Title:
Quality Improvement of 3D Models Reconstructed from Silhouettes of Multiple Images

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Introduction:
Shape-from-Silhouette (SFS) is a technique for estimating the shape of an object from images of its silhouette. It is a simple but effective technique for obtaining a three-dimensional (3D) model of an object by using two-dimensional (2D) images of the object in different views. One of its applications is for product presentation in e-commence, in which a 3D model combined with the object's texture (called 3D color model hereafter) is presented to replace traditional 3D visualization. In 3D visualization, multiple 2D images showing different viewing angles are integrated and a 2D image at a given angle can be displayed via a viewing interface. However, the orientating process is not fluent owing to limited angles recorded. A 3D color model can be displayed alone via a browser or it can be combined with 3D visualization to display the 3D model and 2D images alternatively. The generation of a suitable 3D model from images of multiple views is the very fundamental work as it can affect the success of the later process significantly.

The SFS appeoach has been extensively studied and various methods are available in the literature [1-2,5-7,9]. It is based on a visual hull concept, in which the object geometry is reconstructed using the intersection of multiple sets of infinite polygons from silhouettes of 2D images of different views. The basic problem with the traditional SFS method in terms of the visual hull is that hidden concavities on the object surface cannot be resolved, and so the generated 3D model is not satisfactory. That is, the 3D model may have visual features or irregularities, such as sharp edges, sharp corners, and artifacts, which do not exist on the object. Concavities on the object are usually formed as convex shapes on the model because they are invisible on image silhouettes. On the other hand, an object may have sharp features that should be maintained on the model. However, it is very difficult to distinguish virtual features from real object features on the model, and hence the removal of virtual features becomes very difficult. The SFS method has been studied extensively. However, the algorithm for obtaining 3D points from the visual hull is not accurate enough. None of the available methods studied the improvement of the 3D model generated by the SFS method.

The objective of this study is to propose a quality improvement method to address the inherent problems of a 3D model generated by an SFS approach. As discussed, visual features and irregularities often occur on SFS models. This method is a multiple-step iteration procedure combining a remeshing process and a mesh smoothing process to remove virtual features and artifacts on the original model, while preserving the image silhouettes and the smoothness of the model. The overall flowchart of the proposed method is described and several examples are presented to verify the feasibility of the method.

Main Idea:

We first describe a method for generating a 3D model based on the SFS approach because it is related to the approach that used to improve the original model. To generate a 3D model from the silhouettes of multiple images, the exact polyhedral visual hulls (EPVH) method [3] is employed, in which an octree structure is established to subdivide the volume wherever needed, and a polyhedral intersection algorithm is employed to precisely compute all surface points. All surface points are exactly at the intersection of the polyhedral planes that form the visual hull. The topological relationships of the intersection points and their contributing polygons are recorded for mesh generation. Fig. 1 schematically illustrates an overall flowchart of the proposed 3D model construction method. A calibration mat and the object are separately placed on a turntable and a set of images is captured for each of them, as shown in Fig. 1(a) and Fig. 1(b), respectively. The number of images for both sets of images should be equal, typically either 16 or 32. A calibration algorithm [4] is employed to determine the camera parameters, e.g. viewing direction, camera position, aspect ratio, and focus. The camera parameters are used to obtain the relationship of a local coordinate on each object image and the 3D coordinate and to transform all object images onto the 3D coordinates. The silhouette of each object image is then obtained and recorded as points and line contours. Every line on a contour can form a polygon and a set of polygons is created with respect to one object image. All polygons from various object images are then used to evaluate the intersection points (Fig. 1(c)), which are points on the object surface. A triangulation method is then used to convert 3D points into triangular meshes (Fig. 1(d)). The mesh quality is very poor because the aforementioned problems with the SFS method all appear on this model. The proposed quality improvement method is then implemented. The main purpose is to eliminate sharp edges, corners, and artifacts, while preserving real object features on the model. It is a challenging issue because all virtual features and real object features appear simultaneously. The modified model after the quality improvement is shown in Fig. 1(e). The techniques used for 3D meshes generation and quality improvement of 3D meshes are described below.

