Surface reconstruction post-processing method for 3D-scanned objects

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Abstract. 3D scanning is widely used in multiple applications to obtain high precision / non-destructive documentation of real-life objects, which is especially important in Cultural Heritage (CH) preservation. However, some issues (in particular missing parts which are commonly known as “holes”) affect the accuracy of the obtained 3D model after the scanning procedure and requires time-consuming post-processing procedures, which include manual editing by highly-trained personnel. In this article an automatic method to reconstruct the obtained surface of 3D models is proposed, improving previously obtained results for high-density point clouds.

1. Introduction
3D scanning is widely used in multiple applications thanks to its high-precision measurements of real-life objects. It has particular importance in Cultural Heritage (CH) preservation as a non-destructive documentation method for artworks, which has multiple uses like art conservation tracing and replication.

Although the 3D scanning procedure is getting faster and easier with the use of laser-based techniques, it still requires to be performed by highly qualified personnel to reduce acquisition-related problems (mainly connected with missing parts in the surface of the object seen as holes in the final created 3D model) and complex and time-consuming post-processing procedures (often requiring manually editing the surface) to improve the accuracy of the final result of the created model. All these factors affect the required quality of such procedures used for documentation of CH objects.

As was above mentioned, one of the most recurrent problems in the application of 3D scanning techniques is the appearance of “holes”, due to the absence of measurement data of some parts of the scanned object during the acquisition process. This problem decreases the overall accuracy of the model created and its faithful representation, both problems of particular interest in the CH field.

In this work, a method to improve the accuracy of the computer digital 3D models is described. Its use will allow to increase the speed, reduce the computing costs and the time involved in the post-processing phase. The inverse distance method, developed and used to improve the reconstruction quality of the human face for biometry applications [1], showed good results in the reconstruction of 3D point clouds without the need of a previous mesh creation process [2]. The results are further improved in terms of accuracy and speed by subsampling the surface and applying the corrections in the areas where acquisition data is missing.
2. Method used
Most of the 3D-scanning techniques are based on the response of the object under study to a light source. In some cases, the reflected light is measured to determine the distance to the object (triangulation and time-of-flight techniques), in other cases the deformation of a well-known pattern is evaluated (structured light), in other cases photographs taken from different angles are used to obtain a 3D model using special software reconstruction tools (photogrammetry). The common problem that appears in more or less degree in the use of all these techniques is the presence of areas of the surface in which the sensor cannot measure, generating “holes” in the measurement. This problem could be caused by different factors, but mainly it can be seen when the reflected light is not able to reach the sensor of the device (due to occlusions caused by other parts of the object, highly reflective surfaces like glass or highly light-absorbing like black leather [3-5]). As the sensor is not able to obtain information about the object under study in this area, the device identifies this portion as a “hole” or an empty area in the obtained point cloud. This problem, of course, reduces the overall accuracy of the created digital model, which can compromise the goal of the whole procedure.

To correct these acquisition errors post-processing techniques are used [6]. These techniques include manual procedures, where highly trained personnel reconstruct the missing area trying to keep the shape as close as possible to the original object, and automatic procedures. Automatic procedures [7] use different techniques (from simply “connecting” the mesh using geometrical figures to more advanced techniques that follow the local curvature of the shape) but all have in common a high computing cost and that they are time-consuming processes.

The method of inverse distances was developed for the reconstruction of the 3D surface of a human face in biometry applications. The method uses a small number of points of an irregular grid of measurements to generate the missing points, creating a regular grid along the area. A more detailed description of the method could be found in [2]. In the cited article, it was proven the performance of the method in small areas (300 x 300 pixels), comparable with other more complex methods and requiring less computing power, being able to fix successfully surfaces with missing parts ranging from 3% to 30% of the total area. The method showed a lower performance with a larger number of points (15000 points or more).

To solve this issue, the proposed technique tested along this article detects the holes in the surface of the obtained scan as a first step, then selects an appropriate area around the hole to applies the method. Finally, the processed parts are added to the surface to obtain the final result.

This newly proposed technique shows all the advantages of the method of inverse distances applied to 3D-model correction and improves its performance in high-density point clouds, obtained by modern 3D scanning devices.

3. Results obtained
To test the proposed method, it was developed a script written in Matlab language (R2020b version). In order to properly assess the accuracy of the tested method, the script generates “holes” in the tested scan in a well-known area without any surrounding gaps. Sample areas with different curvatures were used to check the behaviour of the method. The script uses different area sizes and shapes around the hole to calculate the missing information and save the new point cloud in .PLY format. Also, the script calculates the distance between the points of the original point cloud and the new point cloud with the calculated points and obtains its mean value and its standard deviation. Following this procedure, software CloudCompare (2.11.1 version), Meshlab (2020.12 version) and Geomagic (2019 version) were used to compare the original scan and the generated .PLY file, helping to graphically check the location of the maximum difference and the surroundings of the generated testing hole.

