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Creating a Complete Model of the Wooden Pattern from Laser Scanner Point Clouds Using Alpha Shapes

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ABSTRACT

Laser-scanning techniques present non-contact, flexible and accessible tools for digitizing shape and surface of many physical objects. The data obtained from these optical measurement systems is usually in the form of a point cloud (non-ordered set of XYZ coordinates). One of the most requested tasks is the conversion of point clouds into more practical triangular meshes containing useable information. A novel approach for wooden pattern modeling based on an improvement of alpha shape algorithm is proposed, where the data consists of points unevenly distributed in a volume rather than only on a surface. The developed model can record and detect efficiently the defects and the deformed breaks in the wooden structure. Accuracy indicators achieved reached about 89% completeness, 95% correctness and 87% quality for the selected data. This form of three-dimention (3D) geometry representation is anticipated to open the door for future data processing, visualization and monitoring for different engineering applications.

KEYWORDS: Laser scanning, Point cloud, Alpha shape, Modeling, Wooden pattern.

INTRODUCTION

Laser scanning is an active remote sensing system that provides 3D information of physical surfaces with rich details (Rakitina et al., 2008). With the advancement of 3D scanning technology, thousands of 3D points could be acquired every second at high levels of accuracy and complicated objects precisely digitized. The data is obtained in the form of an unorganized point cloud, where no topological connection relations are included. Although the current laser scanners can produce large point clouds, the resolution of data obtained is still insufficient for break-lines, such as edges and cracks (Alshawabkeh and Elkhalili, 2013).

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Break width measurements in laboratory experiments are commonly performed using a crack-scope (small and portable microscope) or crack width gauge card; whereas different methodologies have been traditionally used in the field to quantify and monitor breaks and cracks in real scene surfaces, such as using of geodetic methods, mechanical extensometers and electrical sensors (Rakitina et al., 2008; Rutinger et al., 2010). These procedures have disadvantages, since they require contact tools placed manually on the surface and their application depends on accessibility.

To overcome the shortages of using traditional reconstruction of a detailed surface, shape and defects of objects such as cracks and break-lines is a new challenge in 3D modeling. Reconstruction of surface from scattered scanned points could be achieved through meshing point clouds. The mesh is a network of discrete

cells over the domain. There is a set of methods for 3D reconstruction with different properties (Piazza et al., 2018; Zhu and Yan, 2012). The choice of the proper reconstruction method depends on the nature of the 3D object and on the quality of the digitalization process.

3D reconstruction using Delaunay triangulation is a fundamental approach in computational geometry that is widely used (Piazza et al., 2018; Zhu and Yan, 2012). The main principle of this procedure is to create only such simplexes (tetrahedrons) for which the circumscribed spheres do not contain any other point beside the vertices of a given simplex. As a result of Delaunay-based point cloud processing, the triangle mesh containing all tetrahedrons' faces is created. Applications of Delaunay-based algorithms are constrained only to practically homogenous point clouds because of excessive triangle-removing procedures (Sitnik and Karaszewski, 2008).

One of the earliest approaches is based on α-shapes by Edelsbrunner (1995). Alpha shape is derived from Delaunay triangulation, which offers a concrete definition of the shape to represent the structure of a set of points (Zhau and Yan, 2012). Alpha shapes define a family of simplicial complexes parameterized by $\alpha \in R$. The family of alpha shapes implies filtration and partial ordering of the simplexes of the Delaunay triangulation that may be used for multi-scale topological analysis of the point cloud (Cazals et al., 2005).

Therefore, it is anticipated that building a model structure from laser scanner point clouds could be a valuable tool to overcome some of the previously mentioned deficiencies. This research work utilizes and builds a complete model of the wooden pattern from laser scanner point clouds using alpha shapes. In order to have all details in a regular mesh, a range of alpha values is used for testing the close property of the constructed mesh, where the mesh model is a concave closure of the point data.

Terrestrial Laser Scanner

Terrestrial laser scanners cannot realize an accuracy level similar to laser trackers or close-range photogrammetry, but their priority is the large field of view. An environment within 360° in horizontal direction and more than 300° in vertical direction can be measured by using panoramic laser scanners (Scheider, 2014). The scan duration can be defined by selecting different resolutions and quality levels.

