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TERRESTRIAL LASER SCANNING USED TO DETECT ASYMMETRIES IN BOAT HULLS

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ABSTRACT

We describe a methodology for identifying asymmetries in boat hull sections reconstructed from point clouds captured using a terrestrial laser scanner (TLS). A surface was first fit to the point cloud using a non-parametric regression method that permitted the construction of a continuous smooth surface. Asymmetries in cross-sections of the surface were identified using a bootstrap resampling technique that took into account uncertainty in the coordinates of the scanned points. Each reconstructed section was analysed to check, for a given level of significance, that it was within the confidence interval for the theoretical symmetrical section. The method was applied to the study of asymmetries in a medium-sized yacht. Identified were differences of up to 5 centimetres between the real and theoretical sections in some parts of the hull.

1. INTRODUCTION

The reconstruction of three-dimensional (3D) objects from point clouds captured using a terrestrial laser scanner (TLS) has been the subject of numerous studies in recent years in fields as different as industry, architecture, medicine and land engineering.

The scanner measures an object’s surface by acquiring a dense point-wise sampling of the surface, typically by deflecting a laser-beam in two dimensions across the surface and measuring the distance along with it. Data captured by a TLS is used to reconstruct the surface of objects. The most popular surface reconstruction methods are those that use triangular grids, although others based on radial basis functions, b-splines and piecewise algebraic surfaces are also used.

We propose a method for detecting asymmetries in boat sections using point clouds captured using a TLS and bearing in mind possible uncertainty in the point coordinates. The method is based on fitting a surface to the point cloud using a non-parametric regression method, sectioning the surface into two halves and comparing these using confidence intervals obtained by bootstrapping for the difference between each half. Thus, for a specific level of significance, it can be determined whether or not each boat section can be considered symmetric in relation to a hypothetical axis of symmetry.

2. METHODOLOGY

2.1. SURFACE RECONSTRUCTION FROM A POINT CLOUD

The point cloud, captured using a TLS, was fitted using a non-parametric regression method and a kernel smoothing technique (Wand and Jones, 1995). Non-parametric regression techniques are very useful in this context, as they enable the surface to be modelled without establishing a parametric shape beforehand (Roca-Pardiñas et al. 2008). For each point on the object surface (X,Y,Z) coordinate z can be obtained from (X,Y) using a special unknown function $m(X,Y)$. Each laser point $(X_i^\bullet,Y_i^\bullet,Z_i^\bullet)\, i=1....n$, can be understood as a measure of the real point $(X_i\,,Y_i\,,Z_i\,)$ of the object surface, such that:

$$(X_i^\bullet,Y_i^\bullet,Z_i^\bullet)=(X_i\,,Y_i\,,Z_i\,)+(\varepsilon_i^x,\varepsilon_i^y,\varepsilon_i^z) \quad (1)$$

Where $(\varepsilon_i^x,\varepsilon_i^y,\varepsilon_i^z)$ represents the measurement error in the ith point.

For any given point (x_0,y_0), to obtain an estimate of $z=m(x,y)$ for values of (x,y) close to (x_0,y_0), a Taylor expansion was used under the assumption that the true surface m would be sufficiently smooth and continuous:

$$\hat{m}(x,y)=\theta_0+\theta_1(x-x_0)+\theta_2(y-y_0)$$

To obtain the parameters θ_i, the following function was minimized for a fixed value (x_0, y_0):

$$\sum_{i=1}^{n} W_h(X_i^\bullet - x_0, Y_i^\bullet - y_0) D_i \qquad (2)$$

where

$$D_i = \sqrt{(X_i^\bullet - x_0)^2 + (Y_i^\bullet - y_0)^2 + \left(Z_i^\bullet - \theta_0 - \theta_1(X_i^\bullet - x_0) + \theta_2(Y_i^\bullet - y_0)\right)^2}$$

and

$$W_h\left(X_i^\bullet - x_0, Y_i^\bullet - y_0\right) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{\left(X_i^\bullet - x_0\right)^2 + \left(Y_i^\bullet - y_0\right)^2}{2h}\right\}$$

Note that W_h is a weighting function depending on the Euclidean distance between (x_0, y_0) and $\left(X_i^\bullet, Y_i^\bullet\right)$. The bandwidth h is a trade-off between the bias and the variance of the resulting estimate. If h is too small the resulting estimate $\hat{m}(x_0, y_0)$ heavily depends on observations closest to (x_0, y_0) and tends to yield a wigglier estimate. On the other hand, if bandwidth is too large the estimated surface will be a plane and will not adjust to the real shape of the true surface; it indicates that the estimation has bias errors.