The scan used for these experiments was obtained using a 3D-laser triangulation based scanner (Konica Vivid 910). The scanned object was a marble sculpture called “Primavera” from the collection of the “Tsarskoe Selo State Museum and Heritage Site” (Tsarskoe Selo, Russia). The selected scan shows parts of the left side of the face and hair of the original object. To test the effectiveness of the method where the curvature of the zone is different, three different points were
selected: In the first place, a point in the forehead/hair of the figure, where the surface is almost plain; in second place, a point in the eye, where the curvature is higher and finally in third place a point in the central part of a flower that forms part of the hair ornament, where the curvature was higher than in any other region of the scan. In the tests were used areas around the hole with square and circle shapes, and the numbers of points used for calculation were between 0.5 and 80 times the number of points contained in the original removed area (sizes were calculated using the distance between the centre of the hole and the border of it adding a percentage between 10% and 700%). Figure 1 shows the generated hole and the area used for calculation for the area named “Flower” (higher curvature) and the obtained results. In the represented case, the calculation area used contained 2 times the number of points of the original number of points removed from the hole.

**Figure 1.** Processing of the data using the Matlab script. In (a) the area used to calculate the missing information is shown (in cyan colour). In (b) the generated points using the method (in black colour).

In all the cases, the method was able to calculate the needed points covering the missing information. As we can observe in Table 1, the results are closer to the original information when the number of points used for calculation is larger than 5 times the number of removed points (two times the distance between the centre and the borders of the hole). Also, we can observe that the results oscillate around this value when the number of points used is larger than 15 times (around 3.5 times the hole centre-border distance). The table also shows better results with fewer points in the zones with lower curvature values (Named “Hair” in the table). The calculation area shape didn’t significantly affect the results in our experiments, keeping the same results when comparing areas with the same number of points. The method uses a grid to generate the X and Y coordinates of the new points: different grid sizes were used and the results were almost the same.

**Table 1.** Results obtained in different zones and with different calculation areas.

| Calculation area size (Original hole point number multiplied N times) | 2    | 5    | 10   | 15   | 20   |
|---------------------------------------------------------------|------|------|------|------|------|
|                                                               | Mean (x 10^3) | Mean (x 10^3) | Mean (x 10^3) | Mean (x 10^3) | Mean (x 10^3) | Mean (x 10^3) | Mean (x 10^3) |
| Hair                                                          | 1.19 | 59.3 | 0.52 | 24.5 | 0.5  | 23.6  | 0.5  | 24  | 0.52 | 24.3 |
| Eye                                                           | 1.22 | 67.3 | 0.55 | 29.3 | 0.43 | 22.7  | 0.39 | 21.1 | 0.38 | 20.6 |
| Flower                                                        | 1.33 | 75.3 | 0.46 | 24.1 | 0.41 | 21.2  | 0.41 | 21.3 | 0.42 | 21.5 |

Using cloud comparing software the results were confirmed. The areas with higher curvature show a higher maximum difference, located in the centre of the calculated area (see the results for the different areas in Table 2). Figure 2 shows the results obtained in the area with higher curvature (named “Flower”) using a calculation area size of 5 times the number of points. In this case, the
maximum observed difference is nearly 2.25 but as we can see in the standard deviation value (Table 1) and confirm in the image, the number of points that have a high difference with the original information is low. In Table 2 we can observe that the maximum difference tends to stabilize around 2 with larger calculation areas, no matter the curvature of the region used.

Table 2. Maximum distance between calculation and reference with different calculation areas.

| Calculation area size (Original hole point number multiplied N times) | 2   | 5   | 10  | 15  | 20  |
|---------------------------------------------------------------|-----|-----|-----|-----|-----|
| Hair                                                          | 5.00| 2.12| 2.05| 2.09| 2.10|
| Eye                                                          | 5.84| 2.61| 2.17| 1.97| 1.96|
| Flower                                                       | 8.44| 2.28| 2.08| 2.04| 2.02|

Figure 2. Comparison of the calculated point cloud information and the original.

4. Conclusions
The method is able to calculate and restore the missing information using the coordinates of the points in the surrounding area of the region of interest in all the tested cases. The procedure showed good results when used with calculation areas containing at least 5 times the number of points of the original area. It is interesting to note that the results (mean distance value between reference and newly calculated region, standard deviation of the same distance and maximum of the same distance) start to oscillate when the number of points used for calculation is larger than 15 times the number of points of the created “hole” in the surface. When the method is applied to a flatter surface, the maximum distance is smaller with less points used, but using around 10 times or more the number of points the results are almost the same for zones with different curvatures. Neither the shape of the used area for calculation nor the grid size of the X-Y coordinates used in the method seem to affect the results obtained. A future improvement will be to find a correlation function between the number of points and the curvature of the area, searching for the ideal number of points in each case.
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