Laser scanners create a three-dimensional point cloud by measuring distances, as well as horizontal and vertical angles. For distance measurements, a laser beam is released, reflected by an object and returned back to the receiving part of the distance measurement unit. Since the laser beam is manifold, approximately a circle is projected to the object surface, not only a point. The limiting size to detect fine structures is based on the produced diameter of this circle (Harmening et al., 2016). The size of this area predicates on the range to the laser scanner. In this research work, a Leica HDS 7000 scanner was utilized. Approximately 3.5 mm in a distance of 10 cm from the scanner is the footprint of the laser beam of the HDS7000 scanner. This diameter will be increased with distance and the beam divergence is less than 0.3 mrad. The angular resolution is 7 mrad (horizontal/vertical) (Leica Geosystems, 2011) (see Figure 1).

Detecting Wooden Pattern Using HDS 7000 Scanner

The preliminary processing stage of modeling any structure is detecting it in a point cloud. Mixed pixels must be picked and removed (Pu and Vosselman, 2009). Expression mixed points are known as these points which originate if the laser beam is reflected partly by the object itself and partly by another object beyond it. For that aim, a triangulated mesh of the point cloud is generated. It includes triangulated faces and measured points as vertices (Rakitina et al., 2008).

It should be investigated whether point clouds being measured by terrestrial laser scanners can be refined in a way so that the wooden structure can be identified and modeled, respectively (Scheider, 2014). For that target,

points on the object must be isolated from any disturbing influence like measurement noise and mixed pixels. The wooden pattern is obviously scanned as shown in Figures 2, 3, 4 and 5, respectively

Figure (1): Leica HDS 7000 scanner (Leica Geosystems, 2011)

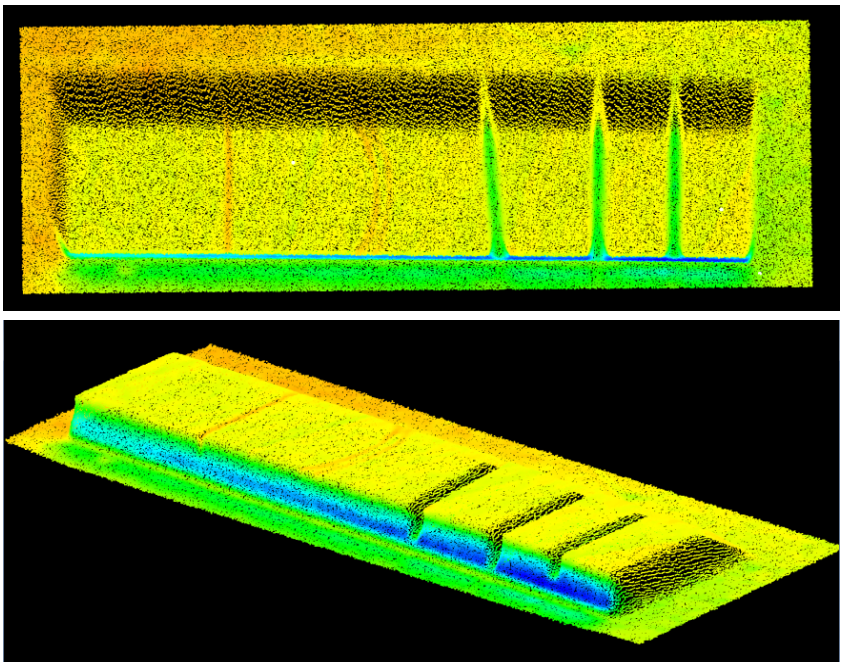

Figure (2): Top view of a wooden panel with deformed breaks

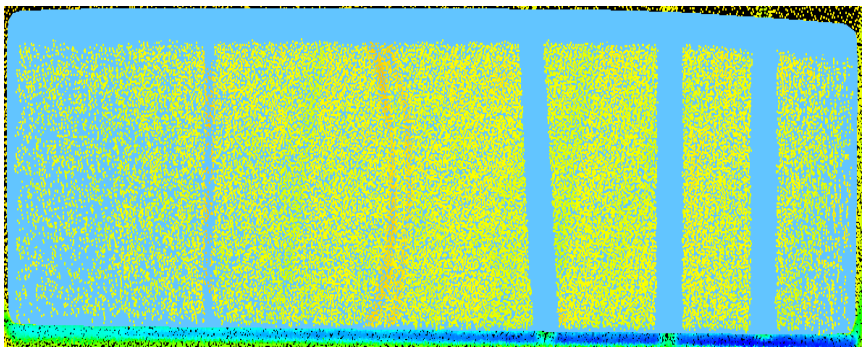

Figure (3): Top view of a wooden panel with deformed breaks; surface is modeled by a closed plane (→ deformed breaks are better visible; deformed breaks 1, 2 and 4 are approximately parallel)