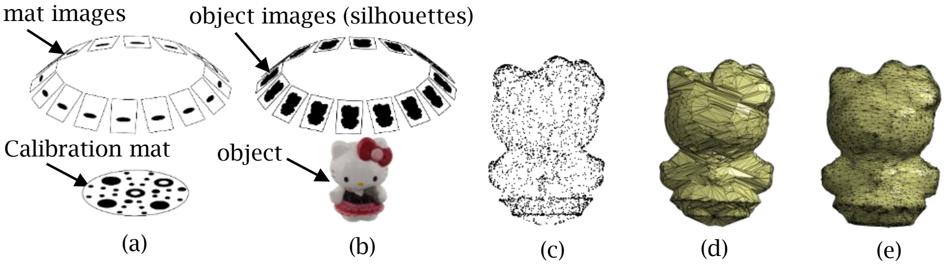

Fig. 1: Overall flowchart of the proposed method for 3D model generation from multiple images, (a) calibration mat and mat images, (b) object and silhouette images, (c) 3D object surface points, (d) triangular meshes of the object, (e) the model after quality improvement.

3D meshes Generation

Figure 2 depicts a flowchart of the calculation of 3D intersection points from silhouettes of multiple images. The input data includes camera point, viewing direction, up direction and silhouette data associated with each object image. Next, a polyhedron for an object image is generated by using the silhouette points of the corresponding image. A polygon is created in terms of the perspective projection by combining the camera point and two neighboring silhouette points. All polygons from the entire silhouette on an object image form a polyhedron. A set of polyhedra can be obtained for all object images. Using the polyhedra, the first volume that encloses the target object is computed. Subsequently, an octree structure is established to subdivide the volume and the number of polygons inside each sub-volume is checked.

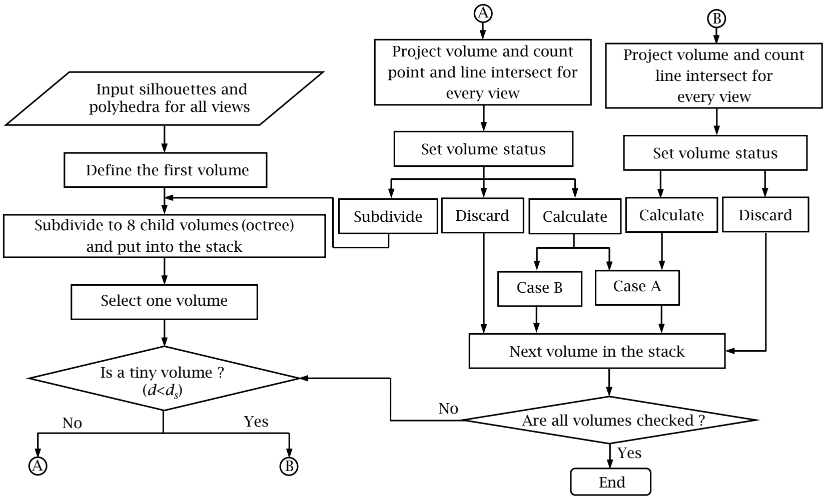

Fig. 2: Flowchart for calculating 3D points from multiple sets of silhouette data.

