Attention-Based Mesh Simplification Using Distance Transforms

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Abstract. Although widely used for image processing, Distance Transforms have only recently started to be used in computer graphics. This paper proposes a new mesh simplification technique based on Distance Transforms that allows taking into account the proximity of a mesh element to the focus of attention for adapting the approximation error which will be tolerated during the simplification process to the relative importance of that mesh element. Experimental results show the feasibility of this approach.

1 Introduction

Thanks to the advances in Computer Graphics realistic renderings of complex scenes can be achieved. Multiresolution modelling is one of the underlying techniques that allow to process complex scenes at interactive rates. Basic principles of this approach were set by James Clark [1] and comprehensive surveys can be found at [2, 3, 4, 5, 6].

The generation of models at different resolutions can be performed by means of simplification methods, providing reduced models that use less computational resources but look similar to the original one when rendered under certain conditions [7, 8]. Within this context, the response of the human visual system plays a crucial role in determining which details become more obvious to the final observer. High visual acuity is known to be limited to a certain visual angle, perceiving a quality degradation in regions that fall outside the focus of attention [9]. Therefore, it may be useless to render a region of a model at high resolution when its quality will be degraded by our visual system.

The goal of this paper is to propose a new technique that allows taking into account the proximity of a mesh element to the focus of attention for adapting the approximation error which will be tolerated during the simplification process to the relative importance of that mesh element. More specifically, the contributions of this work can be briefly summarized as follows:

- Analyzing the applicability of Distance Transforms for detecting the proximity of mesh elements to a focus of attention defined by a point on the screen.
- Proposing a new mesh simplification criterion based on an eccentricity measure, obtained by means of a Distance Transform.
- Presenting a simplification technique using a Distance Transform for selecting the allowed approximation error depending on the eccentricity from the focus point.

The rest of the paper is organized as follows: Section 2 presents a short overview background of mesh simplification algorithms, digital Distance Transforms and the Multi-Tessellation. Section 3 describes the proposed approach, while Section 4 shows some experimental results. Finally the conclusions and future work are presented in Section 5.

2 Background

2.1 Mesh Simplification

Many mesh simplification techniques have been proposed during the last years. Among the methods based on objective metrics, work has been done in order to incorporate other attributes besides geometry like color, texture or normals [10, 11]. Perceptual metrics have also been developed during this time [12, 13]. Lindstrom and Turk use an image metric to guide the simplification process [14]. Reddy introduced a perceptive model to guide the selection of the appropriate level of detail (LOD) [15]. Luebke defined a contrast sensitivity function that predicts the perception of visual stimuli [16].

According to human ocular physiology, high visual acuity is limited by the dimension of the fovea to approximately a visual angle of 2° . Outside this area, the quality of the image perceived by our visual system declines with eccentricity [17].

Some approaches have been proposed in order to deal with the phenomena of foveal vision, either by adapting the image resolution to the eccentricity [17, 18], or by decreasing the mesh resolution in regions far away from the focus point [19, 20]. For example, Baudisch *et al.* present a selection of techniques for the design of attentive displays that take into account the distinction between foveal vision and peripheral vision [17], and Murphy and Buchowski evaluate the visual angle in world coordinates and use it for the resolution degradation in their presented gaze contingent level of detail [19].

2.2 Digital Distance Transforms

Measuring the distance between image elements may be of interest for further processing in many image analysis applications. Basics concepts regarding digital distances can be found in [21, 22].

The application of a Distance Transform to a binary image produces as output a distance image, where each element of this distance image is assigned a distance

label. For any element belonging to the object, its label stores a value indicating its closest distance to the complement of the object.

A distance transform can be computed in two steps by propagating local distances over the image, regardless of its dimensions: 2D, 3D or higher dimensions [21, 23]. Initially, the elements belonging to the object are set to infinity and the elements belonging to the background are set to 0. In the case of a 2D image, during the first step the image is analyzed from top to bottom and from left to right. During the second step, the image elements are visited in reverse order, from right to left and from bottom to top. Each element is updated with the minimum value between its current value and the values of the already visited neighbours incremented by their connectivity weight. The neighbourhood of a pixel and the distance assigned to each of the neighbours define the final Distance Transform.

Distance Transforms and some variations of them in combination with other image processing techniques can be applied for representing and analyzing 3D objects in multiple applications [24, 25, 26, 27]. Distance information computed in the object space has also been applied in computer graphics environments for collision detection [28]. However, the authors are not aware of any previous work applying Distance Transforms from a focus point in the image space in order to guide a simplification process.