Various proposals for optimal selection of h have been suggested (Jones, 1996; Home and Garton 2006), all based on minimizing some error criterion. In this research we used cross-validation, so the bandwidth was selected by minimizing

$$CV = \sum_{i=1}^{n} \min_{x,y} \left\{ \sqrt{(X_i^\bullet - x)^2 + (Y_i^\bullet - y)^2 + \left(Z_i^\bullet - \hat{m}^{-i)}(x,y)\right)^2} \right\} \qquad (3)$$

where $\hat{m}^{-i)}(x,y)$ indicates the fit of $m(x,y)$ leaving out the i-sample data $\left(X_i^\bullet, Y_i^\bullet, Z_i^\bullet\right)$.

2.2. ASYMMETRY DETECTION

In the previous section the mechanism for-nonparametric reconstruction of the true surface was described. Now, for each value of *y*, it is necessary to determine if left and right curves are symmetric in relation to a point of symmetry x_s. To do this we proceed as follows: 1) For a given y, the point of symmetry x_s is obtained as the point in which $m(x,y)$ reach the minimum, that is $x_s = \arg\min_x m(x,y)$.; 2) Once x_s is obtained, we accept symmetry if $m(x,y) = m(2x_s - x, y)$ or, what is the same, if $D(x) = m(x,y) - m(2x_s - x, y) = 0$ for all values of x; otherwise, the cross-section will not be symmetrical.

Nonetheless, in many cases exact symmetry is not required, but it is considered sufficient if $|D(x)| < T$, where T is the admissible maximum tolerance. This tolerance, which should be established beforehand, will depend on the circumstances of each case and the nature of the studied object and its dimensional requirements.

Note that, in practice, the true $D(x)$ is not known, so its estimate $\hat{D}(x)$ is used. Therefore, we consider a cross-section to be symmetric if $\hat{D}(x) = \hat{m}(x,y) - \hat{m}(2\hat{x}_s - x, y) = 0$ where $\hat{x}_s$ is given by $\hat{x}_s = \arg\min_x \hat{m}(x,y)$. Of course, since $\hat{D}(x)$ is only an estimate of the true $D(x)$, the sampling uncertainly of these estimates need to be acknowledged. Hence, a confidence interval (CI) is created for $D(x)$ for a specific level of confidence (e.g., 95%) and it is considered that there is no symmetry when zero is not inside of the CI.

For the construction of the above CI we use bootstrap techniques. Given y, the steps for construction of the confidence interval for the true $D(x)$ are as follows:

Step 1. Obtain the estimated $\hat{D}(x)$ from the original sample data $\left(X_1^\bullet, Y_1^\bullet, Z_1^\bullet\right), \ldots, \left(X_n^\bullet, Y_n^\bullet, Z_n^\bullet\right)$ (as explained above).

Step 2. For b=1 to B (e.g., B=1000), simulate a random sample $\left(X_1^{\bullet b}, Y_1^{\bullet b}, Z_1^{\bullet b}\right), \ldots, \left(X_n^{\bullet b}, Y_n^{\bullet b}, Z_n^{\bullet b}\right)$ by randomly sampling *n* items from the original dataset with replacement and so obtain the bootstrap estimate $\hat{D}^b(x)$.

Step 3. Finally, the *(1−α) 100%* limits for the confidence interval of $D(x)$ are given by:

$$\left(\hat{D}^{\alpha/2}(x), \hat{D}^{1-\alpha/2}(x)\right)$$

where $\hat{D}^p(x)$ represents the *p*-percentile of the bootstrapped estimates $\hat{D}^1(x), \ldots, \hat{D}^B(x)$.

3. APPLICATION EXAMPLE

The method described above was used to determine symmetries for a yacht measuring 12 metres long, with a beam of 4.5 metres and a draft of 2.4 metres. Symmetry along the fore-aft axis of a boat is important for correct sailing behaviour, as asymmetry can cause a shift in the displaced volume and in a different thrust on the port and starboard sides of the hull, causing the vessel to list; another possible outcome of asymmetries is a lateral thrust that causes the vessel to veer from a straight-line course.

The relevance of these effects depends on the planned use of the vessel, its characteristics and the dimensional requirements. In this study we evaluated a boat hull for asymmetries for different values of tolerance T. Applying the method for rebuilding the yacht hull from the point cloud, we obtained the surface shown in Figure 1.

