Simulation for an Automation of 3D Acquisition 
and Post-Processing

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ABSTRACT

Most of the automation for 3D acquisition concerns objects with simple shape, like mechanical parts. For cultural heritage artefacts, the process is more complex, and it doesn't exist general solution nowadays. This paper presents a method to generate a complete 3D model of cultural heritage artefacts. In a first step, MVC is used to solve the view planning problem. Then, holes remaining in 3D model are detected, and their features are calculated to finish acquisition. Different post-processing are applied on each view to increase quality of the 3D model. This procedure has been tested with simulated scanner, before being implemented on a motion system with five degrees of freedom.

Keywords: 3D acquisition, cultural heritage artefacts, scanners automation

1. INTRODUCTION

The demand for high-quality three dimensional (3D) models of complex objects is growing in a wide range of applications (e.g., industrial, training, medical, entertainment, cultural, architectural). Numerous applications require the computer vision approach to object surface reconstruction. These applications relate to fragile objects whose handling is impossible. Only non-contact sensors are usable [1].

Both mechanical and optical geometric measurement sensors are used for 3D object reconstruction and inspection. Mechanical Coordinate Measuring Machines (CMMs) use precise mechanical movement stages and touch probes to achieve very high measurement precision – around 1 μm for a suitably calibrated high-end machine operated by a skilled technician. However, acquisition and operating costs for such precision are high. With a relatively low data acquisition rate, CMMs are generally suitable for sparse sampling applications only. While their measurement precision is inferior to CMMs, optical sensors have lower capital and operating costs and are capable of dense, non-contact sampling at high throughput rates. In many fields, CMM is not adapted: for cultural heritage artefacts and, more generally, complex objects, numerous points are necessary to obtain a reliable 3D model, on which some measurements can be performed.

3D acquisition devices collect 3D coordinates of an object surface. To acquire the shape from all sides, many scans are necessary. Our system is based on several assumptions: the scanner remains calibrated between each acquisition and the object size and material is compatible with the scanner specifications. For each scan, post-processing is required (meshing, smooth, cleaning, ...). Each scan captures a portion of the shape of the object, and in order to merge all of the scans into a single shape we must place them in the same coordinate system. If there is a lack of data, others scans may be necessary. 3D acquisition and post-processing are long and the experience of the user has a significant influence on the resulting 3D model quality.

Proposed method is based on view planning methods, described in section II. To test methods, we use a simulated scanner, described in section III. The proposed method is multi-phase approach (coarse to fine). Two techniques are used: the first is based on Mass Vector Chain (MVC), presented in the section IV, and allows to create a coarse model. The second uses the “holes” (lack of data) in the mesh to define the next best viewpoint, by calculating “position”, “normal” and “size” of each hole remaining in the coarse model. The process is summarized on Fig.1 and fully described in section V. Applications on cultural heritage artefacts and results are shown in section VI.
2. VIEW PLANNING

View planning (or sensor planning) is used to minimize the number of required views to reconstruct a complete 3D model or to ensure that the viewpoints selected are as close as possible to the optimal viewpoint. Some algorithms solve the “next best view” (NBV) problem in order to determine the next position for the range scanner given its previous scans of the object. All these algorithms are described by Scott & al. in [2]. These methods can be classified in two categories: model-based method (Cowan & al. [3], Scott & al. [4], Tarbox & al. [5]) – and non-model based method (Connolly [6], Banta & al. [7][8], Maver & al. [9], Pito & al. [10], Yuan [11]). The first methods are suitable when CAD model of the object is available. This kind of sensor planning has been developed for several different purposes, for example object recognition, general robot vision tasks, inspection of loose tolerance objects, and accurate inspection. The second methods allows viewpoint planning without any a priori knowledge on the shape. They are divided in two categories: the volume based methods and the surface based methods.

The majority of these algorithms leads to good results in the case of simple shapes, like mechanical parts, or convex objects. As yet, view planning for high-quality complex object reconstruction has no general-purpose solution. The goal of these methods is to define several viewpoints to completely cover the object, but they don't take into account the quality of the final produced mesh, except the point clouds density.

3. SIMULATED SCANNER

Simulated scanner enables to be freed from the material constraints. It allows to test different algorithms without dealing with the mechanical constraints.

To test algorithms, a simulated scanner is developed. The simulated scanner uses raytracing to simulate a scanner. 3D model of the object is needed. The procedure is as follows :

– the scanner is positioned manually or automatically for the first position
– the user defines the parameters of the scanner : resolution, angle of view, direction, ...
– the algorithm carries out raytracing : it calculates the intersection of each ray with the 3D model [12]. A point clouds is created and then triangulated.

Fig.1: The proposed method is in two steps (a): the first step allows to create a coarse model with MVC, and the second uses “holes” to complete the unprocessed surface. For each new viewpoint, acquisition and post-processing are carried out (b).
Once the algorithms tested, they can be implemented on a motion system (described in section VI).