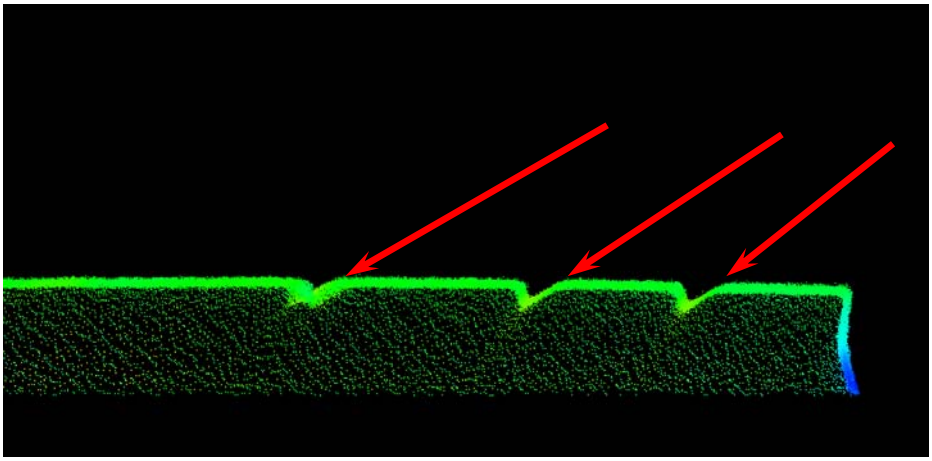

Figure (4): Scan 1: deformed breaks are transverse to the scan direction → arrows show scan direction (visible: deformed breaks 1, 2 and 3)

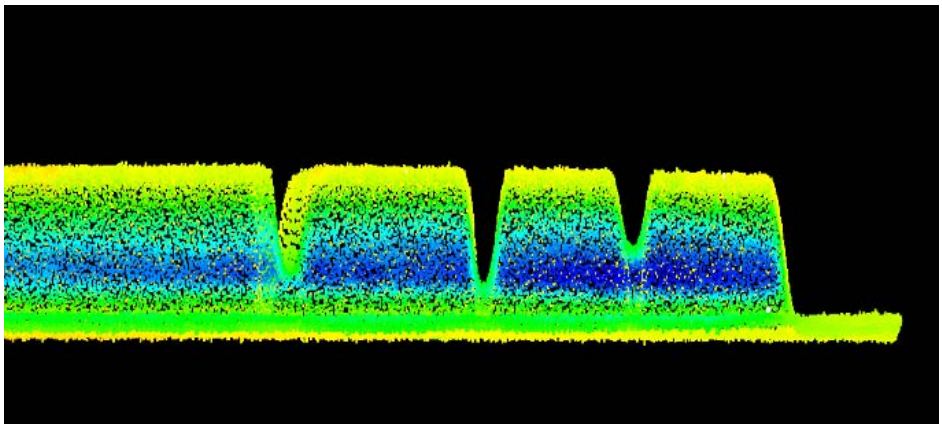

Figure (5): Scan 2: deformed breaks are approximately aligned along the scan direction (visible: deformed breaks 1, 2 and 3)

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Algorithm Bases: Alpha Shapes

Alpha shape was suggested in two dimentions (2D) by Edelsbrunner (1995) and was then expanded to 3D. This methodology can be utilized to reconstruct an object surface from an unorganized point cloud. Our modeling and reconstruction of wooden structure are based on this technique.

