Quality evaluation in a 3D inspection system

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Abstract—Three-dimensional quality control is a common task in industry. These systems are mainly based on 2D technology where overhead/lateral views are the only ones that are inspected. However, these systems cannot deal with complex objects. In this field it is necessary to inspect every part of the object. This is only possible if we have a full 3D representation of the object.

In order to get a 3D representation of an object, our system makes use of an octree carving procedure. This technique presents some limitations on certain regions depending on the topology of the object. Thus, it is useful to estimate the implicit error in the entire object as well as to know which areas are good candidates for a precise quality control.

Three dimensional global and local metrics are presented for mesh volume and mesh surface as well as for octree volume. An intensity texture that informs about the error is also applied to the reconstructed object. A set of synthetic objects have been created and a virtual reconstruction have been carried out in wide range of positions so as to simulate conditions in a free-falling real system. Finally, a complete set of experiments report the differences between ideal and reconstructed objects.

Keywords—octree carving, shape from silhouette, visual hull, 3d metrics

I. INTRODUCTION

Industrial inspection is an important field which requires fast and accurate systems. 2D systems are based only on overhead/lateral views and some regions of the object cannot be analysed. On the other hand, 3D systems are able to capture multiple views across the object, nevertheless classical solutions such as turntable systems where multiple shots are acquired sequentially [1] do not allow real-time reconstruction of the object. In order to get all the views at the same time we propose a single-shot multi-camera acquisition [2].

A shape from silhouette approach [3] has been used to obtain a 3D model. Thus, the 3D object shape is built by intersection of the visual cones formed by back-projecting the silhouettes in the corresponding images. The reconstructed 3D object shape is not guaranteed to be the same as the original object since concave surface regions can never be distinguished using silhouette information alone (see figure 1).

The visual hull [4] is the maximal shape consistent with silhouettes of an object as seen from any viewpoint in a given region which can be constructed by intersecting the cones generated by back-projecting the object silhouettes of a given set of views. The proposed visual hull computation method belongs to volumetric method which is based on the polygonisation of octree structure [5] by using a marching cubes algorithm.

This paper is organised as follows. Section II describes the quality measures used and section III reports the experiments performed and shows examples of reconstructed objects with an intensity error visualization. Finally, conclusions and future work are presented.

II. 3D METRICS

In the previous section we have shown the differences between the real object and its visual hull. In this way it would be useful to get detailed information about the error caused by the visual hull in all the regions of the object, making it possible to select checkpoints in the regions where the object fits the visual hull and to avoid the ones that present bigger differences.

Synthetic objects where all the 3D points are perfectly known have been created. These will be useful in order to calculate the errors between real and reconstructed data.

The scanning system (I3D) is equipped with 16 cameras and gets the images when the object is in free fall, thus every time an object is scanned it presents a different orientation. To simulate this, a wide range of rotations have been applied to the synthetic objects.

Three different types of metrics have been considered. Global metrics take into account the differences between meshes, local metrics inform about the dissimilarities between pairs of points and finally, an intensity map provides visual information about the 3d localisation of the errors.
A. Global metrics

Global metrics show information about the whole object such as surface or volume.

- Mesh surface: Let $M$ be a mesh of triangles and $t$ a triangle that belongs to the mesh, thus the surface of a mesh is computed as the sum of the areas of all the triangles of the mesh.

$$ S_M = \sum_{t \in M} \text{Area}(t) $$

- Mesh volume: The volume of a given triangle mesh is computed as the signed volume of all the tetrahedra formed by every triangle and the origin. Let $H_t$ be the tetrahedron defined by a given triangle $t = \{a, b, c\}$ and the origin $d$. Thus, the volume $V_T$ of a single tetrahedron is computed as:

$$ V_T(H_t) = \frac{\det(a - b, b - c, c - d)}{6} $$

For a closed triangle mesh, the mesh volume $V_M$ will be computed as the sum of the signed tetrahedron volume.

$$ V_M = \sum_{t \in M} V_T(H_t) $$

- Octree volume: Let $x$ be a voxel and $X_I$ the set of voxels that are not outside the object. The volume of an octree is then computed as the sum of the cube volumes that belong to $X_I$.

$$ V_O = \sum_{x \in X_I} \text{CubeVol}(x) $$

B. Local metrics

Local metrics inform about the differences in pairs of points from two aligned meshes [6].