4. MASS VECTOR CHAIN (MVC)

MVC [11] allows to estimate a view direction from surface patch. In our case, each face is considered as a surface patch.

By definition (Fig.2), a mass vector chain of an object is a serie of weighted vectors. In this serie, a vector \( \vec{V}_i \), is assigned to each individual surface patch \( S_i \) of the object. This vector points to the average normal direction \( \vec{n}_i \), of the surface patch \( S_i \) and its weight is the projected region \( R_i \) on a plane \( P_i \) perpendicular to \( \vec{n}_i \)

\[
\vec{V}_i = \vec{n}_i R_i
\]  

(1)

For the surface patch, \( \vec{n}_i \) is its average visible direction and \( R_i \) is the surface size when viewed in that direction.

It has been demonstrated [11] that, for an object of convex surfaces, the total Gaussian mass of the surfaces must be zero,

\[
\iint_S G(n(s)) n(s) ds = \iiint n(s) ds = 0
\]  

(2)

where \( G(n(s)) \) is the Gaussian mass with a same \( n(s) \). This conclusion also applies to ordinary objects. Since the total Gaussian mass of an object is the sum of subtotals of individual surface patches, (2) can be further grouped in terms of surfaces.

\[
\iiint n(s) ds = \sum_{j=0}^{m-1} \int_{S_j} n(s) ds = 0
\]  

(3)

On the other hand, the total mass vector of an object is the sum of all its mass vectors, i.e.

\[
\sum_{j=0}^{m-1} \vec{V}_j
\]  

(4)

The total mass vector can be derived. The result points out that the boundary surfaces of an object compose a closed surface boundary only when their mass vectors form a closed chain.

\[
\sum_{j=0}^{m-1} \vec{V}_j = \sum_{j=0}^{m-1} \int_{S_j} n(s) ds = 0
\]  

(5)

The mass vector sum of a closed object model is a zero vector. If, during reconstruction, the total of all mass vectors of a building model is a no zero vector \( \vec{V}_{dir} \), there must be some unprocessed surface patches whose mass vectors sum to be the negative of \( \vec{V}_{dir} \). If the number of processed surface patches is \( m' \), then, from the relation
\[ \sum_{j=0}^{m'-1} \tilde{V}_i + \sum_{j=m'}^{m-1} \tilde{V}_i = 0 \]  

we obtain

\[ \sum_{j=m'}^{m-1} \tilde{V}_i = - \sum_{j=0}^{m'-1} \tilde{V}_i = - V_{dir} \]  

Defined to be the average normal \( \tilde{n}_i \), each mass vector \( \tilde{V}_i \), is actually the average visible direction of that surface patch. Therefore, \( V_{dir} \) provides an estimated direction from which these unprocessed surface patches could be observed (Fig.3).

This can be further explained by the sphere represented in Fig.3 for convex surfaces. Since a convex object has a unique extended Gaussian image expression [11], a Gaussian sphere [13] covering the object stands for its boundary condition, or a circle in a two-dimensional case. Suppose four surface patches are extracted; the total mass vector is \( \tilde{V} = \tilde{V}_0 + \tilde{V}_1 + \tilde{V}_2 + \tilde{V}_3 \). It is obvious that the average visible direction of the unprocessed big arc from \( b \) to \( a \) is in the opposite direction of \( v \). Even if more surface patches are processed after several views, the negative of the updated total mass vector, which is \( v' \) in the figure, still points to the visible direction of the unprocessed portion. An example of MVC is shown in Fig.4.

A similar Gaussian sphere can also be used to examine the boundary of concave surfaces. Surfaces must be extracted to identify concave and convex surface. But here, no surface is extracted, there is no differentiation between concave and convex shape, because MVC are used only to deliver a coarse model.

(a)  

(b)

Fig.4: Red sphere represents scanner position. MVC is calculated (a) and gives direction for the next view (b)
5. PROPOSED SOLUTION TO NBV PROBLEM

The proposed method is in 3 steps and is a surface based-method. The first step is the positioning of the scanner. It is placed at a preset distance from the object, calibrated from the object size.

The next step is the acquisition of a 3D coarse model. A first range view is acquired. MVC is computed to determine the next position and the simulated sensor is moved consequently. The MVC method previously described is capable only of estimating viewing direction, not position. Then, for each new acquisition, the scanner is directed towards the center of mass of previous acquisitions, at a present distance. Information of position of the simulated scanner allows to readjust each scan in the same coordinate system (registration). Each scan is segmented (object-environment), by using a flood-fill algorithm. The procedure is working at follows:

- Three points (or more) are projected on the 3D views. For each intersection points $I$, a graph of connexity is calculated.
- The graph which contains the most important amount of points is selected. We consider that only one object is acquired.
- The points in others graphs are removed.