If it is less than 3, this sub-volume is deleted; if it is larger than 3, this sub-volume is put on a stack and checked again later; if it is equal to 3, a 3D intersection point is computed using those three polygons. Each 3D intersection point is evaluated based on two conditions: (1) case A: three polygons are from three different images and (2) case B: two of the connected polygons are from one image, and the third polygon is from the other image. The topological relationships of the polygons and 3D intersection points are recorded, including indices of the polygons contributing to each intersection point and indices of the points lying on each polygon. With this kind of topological data, 3D triangular meshes can be generated in a systematic manner. A detailed description of the generation of 3D points is provided in Phothong et al. [8]. The algorithm for generating 3D meshes form 3D points obtained previously is described below. Consider that a polygon S_1 as in Fig. 3(a) is checked to arrange the sequence of its 3D points, $\boldsymbol{P}_1 \sim \boldsymbol{P}_5$. Starting from $\boldsymbol{P}_1$, all polygons that contribute to $\boldsymbol{P}_1$ are selected (S_2 and S_3). The points that share the same pair of polygons, namely S_1 and S_2, and S_1 and S_3, respectively, are then selected. The points selected are $\boldsymbol{P}_2$ and $\boldsymbol{P}_5$ in Fig. 3(a). The point which can yield a counterclockwise direction is chosen as the next point, namely $\boldsymbol{P}_2$ in Fig. 3(a). This procedure is repeated for all points on S_1 and it finally yields a set of 3D points arranged in a counterclockwise direction. Once a polygon is complete, the procedure shifts to the next polygon. This process stops when all polygons have been processed. For generating 3D meshes from a set of 3D points arranged in sequence, it may be possible to apply an algorithm to connect every three points directly as shown in Fig. 3(b). Finally, all triangular meshes are integrated and saved as a triangular model, which represents the original 3D model from the SFS method.

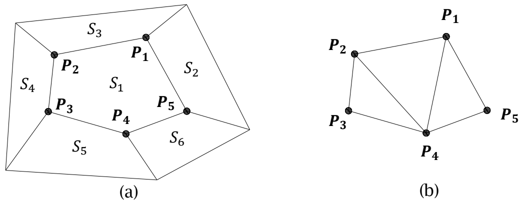

Fig. 3:3D meshes generation algorithm, (a) the connection of surface polygon and points, (b) triangular meshes generation process.

Quality Improvement of 3D Meshes

As discussed, the quality of the original 3D model must be further improved before it can be used for texture mapping. As the original 3D model only represents the convex hull of an object, the removal of artifacts is one of the priorities because it can dominate the distortion on the outline shape. On the other hand, virtual sharp edges and corners appear frequently on the original model because of the shape created by convex hulls. Conventional mesh smoothing methods are invalid here because they may smooth both virtual features and real object features.

To eliminate virtual features, while preserving real object features on the original 3D model, a quality improvement method is proposed for upgrading each vertex iteratively by simultaneously enforcing a silhouette consistency force and a smoothing driving force. The silhouette consistency force is to maintain the silhouette consistency between the projected boundary of 3D meshes on each image plane and the corresponding image silhouette. The smoothing driving force is to smooth virtual features and artifacts. However, these two driving forces are conflicting in nature. When the silhouette consistency force is stronger, the silhouette consistency improves, but virtual features and artifacts may remain significant. In contrast, when the smoothing driving force is stronger, the model can become smoother, but the silhouette consistency may become worse. On the other hand, the mesh size has an important influence on both driving forces. The mesh size should be kept relatively small near real object features, and relatively large near flat regions. In this way, the effect of the silhouette consistency force can be restricted to regions near the projected boundary, while the effect of the smoothing driving force can be enhanced near flat surfaces. A remeshing process can be implemented to adjust the mesh size locally or globally. Two quality improvement methods: regular and irregular meshes are proposed and compared in this study.

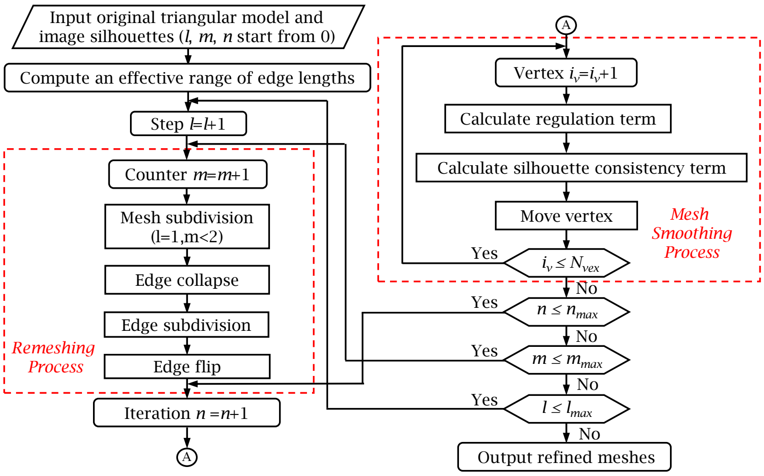

Fig. 4: Overall flowchart of the proposed quality improvement method using irregular meshes.

