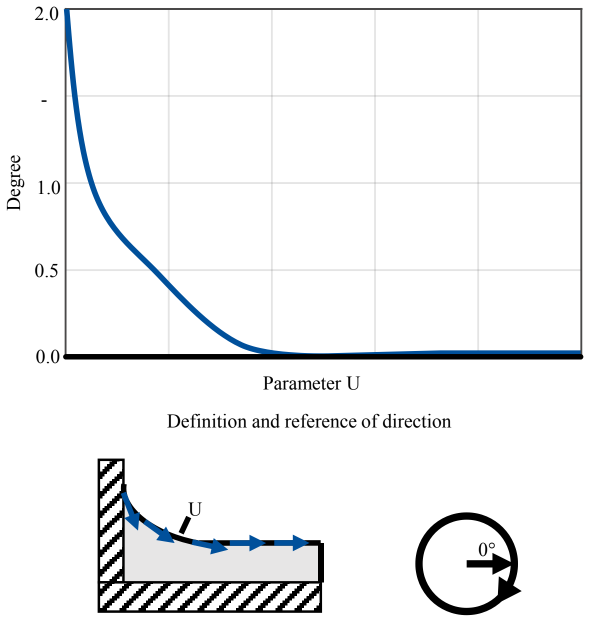


Fig. 5. Qualitative behaviour of a tangent along the surface.

For the usage during an automated quality control, this is the fastest and safest way. For guaranteeing the additional continuity between two NURBS-patches, the curvature at the common edge must be determined. In order to ensure curvature continuity across the surfaces, the curvatures along the common edges have to be alike.

Regarding Surfaces 3, the quality control is more individual than for the other surfaces. All surfaces with special requirements need to be defined by the design engineer. For the quality control of the filling of mega yachts, this has to be done manually beforehand. This process has to be implemented in the design process. The related points in the model of the current state can then be identified automatically by comparison of position and form. Afterwards, the special requirements for the surface can be evaluated. For the anchor pocket, this means e.g., an automated calculation of the distance between filled surface and the edge of the anchor pocket. For the transition area, the automated evaluation is more difficult, as the end of the transition has to be defined. For this, the direction of the maximum cuvature vector is useful. As it changes heavily along the transition area, the changes along the main surface are quite weak. In Figure 5, this is demonstrated with a two-dimensional example.

The challenge with windows and other openings is the automated recognition of groups. As described before, a big aesthetic factor of openings is their position and size towards each other. To evaluate the aesthetics of openings, it is important to mark related openings during the design process.

During the quality control process, it is possible to compare their position and orientation automatically. For instance, if a group of rectangular openings that are planned to be side by side are evaluated, the upper and lower edges of the openings can be easily tested for collinearity, while the vertical edges are tested for parallelism and distance. With these tests, it is easily possible to confirm position and orientation accuracy for openings.

## 7. Summary and outlook

In this paper, it is described how smooth surfaces on mega yachts are created and evaluated. It is shown how this process can be improved. For this improvement, it is necessary to define certain universal criteria for aesthetic surfaces. It is shown how aesthetics is described in a more general way and what is important for the evaluation of mega yachts. Afterwards, a mathematical description of the requirements is given and it is shown how these can be used for an automated quality control approach. To make the automation possible, there are still several steps to take. Currently, the list of Surfaces 3 is expanded with more yacht features and the corresponding requirements for aesthetics. The basis for the software realisation of the presented ideas has been done based on the open-source software development kit "Open CASCADE Technology" [14]. The process reliability and velocity is highly dependent on the quality of the design model and the point cloud. Thus, in order to make an automated quality control operative, the cleaning of the point cloud must be improved. Furthermore, some functions need to be implemented in the design process.

Amongst the automation of the evaluation, another important step for improvement of the filling process is the automated generation of the desired state. For this process, the same mathematical criteria are used. By deforming the design model towards the point cloud, this model is created. The development of this process has high priority and is a big step for the improvement of the filling process.

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