Then, the view is cleaned: all the abnormals faces (three faces with one same edge, spikes, ...Fig.5) are removed. Besides, all the points of which the angle of view is higher than a given angle ($\approx 60^\circ$) are also removed.

![Fig.5: Post-processing: abnormals faces (a), crossing faces (b) and spikes (c) are removed.](image)

If the new view don't contribute to decrease the size of unprocessed surface, this step ends.

In the last step, all the boundary loops (“holes”) remaining in the 3D model are selected. Here, a hole shows a lack of faces, whereas a physical hole has a surface. The detection of the holes is done by locating the edges of the model which belong only to one face. For each hole thus found, its “normal”, its “position” and its “size” is calculated (Fig.6)

The “position” $P_h$ corresponds to the “center of mass” of the hole, obtained starting from the $m$ vertice $P_i$ composing the hole.

$$P_h = \frac{1}{m} \sum_{i=1}^{m} P_i$$  \hspace{1cm} (8)

The “normal” $\vec{V}_h$ is given by totaling the normals $\vec{V}_i$ of the vertice which form the hole.

$$\vec{V}_h = \sum_{i=1}^{m} \vec{V}_i$$  \hspace{1cm} (9)

The “size” $D$ of the hole corresponds to the maximum distance between the “center of mass” $P_h$ and the points which form the hole.

$$D = \max_i (|P_i, P_h|)$$  \hspace{1cm} (10)

These three parameters allow to calculate the next position: the scanner is directed towards the center of the hole,
according to a direction reverses with the normal of the hole, if there is not self-occlusions. Else, a Gaussian sphere [13] is defined, corresponding to a “sphere of positions” (Fig.7). For each points of hole, positions are tested, and the position from which the most of points are visible is selected for the next view.

Then, new 3D view is segmented before merging: faces corresponding to the hole are only preserved: on the new 3D view, all the points $P_i$ which verify $|P_i P_h| > D$ are removed (Fig.8).

Fig.6: Holes features: normal, size, position

Fig.7: Viewsphere for self occlusions

Fig.8: Segmentation of the new view. The redundant data is removed for each new acquired view.
6. RESULTS

Proposed system on which algorithms has been tested uses a motion stage four axes and a rotative stage, on which a scanner is set, allowing five degrees of freedom. This system provides travel range from 1370 mm (X axis), 990 mm (Y axis), 440 mm (Z axis), 320° (α axis) and 360° (β axis). The used scanner is a laser triangulation-based device (Konica Minolta Vi910 [14]). To illustrated our results, studied artefacts is a small head (95x75x35 mm) shown in Fig. 10a.

![Diagram of the proposed system](image)

First position is selected in order to fit the field of view on the studied object (Fig. 10b). Acquisition is performed from this position (Fig. 10c) and then MVC is calculated and a new direction is determined (Fig. 10d). The system moves to place the object and the scanner in the new position. New view is acquired (Fig. 10e) and merged with the first view (Fig. 10f), after being cleaned (segmentation object-environment, delete abnormals faces, ...). Fig. 10h and Fig. 10i shows the 3D model before and after acquisition of the third view. This procedure is repeated until the stop criterion is reach. This criterion is calculated from the views surface. If the redundant surface between the 3D model without the new view and the 3D model with the new view is greater than 90%, this step ends.
In this example, MVC allows the capture of six views (only three are represented in Fig. 10). The obtained 3D model is shown in Fig. 11.

In this model, two remaining holes are present, with two opposite “normals”: one on the top of the model, and one below, where the object is set. The second hole is ignored (acquisition is impossible). The features of the first hole is calculated (position, normal, size), and a direction is found (Fig.11). New view is segmented and redundant data are removed (Fig.12).
Proposed solution allows to obtain automatically complete 3D model of the studied artefact with seven views. Proposed system allows to move object and scanner with five degrees of freedom. This system is well adapted for small objects (100x100x100 mm) but not for larger objects: travel range may be insufficient, the lower part of the object isn't visible, ... For these objects, methods must be implemented on others systems, like CMMs or robotized arm.

7. CONCLUSION

In this paper, a simulation tool is introduced to simulate the acquisition of 3D models. This tool allows to simulate different NBV solutions and post processing. Presented solution uses mass vector chains. The simulation is able to predicate the viewing direction of unprocessed surfaces and create a coarse model, with remaining holes. From analysis of holes in mesh, the simulation calculates the best next viewpoint to acquire the missing data. Our proposed method leads to help view planning in the automatic creation of high-quality geometric models. Future work concerns the application of these methods to various 3D scanners. We plan to demonstrate that our method is applicable to different 3D measurement devices available in our research team (time-of-flight system, laser triangulation, ...)

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