Delaunay Triangulation

A set ***P*** of points can be applied to build a complex if the points do not lie in a plane. Delaunay triangulation is a natural option to realize it. In previous studies, various Delaunay triangulation techniques were suggested (Zhu et al., 2008), where Lawson flip technique is an exemplary one. In Lawson's method, the tetrahedron bounding the point set ***P*** is firstly organized, then the other points are integrated into the triangulation one by one. Each time, the triangulation should be correctly adjusted to satisfy the Delaunay property (the circumsphere of every tetrahedron does not include any other points). Any one of the tetrahedrons, which do not satisfy a local Delaunay property, is overturned and flipped. The flip procedure in 3D can be explained as follows. The triangulation in 3D is a group of tetrahedrons building a simplicial complex. Based on the available dataset, this research work will demonstrate the case of two tetrahedrons incident to a triangle ***ace*** (see Figure 6). If the circumsphere of tetrahedron ***aecd*** does not include ***b*** and the circumsphere of tetrahedron ***aecb*** does not include ***d***, the triangle ***aec*** should be considered as a local Delaunay. Otherwise, this status can be adjusted by inserting a new edge ***bd***. So, the complex is a Delaunay triangulation. The final outcome of Delaunay triangulation of the point set is its convex hull containing different tetrahedrons.

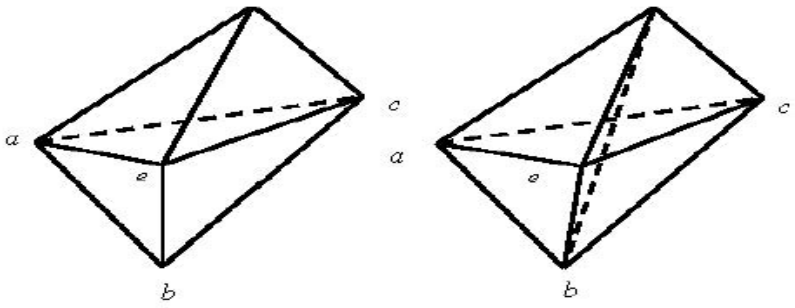

Figure (6): Flipping in three dimensions (Zhu et al., 2008)

Alpha Shape

The principle of alpha shape creates the conjectural idea of shape for spatial point sets on user's selection. Alpha shape is a mathematically well-defined general statement of the convex hull. Its outcome is a chain of subgraphs of the Delaunay triangulation, relying on various alpha values. Given a finite point set, a group of simplexes can be counted from the Delaunay triangulation of the point set. The desired level of detail will be controlled depending on an actual alpha parameter. All actual alpha parameters lead to a whole group of shapes. The alpha shape of a point set is composed of the set of points, edges, triangles and tetrahedrons, which are content with the restricted condition (the alpha test) (Wei, 2008). This latter test stratifies for each triangle ***t*** of the triangulation. If ***t*** is not on the boundary of the convex hull, there must be two tetrahedrons ***p*** and ***q***, which are incident to ***t***. Tetrahedrons ***p*** and ***q*** are examined to be in the circumsphere of ***t*** or not. Two conditions must be satisfied as follows. If both tetrahedrons ***p*** and ***q*** are not in that circumsphere and the radius of the circumsphere

is less than the alpha value, alpha test is satisfied by ***t*** and the latter is considered as one member of the alpha shape. Therefore, alpha shape is considered as a subset of the triangulation.

If alpha will be enormous enough, the shape is the convex hull of the point set. Otherwise, if alpha is close to 0, no tetrahedral triangles and edges could exceed the alpha test, thus the alpha shape is the point set. If any modification of the alpha values occurs, the subset will follow the topology of the point set. Therefore, if this research work selects a suitable value for alpha, the reasonable surface for the wooden structure will be found. The alpha shape is a sub-complex of the Delaunay triangulation of the point set ***P***. There is a ball eraser with alpha as its radius; the latter will move over all possible positions in the 3D space with no point of P included. This eraser will skip all simplexes whose size is bigger than alpha and it can pass through. Finally, the remaining simplexes build the alpha shape.