2.3 Multi-Tessellation

The Multi-Tessellation method, originally called Multi-Triangulation, was introduced by De Floriani *et al.* [29]. It provides a general multiresolution framework for polygonal meshes offering several attractive features like selective refinement, locality or dynamic update [30].

Multi-Tessellation, MT for short, is a hierarchical model that can be generated during an off-line simplification process, provided that the simplification method has been adapted in order to build an MT. The MT stores the mesh updates together with the approximation error.

Once the MT has been built, it can be queried at run time for extracting a simplified mesh fulfilling some defined restrictions. Some useful restrictions are already implemented in the distributed package [31], while the implementation of new ones can be easily done.

3 Method Description

The approach followed here classifies the mesh faces or vertices attending to their proximity to a focus of attention for a particular point of view. This focus of attention is set in image coordinates and its position may be obtained by several means such as eye trackers or pointing devices.

The classification process uses a Distance Transform, computed over the 2D image; this transform provides for each pixel of the image its distance to the attention point. A labelled mesh is obtained by backprojecting the distance

value of a pixel to the mesh elements that project into it. These tags may be assigned either to mesh vertices or faces, and they represent the distance of the mesh element to the attention point, measured in the image space. The tags assigned to the polygonal mesh elements can then be used in different ways to guide the simplification process, providing a criterion for modifying locally the approximation error allowed in areas close to the attention point.

The projection of the mesh over the 2D visualization plane and the backprojection of distance labels for every pixel of the image is an expensive process in terms of computation time. Nevertheless, it has to be pointed out that the mesh projection process can be performed off-line in order to obtain a discrete set of edited models that can be further processed by any other multiresolution methods.

To reduce the method's computational requirements, some auxiliary information is collected previously to the simplification and rendering stage. In particular, a 2D grid is created on the visualization plane, which needs a resolution level that has to be selected by the user according to the input mesh level of detail and to the desired output mesh's level of detail.

Every cell in the 2D grid has an associated list containing the indexes of the vertices that project into it. In a straightforward way, every vertex of the 3D model can also be labelled with the indexes of the 2D grid cell where it projects. This information is very useful to speed up the backprojection of distance labels to the mesh vertices, since the computation of the Distance Transform will be carried out in an image with the same resolution as this 2D grid.

The same process can be applied for backprojecting the distance values to the mesh's faces instead of to the vertices.

The use of a Distance Transform from a focus of attention requires the modification of the technique presented in [32] by computing the Distance Transform on-line during the simplification process. Thus, the grid computation can be used for any focus of attention given a certain point of view.

It must be highlighted that the computation of the 2D grid for a particular point of view is performed in a preprocessing stage, producing a mapping between the mesh vertices and the 2D grid cells that will be used later on during the simplification stage. The MT package has been used in this work to present the results obtained by integrating the distance to the focus of attention into the extraction criteria. Figure 1 shows a scheme of the proposed mesh simplification process. The following Sections describe each of the method's stages.

3.1 Mesh Mapping: 2D Grid Computation

The focus of attention is set in the screen space. Therefore the distance of the mesh elements to the attention point must be computed for a certain point of view. Given a visualization plane, the 3D mesh is projected onto it by applying the proper projection matrix to each vertex coordinates. The visualization plane is then partitioned into cells forming a grid which can be seen as a 2D digital image. Every vertex belonging to the projected polygonal mesh is tested to find

Fig. 1. Overall scheme of the mesh simplification process

(a) Distance Transform to the focus of attention, with weights 5, 7, 11 for edge, vertex and knight neighbours

(b) Distance Transform in 2(a) displayed over the 3D model projection

(c) Backprojection of distance labels onto the 3D model

Fig. 2. Distance Transform backprojection

the cells of the 2D grid where the vertex is projected. This way, every vertex v_k stores information about the indices (i, j) of the grid cell associated to it.

Two remarks can be pointed out:

- It is possible to perform the whole process using different resolution levels for the 2D image onto which the mesh is projected. This affects in turn the resolution with which the 3D mesh analysis process is carried out.
- As mentioned above, the procedure is computationally expensive, although it is affordable as a mesh preprocessing stage.

3.2 Mesh Simplification

This stage represents the final goal of the proposed method, which is to obtain a simplified mesh where the region close to a focus of attention remains at higher resolution, while the approximation error increases with eccentricity.

Before the mesh simplification, the preprocessing stage described in the previous section has to be carried out, storing for each vertex the indexes of the

2D cells where the vertex is mapped. The following paragraphs explain in detail each of the steps taken during the simplification process.