- Hausdorff distance: Let $e(p, M)$ represent the distance from a mesh point $p$ to a 3D object $M$:

$$ e(p, M) = \min_{p' \in M} d(p, p') $$

with $d$ the Euclidean distance between points $p$ and $p'$. Then the asymmetric Hausdorff distance between two 3D objects $M$ and $M'$ is

$$ H_a(M, M') = \max_{p \in M} e(p, M') $$

The symmetric Hausdorff distance also known as maximum geometric error is defined as follows:

$$ H_s(M, M') = \max\{H_a(M, M'), H_a(M', M)\} $$

- Mean distance: Another definition of the Hausdorff distance called mean geometric error is defined as:

$$ H_{mean}(M, M') = \frac{1}{\text{Area}(M)} \int_M e(p, M')dM $$

C. Intensity metrics:

Apart from numerical information about the differences of pair points, the object is shown with an inverted grayscale so as to inform about the error produced by the visual hull (see Fig. 1). The minimum error is represented as black and the maximum error is represented as white. This representation allows to get a visual idea of the localisation of the errors.

Let $p$ be a point that belongs to an object $M$ and let $M'$ be a test object. Thus, the intensity of $p$ is computed as:

$$ I(p, M, M') = \frac{e(p, M')}{H_s(M, M')} $$

Let $M_R$ be a set of rotations of $M$, the intensity map for that set of rotations is then defined as:

$$ I(p, M_R) = \max_{M' \in M_R} (I(p, M, M')) $$

III. Experiments

A set of virtual objects have been created with different complexities. Starting from a simple sphere, and going for more complex objects such as springs.

![Figure 2. Silhouettes from the 16 views of a spring.](image)

The scanning system (I3D) computes the 3D model when the object is in free fall, thus every time an object is scanned it is oriented in a different way. In order to simulate this behaviour random rotations have been applied to the synthetic objects. Thus, we obtain sets of 16 images corresponding to virtual cameras (see figure 2).

Then, the reconstruction is performed by means of an octree carving procedure [5] followed by a marching cubes algorithm. Finally, in order to compare them, test object is aligned to the reference by applying an ICP algorithm [7].

A. Computing the theoretical surfaces

Theoretical 3D points from geometric shapes has been obtained by means of a software designed for this task. Then
MeshLab [8] was used to generate the meshes from the point sets. Table I shows the number of points and triangles of the shapes used in our experiments. The resolution adopted is 200 points per revolution (sphere, cone, cylinder, spring) or per face (pyramid, cube).

<table>
<thead>
<tr>
<th>Shape</th>
<th># Vertices</th>
<th># Triangles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>19802</td>
<td>39600</td>
</tr>
<tr>
<td>Cube</td>
<td>240002</td>
<td>480000</td>
</tr>
<tr>
<td>Cylinder</td>
<td>40202</td>
<td>80400</td>
</tr>
<tr>
<td>Cone</td>
<td>40002</td>
<td>80000</td>
</tr>
<tr>
<td>Pyramid</td>
<td>160002</td>
<td>320000</td>
</tr>
<tr>
<td>Spring</td>
<td>200202</td>
<td>400400</td>
</tr>
</tbody>
</table>

Table I
THEORETICAL SURFACES DETAILS

In order to ensure that a resolution of 200 points per revolution/face is enough, the area and the volume of the mesh models were compared with the theoretical geometric ones. Concerning the volume, errors were systematically lesser than 0.1% while area errors were lesser than 0.5%.