Suppose that a circle with a radius $\boldsymbol{\alpha}$ is rotating around the point set ***S***. If $\boldsymbol{\alpha}$ value is bigger than a threshold, the circle will not fall into the area of ***S.*** The rotating path will format the boundary of this point set ***S***. When the $\boldsymbol{\alpha}$ value is close to infinity ($\boldsymbol{\alpha \to \infty}$), $\boldsymbol{\alpha}$-shape will be the convex hull (Akkiraju et al., 1995). On the other hand, when the $\boldsymbol{\alpha}$ value is close to zero ($\boldsymbol{\alpha \to 0}$), every point will be the boundary. Figure 7 shows that when the point set ***S*** includes evenly distributed points and $\boldsymbol{\alpha}$ is close to an optimal value, the $\boldsymbol{\alpha}$-shape can show the inner and outer edges of the polygon at the same time. For each real number α, utilize the notion of a generalized disk of radius $1/\alpha$. The alpha algorithm is realized as follows:

- If $\boldsymbol{\alpha = 0}$, it is considered as a closed half-plane;
- If $\boldsymbol{\alpha > 0}$, it is considered as a closed disk of radius $\boldsymbol{1/\alpha}$;
- If $\boldsymbol{\alpha < 0}$, it is the closure of the complement of a disk of radius $\boldsymbol{-1/\alpha}$.

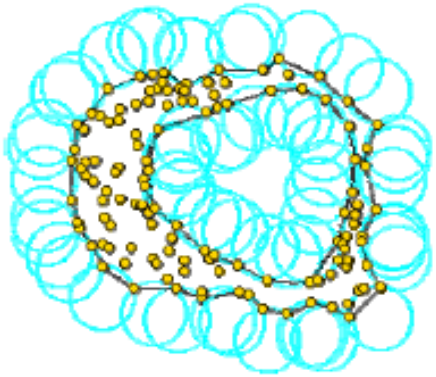

Figure (7): Alpha shape algorithm extracting principle (Wei, 2008)

Building the Mesh 3D Model of the Wooden Structure

From the above analysis and the range image data collected from a single scan in Figures 4 and 5, the reorganization between the dense region and the scattered region of the data can be done by observation, but this separation method is very difficult to be done in a computer because of measurement noise and scanning errors. Therefore, it is expected that the data might contain holes and gaps. In spite of the fact that the dense region, the scattered region, the convex region and the concave region might be distinguished, some mistakes in topological reconstruction will happen during the algorithms processing very dense point sets. So, this research work must build topological structure of points at first, where Delaunay triangulation is an ideal selection. The algorithm of this paper includes four steps:

1- Triangulate point set $\boldsymbol{P} = \{\boldsymbol{p_i}\}$ with Delaunay triangulation; therefore, a set of connected tetrahedrons $\boldsymbol{T}=\{\boldsymbol{T_J}\}$ results. Flipping method in (Zhu et al., 2008) is applied to evaluate and reform irregular triangulation in $\boldsymbol{P} = \{\boldsymbol{p_i}\}$. All tetrahedrons $\boldsymbol{T}=\{\boldsymbol{T_J}\}$ will comprise a convex solid, where the framework of this solid is a convex hull.

2- Calculate all radii, $\boldsymbol{R}(\boldsymbol{T_j})$, of circumference of every tetrahedron after triangulation. This calculated value is considered as one attribute of a tetrahedron $\boldsymbol{T_j}$. The radii, $\boldsymbol{r}(\boldsymbol{F_k})$, of the circumcircle of each face of a tetrahedron are calculated furthermore, where the latter are considered as an attribute of each face.

3- Classify and distinguish tetrahedrons $\{\boldsymbol{T_J}\}$ and all their faces. The size of $(\boldsymbol{T_j})$ is considered as a rule to classify all $\{\boldsymbol{T_J}\}$. This classification is applied by the relation of $\boldsymbol{R}(\boldsymbol{T_j})$, with threshold $\boldsymbol{\alpha}$, where $\boldsymbol{\alpha}$ is given by users. The range of $\boldsymbol{\alpha}$ should be appropriate. After that, all tetrahedrons are separated into two divisions according to a real value: interior tetrahedrons and exterior tetrahedrons; where:

   (i) $\boldsymbol{T_J}$ is classified as an exterior tetrahedron if $\boldsymbol{R}(\boldsymbol{T_j}) > \boldsymbol{\alpha}$,
   (ii) Otherwise, it is classified as an interior tetrahedron.

All faces $\{\boldsymbol{F_k}\}$ from each tetrahedron $\boldsymbol{T_J}$ are separated into three divisions too: interior faces, exterior faces and boundary faces. The classification principle is as follows:

   (i) The face is classified as an exterior face if it is located on the convex hull which belongs to an exterior tetrahedron.
   (ii) Otherwise, it is a boundary face if it belongs to an interior tetrahedron.