1. **Focus of Attention Selection:** There are many ways to select the focus of attention. For example, eye-tracking devices can be used to select the areas where end user watch more carefully; also guidelines can be established for categories of objects or actors. Moreover, automated procedures considering aspects such as motion speed or the presence of events such as lights or moving distractors that drive the observer's attention to a certain area can be devised. Last, "focus of neglect" can also be introduced in order to decrease the resolution in specific areas of the object model. In this work, selecting the focus of attention is performed just by clicking with the mouse on a point in the 2D projected image.
2. **Distance Transform Computation:** Once the focus point has been established, the next step consists in computing a Distance Transform over the 2D image. This way every pixel in the distance image will be labelled with its distance to the focus.

In this work, the resolution of the distance image is the same as the resolution of the 2D grid computed in the stage described in section 3.1. In consequence, a pixel in the distance transform is equivalent to a cell in the 2D grid.

3. **Distance Values Backprojection:** The goal of this step is to assign a value to every mesh node representing its distance to the focus of attention for a certain point of view. Given the already computed distance transform and the preprocessed mesh which stores for each vertex the reference to the 2D grid cell where it projects, the process is straightforward: the distance value of a pixel is assigned to every vertex that projects onto it. Figure 2 shows this process graphically.
4. **Level Of Detail Extraction:** It is in this last stage where the extracted distance values are used for mesh simplification purposes. Evidently, how distance labels are used depends on the selected simplification technique. The work presented here has been based on the Jade approach, a vertex decimation technique based on the global error [33]. The distance information is computed for the vertices of the original mesh. Since the vertices belonging to a simplified model are a subset of the original mesh, the precomputed distance labels are valid for any level of detail ¹. The proximity of every facet to the focus of attention is taken into account during this stage. This means that for a given error threshold, the error allowed in regions close to the focus point is reduced according to a predefined law. The implemented solution, requires the definition of two parameters:
 - Distance interval: range of distance labels which identify the region where a more accurate approximation is desired.
 - Error factor: the purpose of this parameter is to define an error threshold for the portion of the mesh within the region of interest. This threshold,

¹ Multi-Tessellations obtained through the application of the Jade method are freely distributed with the MT-Package.

different from the global error threshold, is defined as a function of the global error threshold.

The size of the region of interest can be simply modified by changing the range of distance labels that define it. In our case, the range is defined by setting a threshold over the minimum distance of the vertices belonging to a face. Other solutions can be easily devised.

The error factor allows to refine the quality of the approximation in the region of attention taking into account the threshold error fixed for the rest of the model. This way, the allowed error in the region of interest is $f \cdot e$, where e is the error permitted in the rest of the model and f is the error factor. Again, other error functions are also feasible.

It has to be noted that this approach uses only two approximation errors. The proposed technique can be easily extended in order to produce a variable approximation error which is dependent on the distance to the focus of attention. Nevertheless, the fact that the Multi-Tessellation method produces smooth transitions between regions with different levels of detail makes this approach less necessary.

4 Results

The experimental results presented in this section were obtained by applying the technique previously described to the Multi-Tessellation models distributed together with the MT-Package.

Figure 3(a) shows the full resolution mesh of the Stanford bunny rendered with smooth shading. As it was explained in paragraph 3.2.1 the focus of attention is established by clicking with the mouse on a pixel of the screen. In this first example, a pixel in the bunny's head is chosen as the focus of attention (pixel (34,89) in an image of dimensions 250x248). Figure 3(b) shows the result of computing a Distance Transform from the selected point over the image. The distance of a pixel is represented by a grey level, restricted to a maximum value of 255 only for displaying purposes.

Figure 3(e) shows a simplified model where the mesh has been refined taking into account the attention area. It can be observed how the bunny's head shows a high resolution, while the rest of the model has been strongly simplified. In these example, all the vertices with a distance label less than 178 have been preserved by setting an error factor of 0, obtaining a mesh with no simplification error in this region. Figure 3(c) shows the mesh of Figure 3(e) rendered in wireframe. The extremely high density of faces in the bunny's head can be appreciated. This restrictive error threshold can be relaxed, while still producing a simplified model where the bunny's head keeps a good resolution, as can be seen in Figure 3(d). In this case, the error factor has been set to 0.05; this means that the allowed error in the region of attention is 0.05 times the error allowed in the rest of the model.