B. Results

In order to get a good estimation of the error and simulate the object in multiple positions, the virtual objects created above were rotated with a 6-degree step on the x and y axes, in a [0, 180] degree range which provides 900 rotations for each object. As the objects are centered and cameras are arranged in a spherical shape, only two axes of rotation are necessary to cover all the angles between a part of the object and a camera. Taking into account that the scanning system uses sixteen cameras, a total of 14600 different views are used to model an object.

1) Global metrics: In the Table II, we can observe the surface errors. The value is the mean of all the rotations. The best result (< 2%) is for the pyramid while the spring exhibits the worst result. This is due to a limitation of the visual hull and makes the octree carving reconstruction to obtain some additional blobs inside the spring. This problem can be solved by increasing the number of cameras or its resolution.

<table>
<thead>
<tr>
<th>Shape</th>
<th>err (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>2.64</td>
</tr>
<tr>
<td>Cube</td>
<td>2.36</td>
</tr>
<tr>
<td>Cylinder</td>
<td>2.46</td>
</tr>
<tr>
<td>Pyramid</td>
<td>1.68</td>
</tr>
<tr>
<td>Cone</td>
<td>2.48</td>
</tr>
<tr>
<td>Spring</td>
<td>22.61</td>
</tr>
</tbody>
</table>

Table II
SURFACE DIFFERENCE MEASUREMENTS

It can be seen that the volume of the octree is systematically greater than the one from the model. These observations agree with those of Szeliski in [5].

To go further in the errors analysis, the figure 3 illustrates the distribution of them according to the octree depth. The red central line corresponds to the median value, the box corresponds to the ± quartile distribution. From the figure we see that higher depths obtain better results in area, mesh volume and octree volume.

2) Local metrics: Table IV shows local metrics for the different objects. It can be observed that the sphere gets the best results while cube and cylinder present bigger errors. This is due to the presence of sharp angles and it is a normal behaviour in visual hull based methods. However it is important to remark that all the objects present a small geometric mean distance.

<table>
<thead>
<tr>
<th>Shape</th>
<th>$H_s$</th>
<th>$H_{mean}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>2.76</td>
<td>0.106</td>
</tr>
<tr>
<td>Cube</td>
<td>6.23</td>
<td>0.14</td>
</tr>
<tr>
<td>Cylinder</td>
<td>6.50</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table IV
LOCAL ERROR MEASUREMENTS

3) Intensity: Figure 4 shows the differences from synthetic objects and their reconstructed visual hulls. In order to get an estimation of the error the objects have been rendered in 100 random positions. Then a reconstruction for each one has been performed and the error for every vertex in the reference surface has been stored. Finally, the maximum error $I(p, M)$ for all the vertices has been calculated and it is represented in an inverted grayscale, that is, black means no error and white means a bigger error.

These results are coherent to the ones presented before and show how shapes with sharp angles like the ones of the cube get a bigger error. Regions that are near to sharp edges are well modelled because they are close to the silhouette edges and regions that lie in the centre of a plane as the middle of a cube face are not so well modelled. This information is useful to determine which parts of an object are candidates for a high precision quality control and which parts are not.

IV. CONCLUSIONS

This paper presents the performance of a 3D inspection system. In order to evaluate the quality of a reconstructed object a complete set of metrics is presented. Local, global and
intensity information is provided. Volume and area measures for geometric shapes inform about the accuracy of the system. Extensive experiments have been carried out and its low error validate the system architecture. Local metrics give an estimation of the error produced by the visual hull and it can be seen as a complexity estimation of the object. The intensity texture in the reconstructed object permits to select the areas which are better modelled. As a future work we are considering to apply stereo algorithms on the areas with higher errors so as to get a better 3D estimation and alleviate the error of the visual hull.


Figure 4. Differences from synthetic object and visual hull in grayscale.

REFERENCES