For each face which is not located on the hull, the classification principle is as follows:

   (i) It is considered as an exterior face if it is an intersection face of two exterior tetrahedrons.
   (ii) It is considered as an interior face if it is an intersection face of two interior tetrahedrons.
   (iii) It is considered as a boundary face if it is an intersection face of one interior tetrahedron and one exterior tetrahedron. All boundary faces will build a mesh $\boldsymbol{M}$; it is considered as a concave approximation of the wooden structure.

The largest radius of all $\boldsymbol{R}(\boldsymbol{T_j})$and all $\boldsymbol{r}(\boldsymbol{F_k})$ is considered as $\boldsymbol{r_{max}}$ and the smallest radius of all $\boldsymbol{R}(\boldsymbol{T_j})$ and $\boldsymbol{r}(\boldsymbol{F_k})$ is considered as $\boldsymbol{r_{min}}$. This research work achieves an interval $\boldsymbol{[A,\ B]}$, where $\boldsymbol{A = \lambda\, r_{min}}$, $\boldsymbol{B = \mu\, r_{max}}$, $\boldsymbol{\lambda = 0.6}$ and $\boldsymbol{\mu = 1.3}$. The $\boldsymbol{\alpha}$ value should be limited to the interval $[\boldsymbol{A, B}]$; otherwise, if $\boldsymbol{\alpha > B}$, the mesh $\boldsymbol{M}$ will be a convex hull and if $\boldsymbol{A < \alpha}$, the mesh M will not be a convex hull.

4- Checking and validating of particular alpha values: $\boldsymbol{\alpha}$ must lay in the interval $\boldsymbol{[A, B]}$. Finding the suitable $\boldsymbol{\alpha}$ value is an iterative and repeated process. This research work initializes $\boldsymbol{\alpha}$ as the average value of $\boldsymbol{A}$ and $\boldsymbol{B}$. In each iteration step, the check must be done if the boundary triangles constitute a wooden surface; if so, the alpha value can be decreased; otherwise, it is increased.

Depending on the data quality and point density provided by the laser scanner system, the complexity of the wooden structure model can be adjusted. The minimum required model parameters, which are derived from the separated alpha shape point clouds, are radii $\boldsymbol{R}(\boldsymbol{T_j}), \boldsymbol{r}(\boldsymbol{F_k})$, $\boldsymbol{[A, B]}$ and threshold $\boldsymbol{\alpha}$. Figure 8 shows the workflow of this algorithm.

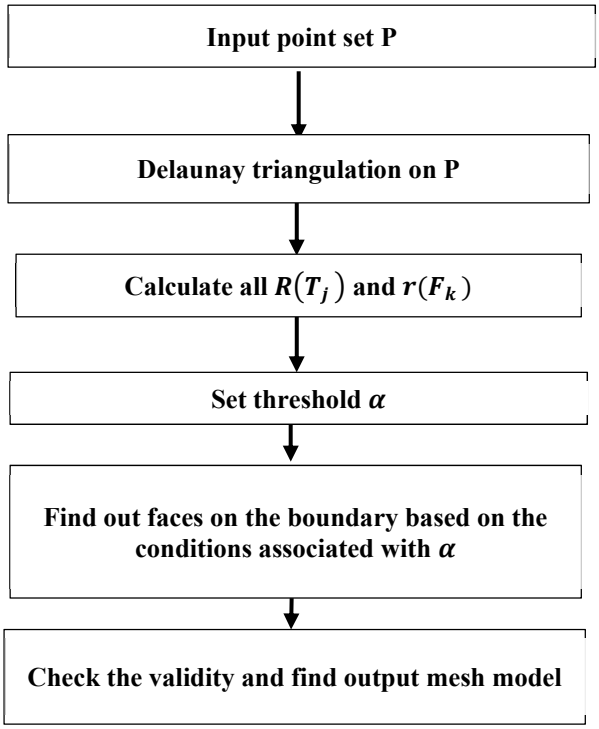

Figure (8): Workflow of algorithm

Experimental Results

The algorithm of this paper is written with C language with the support of OpenGL for graphics. Tests were done on a PC with P4, 3.0 GHz processor and 1 G RAM. CGAL library is utilized to execute Delaunay triangulation. To estimate and evaluate the results, the developed model by using alpha shapes was applied to the dataset of laser scanner point clouds for a wooden pattern containing three deformed breaks. An exemplary visualization for this wooden pattern after modeling it was constructed. Point cloud processing is realized by MeshLab (Meshlab, 2018) (Figures 9, 10 and 11, respectively).