Figure 4 depicts a flowchart of the quality improvement algorithm using irregular meshes, which includes a remeshing process and a mesh smoothing process. It starts by computing the maximum and minimum edge lengths d_{max} and d_{min} respectively, of each position of the object from the original model to use in the mesh subdivision, edge collapse, and edge subdivision in the remeshing process. The symbol l denotes the iteration step. In each iteration step, both remeshing process and mesh smoothing process are implemented in sequence. The remeshing process is performed iteratively m_{max} times. In each remeshing process, the mesh smoothing process, including a silhouette consistency term and a regulation term, is implemented iteratively n_{max} times. Each vertex on the 3D mesh is upgraded iteratively in accordance with the silhouette consistency term and the regulation term.

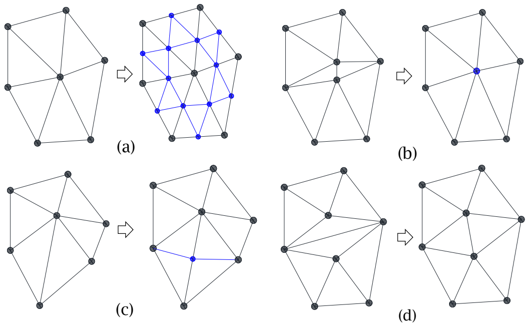

Fig. 5: Four remeshing operations: (a) mesh subdivision, (b) edge collapse, (c) edge subdivision, and (d) edge flip.

The remeshing process includes four operators: mesh subdivision, edge collapse, edge subdivision, and edge flip. *First*, mesh subdivision (Fig. 5(a)): all 3D meshes on the model are subdivided simultaneously, where each mesh is subdivided into four sub-meshes uniformly. Second, edge collapse (Fig. 5(b)): an edge is reduced to a vertex. This operator performs wherever the edge length is less than d_{min}. *Third*, edge subdivision (Fig. 5(c)): the edges that satisfy some criteria are subdivided. Each edge is subdivided by a vertex; the neighbor triangles are also subdivided into two triangles. This operator performs wherever the edge length is larger than d_{max}. *Fourth*, Edge flip (Fig. 5(d)): it adjusts the regularity of the meshes locally. Narrow triangles can be reduced when edge flip is implemented.

The mesh smoothing process includes two terms: silhouette consistency term (F_{sil}) and regulation term (F_{int}). The silhouette consistency term (F_{sil}) is determined by two parameters: surface normal (N_i), evaluated by using the average surface normal of all meshes neighboring a vertex, and amplitude of the silhouette consistency term (d_{sil}), determined by the shortest distance between the projected vertex (V_{ip}) and nearest bounding point of the silhouette images (V_{is}), as shown on Fig 6. The regulation term (F_{int}) is determined by the difference vector of the vertex considered to the center of all its neighboring vertices. In mesh smoothing, each vertex in 3D space is individually checked to calculate its new position in terms of the silhouette consistency term and the regulation term.

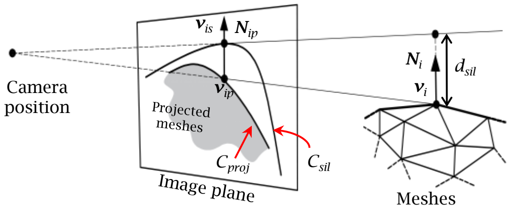

Fig. 6:The silhouette consistency term for the mesh smoothing process.

Examples and discussion

Several examples were employed to evaluate the performance of quality improvement algorithm with irregular meshes. The object was placed on a turntable and sixteen images distributed uniformly around the object were captured by a camera. The silhouette of each image was extracted and expressed as silhouette points, in which the distribution of the points is irregular in accordance with the shape of the contour. The inputs were silhouette points for all sixteen images and camera parameters associated with all images were captured. The output was the surface triangular model of the object. A comparison of the results using regular meshes and irregular meshes for different examples is presented.