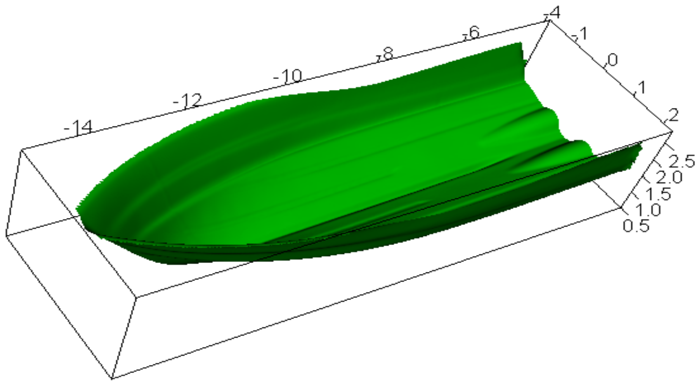

Figure 1: 3D surface of the boat hull reconstructed using non-parametric regression with kernel smoothing.

From this surface we obtained 23 cross-sections perpendicular to the central fore-aft line, one for each 0.25 metres of the yacht hull. Figure 2 shows three of these cross-sections. A symmetric half was generated in order to compare the two sides of the boat. Quantitative values of differences between real and symmetric parts were obtained for each section.

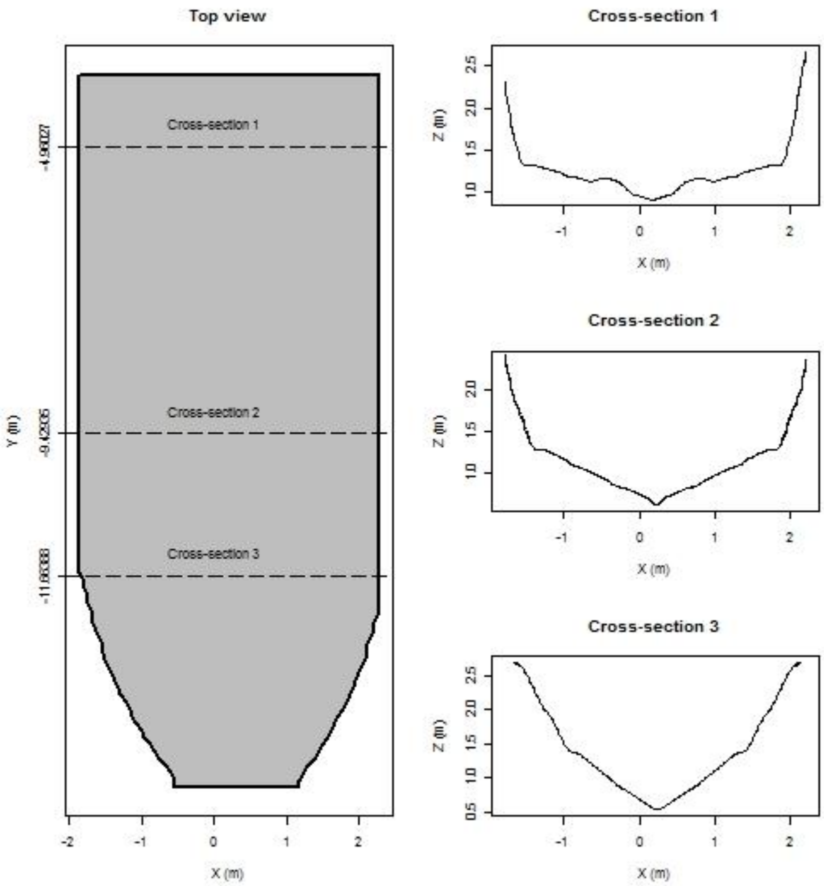

Figure 2: Detail of three cross-sections from the bow of the yacht (*solid line*) and the symmetric half (*dot line*) generated in order to compare the symmetry of both sides.

Figure 3 (left) shows two estimated cross-sections and the corresponding symmetrical sections. Figure 3 (right) shows estimated difference $\hat{D}(x)$ together with the 95% confidence interval. Areas with asymmetry, for $T = 0$, are areas where the two lines defining the confidence interval are above or below zero.