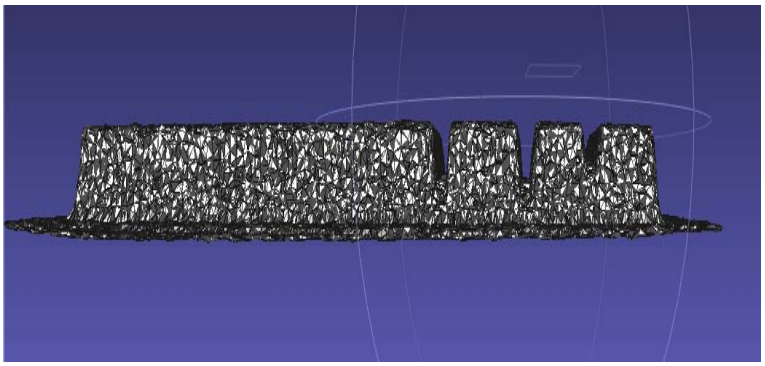

Figure (9): Creating a model with alpha shapes for scan (1) for the wooden pattern computed with MeshLab

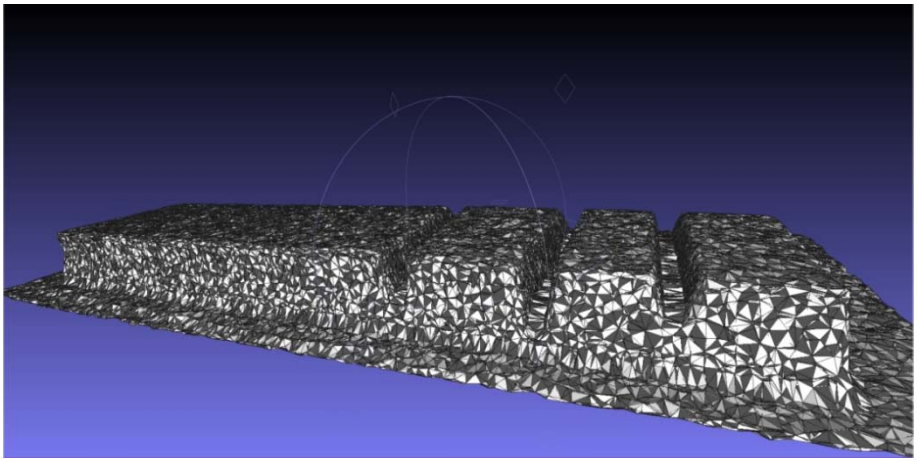

Figure (10): Creating a model with alpha shapes for scan (2) for the wooden pattern computed with MeshLab

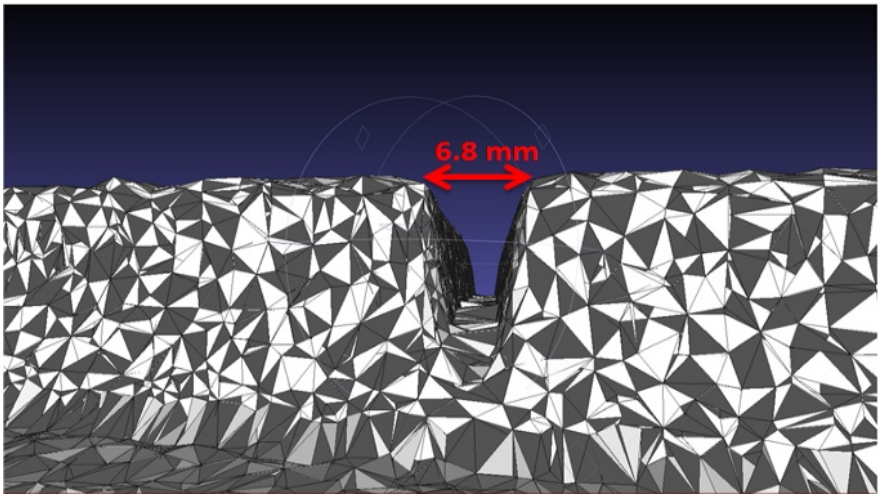

Figure (11): Creating a model with alpha shapes for the wooden pattern computed with MeshLab: deformed break 3 in detail