Figure 4 shows the full resolution mesh of a shell rendered with smooth shading. Besides the quality of the simplification within the region of interest, the

Fig. 3. Distance Transform based simplification of a 3D mesh

Fig. 4. Original mesh of the 3D model of a shell

presented method allows to parameterize the extension of this region. It is known that the size of the focus of attention depends on some factors, like the task the observer is performing at a given time [17]. Figure 5 shows the effect of modifying the diameter of the attention region, by setting different thresholds over the distance labels which will define the region of interest. It can be observed how the high resolution area extends itself as the distance threshold is increased.

Fig. 5. Simplifications of a 3D mesh varying the distance threshold, rendered with smooth shading (5(a), 5(d), 5(g), 5(j)), flat shading (5(b), 5(e), 5(h), 5(k)) and in wireframe (5(c), 5(f), 5(i), 5(l))

Regarding computational issues, the cost in terms of memory requirements is just one extra variable per vertex. In case of tagging the mesh faces or mesh edges, an additional value per tagged element would be required. With respect to computational cost, it has to be noted that all the heavy computation is performed at preprocessing time. The most expensive step is the mesh mapping

over the 2D grid, in order to collect the information needed for backprojecting the distance values. Efficient implementations for these operations using spatial data partitioning could be considered. As it was explained above, the computation of the Distance Transform can be performed involving only two passes over the 2D image.

5 Conclusions and Future Work

Simplification algorithms are usually guided by some criteria in order to select which elements of the mesh shall be removed or replaced. Introducing distance labels into the guiding metrics is a straightforward process, opening a new way to design a range of techniques which are useful for including perceptually motivated criteria in mesh simplification algorithms.

The results presented here suggest that the use of distance information is a promising approach for attention-based mesh simplification techniques, since adding distance labels to mesh elements provides a natural way to model the degradation of the perception's resolution with eccentricity.

The fact that some distance information can be assigned to any element of the mesh (vertices, edges or faces) facilitates adapting these techniques to a wide range of simplification methods. The nature of the basic underlying operator (vertex removal, edge collapse, etc) does not impose additional limitations. Furthermore, the applicability of distance labels goes from off-line simplification processing to run-time selective refinement.

The work presented here computes the mesh elements' distance to a screen point of attention for a fixed point of view. Future work includes:

- Extending the method for covering all possible points of view in a way which is both performant and computationally efficient.
- Integrating distance to the attention focus into other mesh simplification methods besides the Jade method.
- Extending the method in order to deal with multiple focuses of attention.
- Including "focus of neglect", in order to explicitly select areas where low resolution is preferred.

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References

1. Clark, J.H.: Hierarchical geometric models for visible surface algorithms. *Communications of the ACM* **19** (1976) 547–554
2. Puppo, E., Scopigno, R.: Simplification, LOD and multiresolution principles and applications. In Fellner, D., Szirmay-Kalos, L., eds.: *EUROGRAPHICS'97*. Volume 16. (1997) Tutorial Notes PS97 TN4.
3. Garland, M.: Multiresolution modeling: Survey & future opportunities. In: *EUROGRAPHICS'99*. (1999)
4. Luebke, D.P.: A developer's survey of polygonal simplification algorithms. *IEEE Computer Graphics and Applications* **21**(3) (2001) 24–35
5. Luebke, D., Reddy, M., Cohen, J.D., Varshney, A., Watson, B., Huebner, R.: *Level of Detail for 3D Graphics*. Morgan Kaufmann (2003)
6. De Floriani, L., Kobbelt, L., Puppo, E.: A survey on data structures for level-of-detail models. In N.Dodgson, M.Floater, M.Sabin, eds.: *Advances in Multiresolution for Geometric Modelling*. Series in Mathematics and Visualization. Springer Verlag (2004) 49–74
7. Xia, J.C., Varshney, A.: Dynamic view-dependent simplification for polygonal models. In Yagel, R., Nielson, G.M., eds.: *IEEE Visualization '96*. (1996) 335–344
8. Hoppe, H.: View-dependent refinement of progressive meshes. In: *SIGGRAPH'97, Computer Graphics Annual Conference Series*, ACM (1997) 189–198
9. Ferwerda, J.A.: Elements of early vision for computer graphics (tutorial). *IEEE Computer Graphics and Applications* **21**(5) (2001) 22–33
10. Garland, M., Heckbert, P.: Simplifying surfaces with color and texture using quadric error metrics. In: *Proceedings of IEEE Visualization'98*. (1998) 263–270
11. Cohen, J., Olano, M., Manocha, D.: Appearance-preserving simplification. In: *Proceedings of SIGGRAPH 98*. (1998) 115–122
12. O'Sullivan, C., Howlett, S., Morvan, Y., McDonnell, R., O'Connor, K.: Perceptually adaptive graphics. In Schlick, C., Purgathofer, W., eds.: *Eurographics State-of-the-Art Report (EG-STAR)*. Volume 6., Eurographics Association (2004) 141–164
13. Cheng, I., Boulanger, P.: A 3D perceptual metric using just-noticeable-difference. In: *Proc. of Eurographics 2005, Eurographics (2005)* 97–100
14. Lindstrom, P., Turk, G.: Image-driven simplification. In: *ACM Transactions on Graphics*. Volume 19 of 3. (2000) 204–241
15. Reddy, M.: *Perceptually Modulated Level of Detail for Virtual Environments*. Ph. D. dissertation, University of Edinburgh (1997)
16. Luebke, D.P.: *View-dependent simplification of arbitrary polygonal environments*. Ph. D. dissertation, University of North Carolina (1998)
17. Baudisch, P., DeCarlo, D., Duchowski, A.T., Geisler, W.S.: Focusing on the essential: considering attention in display design. *Communications of the ACM* **46**(3) (2003) 60–66 SPECIAL ISSUE: Attentive user interfaces.
18. Kleinfelder, S.: Foveated imaging on a smart focal plane. Web (1999) Retrieved june 26, 2006, from source.
<http://scien.stanford.edu/class/psych221/projects/99/stuartk/fovis.html>
19. Murphy, H., Duchowski, A.: Gaze-contingent level of detail rendering. In: *Proceedings of EuroGraphics 2001*. (2001) 219–228
20. Levoy, M., Whitaker, R.: Gaze-directed volume rendering. In: *SI3D '90: Proceedings of the 1990 symposium on Interactive 3D graphics*, New York, NY, USA, ACM Press (1990) 217–223