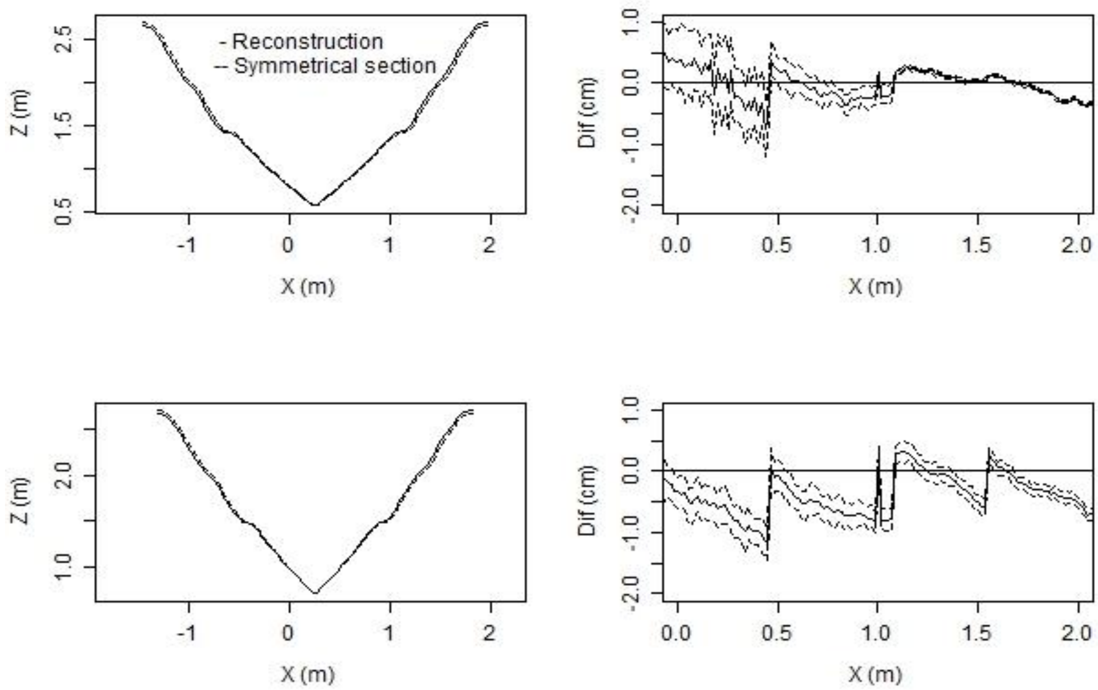

Figure 3: Cross-sections obtained for different values of *Y*. For each case, an *XZ* graph shows the difference between the estimated and the symmetric curves, together with the 95% pointwise confidence intervals.

Greater asymmetries were observed in the bow area and above the waterline; occasionally the differences detected were above 4 centimetres (Figure 4).

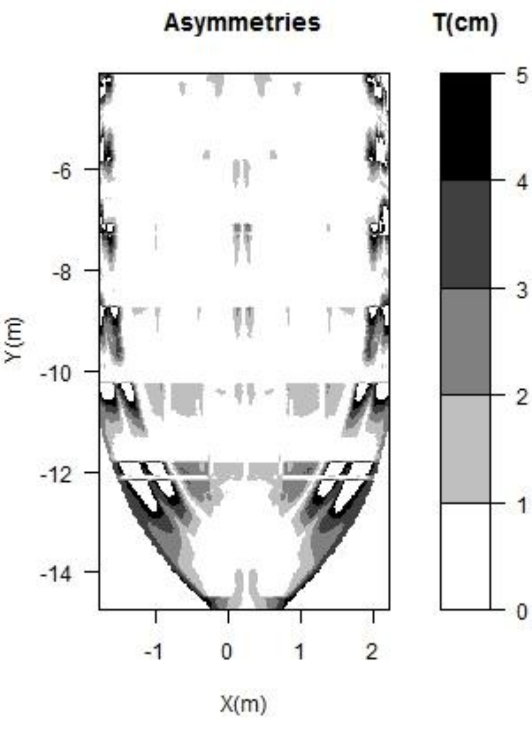

Figure 4: Asymmetries, for different tolerance values, detected on the surface of the boat hull.

3. CONCLUSIONS.

This article describes an approach to detecting asymmetries in boat hulls using a point cloud obtained with a TLS. An important aspect of the proposed methodology was that the implementation of a bootstrapping resampling technique took account of any uncertainty in the coordinates recorded by the TLS. Thus, for each section of the boat, a confidence interval was obtained that enabled asymmetries to be identified for a pre-established confidence level and for a specific tolerance (maximum admissible difference between the theoretical and real sections).

Applying the proposed methodology to different sections along the axis of the vessel meant that areas where asymmetries exceeded the tolerance value could be represented in a way that could be useful in improving the quality of a boat.

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