Figure 7 shows the original images and the original 3D meshes constructed using the proposed mesh generation method, where the left and right plots in the figure panel denote the original image and the 3D meshes, respectively. Since the proposed 3D modeling method is based on visual computation, we will focus on the accuracy of the outline appearance. Note that artifacts appear as convex shapes on the model, especially near the bottom and the concave regions of the model. Some of the artifacts are even large enough to distort the outline shape. Also, it is normal that any concavity on a part surface may not truly be reproduced with this method alone. The number of faces in the model was less than 10,000, which will not induce any sluggishness during data download and website operation.


Fig. 7:Original images and triangular meshes reconstructed for example shoe.

The results of the quality improvement for the aforementioned example are shown in Fig. 8, where the left and right plots in the figure panel depict irregular meshes and regular meshes, respectively, and the parameters l_{max}, m_{max}, and n_{max} are respectively set to 1, 5, and 10. The results show that the outline shape of the object is preserved quite well with all virtual features and artifacts completely removed. Table 1 lists the number of vertices and faces for the original 3D meshes, the modified meshes using irregular meshes, and the ones using regular meshes for three examples. The CPU time required for both quality improvement methods are also indicated. The CPU time required for irregular meshes is less than that of regular meshes. The primary reason is that mesh subdivision is implemented on all meshes in the algorithm of regular meshes, whereas it is implemented adaptively in the algorithm of

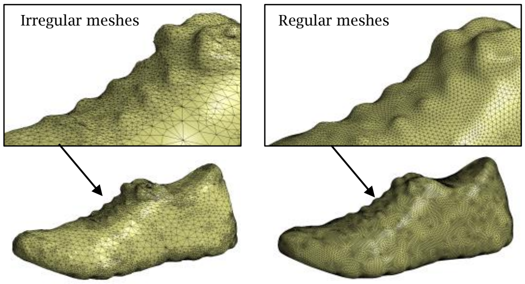

Fig. 8:Quality improvement of meshes for example shoe.

irregular meshes. The results also show that the algorithm of regular meshes performs slightly better than the algorithm of irregular meshes, which is because it employs more vertices and faces to describe a model. However, as several parameters in the smoothing process can be adjusted, it could be possible to further study the smoothing process to improve the accuracy of the algorithm of irregular meshes. If so, the algorithm of irregular meshes would be more feasible than the algorithm of regular meshes for real applications.

Case	Initial 3D model		Irregular meshes improvement			Regular meshes Improvement		
	Vertices	Faces	Vertices	Faces	CPU times (sec)	Vertices	Faces	CPU times (sec)
Shoe	5,129	10,254	14,178	28,352	295	31,953	63,902	478
Cat doll	4,264	8,524	12,153	24,302	249	40,520	81,036	346
Horse	6,793	13,592	25,869	51,742	411	106,403	212,810	2,180

Tab. 1: Triangular meshes obtained and CPU times required for three examples.

Conclusions:

A 3D model based on the SFS approach inherently possesses virtual features and artifacts. These not only affect the smoothness of the model, but also distort the accuracy of the outline shape. Since both virtual features and real object features appear simultaneously, conventional mesh smoothing techniques cannot handle this problem. The proposed quality improvement method in terms of irregular meshes employs a remeshing process and a smoothing process to eliminate all virtual features and artifacts while preserving the smoothness of the model. It can maintain an irregular distribution of mesh size with a low density of meshes near flat regions and a high density of meshes near real object features. The results show that all artifacts, shape edges, and corners are completely eliminated for all three cases, which is the most important contribution of the proposed method. In addition, the method of irregular meshes can yield fewer vertices and faces on the model than that of regular meshes. The CPU time required for the method of irregular meshes is also much lower than that of regular meshes. However, as the overall iteration procedure is very complex and several parameters are used in the algorithm, further study should be performed to improve the robustness of the proposed quality improvement method.

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