21. Rosenfeld, A., Pfaltz, J.: Sequential operations in digital picture processing. *Journal of the Association for Computing Machinery* **13**(4) (1966) 471–491
22. Rosenfeld, A., Pfaltz, J.: Distance functions on digital pictures. *Pattern Recognition* **1** (1968) 33–61
23. Borgefors, G.: Distance transformations in digital images. *Computer Vision, Graphics and Image Processing* **34** (1986) 344–371
24. Perry, R.N., Frisken, S.F.: Kizamu: A system for sculpting digital characters. In Jain, L.C., ed.: *Proc. of ACM SIGGRAPH*, ACM Press (2001) 47–56 ISBN: 1-58113-374-X.
25. Svensson, S.: Representing and Analyzing 3D Digital Shape Using Distance Information. Ph. D. dissertation, Swedish University of Agricultural Sciences (2001)
26. Šrámek, M.: Distance fields in visualization and graphics. In Viola, I., Theussl, T., eds.: *Proc. of CESC'2002*, Budmerice, Slovak Republic (2002) 13–16
27. Jones, M.W., Bærentzen, A., Šrámek, M.: Discrete 3D distance fields: Techniques and applications. *IEEE Transactions on Visualization and Computer Graphics* **12**(4) (2006) 581–599
28. Teschner, M., Kimmerle, S., Zachmann, G., Heidelberger, B., Raghupathi, L., Fuhrmann, A., Cani, M.P., Faure, F., Magnetat-Thalmann, N., Strasser, W.: Collision detection for deformable objects. In: *Eurographics State-of-the-Art Report (EG-STAR)*, Eurographics Association, Eurographics Association (2004) 119–139
29. De Floriani, L., Magillo, P., Puppo, E.: Building and traversing a surface at variable resolution. In: *Proceedings of IEEE Visualization 97*. (1997) 103–110
30. De Floriani, L., Magillo, P., Puppo, E.: Efficient implementation of multi-triangulations. In: *Proceedings of IEEE Visualization 98*. (1998) 43–50
31. Geometric Modeling and Computer Graphics Research Group. DISI - Dipartimento di Informatica e Scienze dell'Informazione University of Genova: The MT (Multi-Tessellation) Package. Web (2005) Retrieved june 26, 2006, from source. <http://gmcg.disi.unige.it/>
32. Mata, S., Pastor, L., Rodríguez, A.: Silhouette detection for adaptive polygonal mesh simplification using distance transforms. In Braz, J., Jorge, J., Dias, M., Marcos, A., eds.: *Proc. International Conference on Computer Graphics Theory and Applications, GRAPP'06*, Setbal, Portugal, INSTICC (2006) 43–50
33. Ciampalini, A., Cignoni, P., Montani, C., Scopigno, R.: Multiresolution decimation based on global error. In: *The Visual Computer*. Volume 13 of 5. (1997) 228–246