The detection and modeling algorithm was tested for the selected data (114997 laser points), then the completeness, correctness and quality were calculated (89% completeness, 95% correctness, 87% quality). Accordingly, Figure 11 shows deformed break 3 in detail. It is obvious that there is a problem in the lowest points. The problem is that triangulation closes the deepest parts of the deformed break. This problem is considered as a challenge in future investigations.

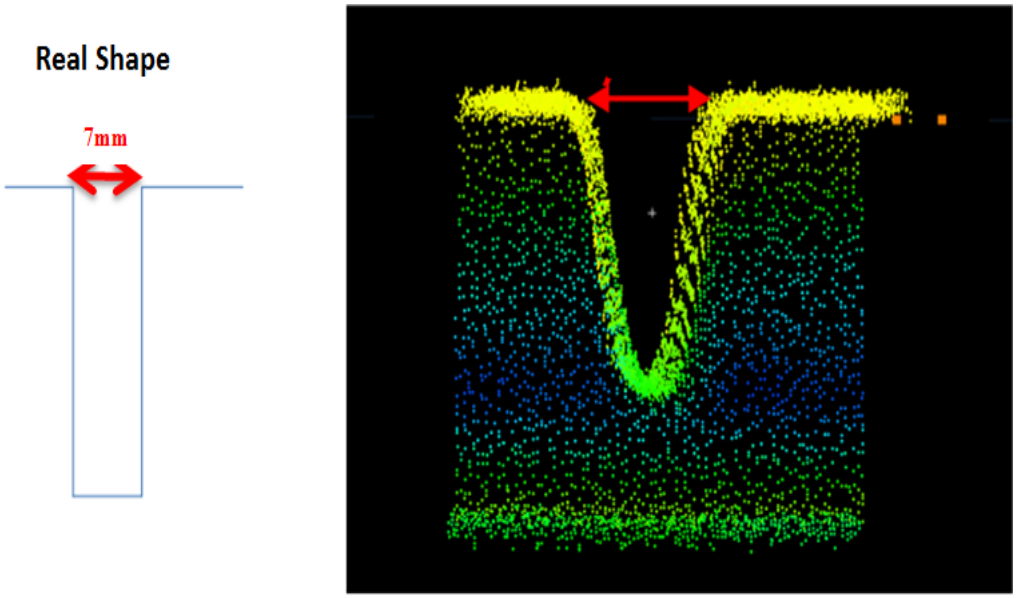

Figure (12): Scan 2: deformed break 3 in detail compared with the real shape

The realistic appearance of the model is checked against photographs and the original point cloud for validation purpose. The comparison shows that the general crown shape type (Figure 11 for deformed break 3 for example) matches the original shape very well (Figure 12). For example, it is obvious that the width of deformed break 3 in reality is about 7 mm (Figure 12), whereas the same width using the detection and modeling algorithm in this research work was 6.8 mm. This comparison proved that the algorithm mentioned in this study is effective and very practical for future data processing, visualization and monitoring.

CONCLUSIONS AND FUTURE WORK

Detecting and modeling small structures like decoration elements, cracks, deformed breaks,… etc. are a challenge, which requires special acquisition methods and special processing algorithms. Summing up a complete model of the wooden pattern from laser scanner point clouds using alpha shapes is presented in this work. It can be shown that the wooden pattern contains three deformed breaks. Deformed breaks are transverse to the scan direction in one approach and are approximately aligned along the scan direction in another approach.

The experiments proved that the algorithm mentioned in this study is effective and very practical in extraction and regularization. These methods provide a good solution for LIDAR data processing and 3D urban model rebuilding.

Future work should focus on lowest point problem. The problem is that triangulation closes the deepest part of the deformed break. This problem is considered as a challenge in future investigations. Also, the detection of deformed breaks may be improved by automation. Furthermore, detected and modeled structures using alpha shape can be compared to the results obtained from photogrammetric methods.

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