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Occluder Shadows for Fast Walkthroughs of Urban Environments

Peter Wonka[*] and Dieter Schmalstieg[+]

[*]IRISA Rennes, France, and Vienna University of Technology, Austria, email: wonka@cg.tuwien.ac.at

[+]Vienna University of Technology, Austria, email: dieter@cg.tuwien.ac.at

Abstract.
This paper describes a new algorithm that employs image based rendering for fast occlusion culling in complex urban environments. It exploits graphics hardware to render and automatically combine a relatively large set of occluders. The algorithm is fast to calculate and therefore also useful for scenes of moderate complexity and walkthroughs with over 20 frames per second. Occlusion is calculated dynamically and does not rely on any visibility precalculation or occluder preselection. Speed-ups of one order of magnitude can be obtained.

1. Introduction

In walkthrough applications for urban environments, a user navigates through a city as a pedestrian or vehicle driver. Such a system is useful for example in traffic simulation, visual impact analysis of architectural projects and computer games. A desirable goal is real-time rendering with about 20-30 frames per second (fps), that are sustained even when the viewer's speed is high (e. g., 100km/h when driving in a fast car).

Scene complexity for large urban environments defeats any naive approach of trying to render everything in hardware. To remove larger scene parts before the final rendering traversal, two approaches seem to be promising:

1. One way is to use impostors[14], mainly texture maps (textured depth meshes), to replace complex geometry. One texture map is valid only for a few frames and has to be updated frequently, which is only fast enough for a small number of impostors.
2. The second method is to use occlusion culling[7]. A number of polygons are selected as occluder in each frame and the part of the scene that is occluded by one of these occluders is not visible and can be culled.

Figure 1: *View from Klosterneuburg, Austria. Note how only a few buildings are visible because of occlusion.*

To understand optimization possibilities suitable for an urban model we have to analyze how an urban environment looks like and examine its special properties, which may be exploited by an acceleration algorithm. For the design of our occlusion algorithm we tried to analyze the visibility and occlusion of real and virtual urban environments using data of European cities:

- Typically an urban environment is modeled with a ground mesh or plane, with different objects placed on top of it. These are mainly buildings, trees and bushes, other smaller decorating objects like traffic lights, traffic signs, streetlights, mailboxes and the road network (if it is not directly a part of the ground). This type of environment is often referred to as 2½

dimensional. We can profit from this fact for the design of our data structures and algorithm.

- For most parts of a walkthrough the view is rather restricted. Only from a few viewpoints the observer can see further than a few hundred meters. Figure 1 shows a typical view of a location in the city of Klosterneuburg, Austria, with a view between 100 and 200 meters. For such views a small set of buildings or blocks (about 20) occludes the rest of the model.
- For more open parts of the scenes however, like the place in front of a train station or the view along a broader straight street or a riverside, a few occluders are no longer sufficient. We still have very good occlusion, but the occlusion is made up with a larger number of occluders (up to a hundred). In the foreground of our scene overview we see a wide open space where a larger number of occluders is necessary.

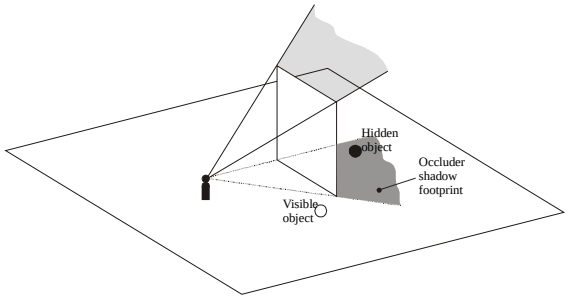

Figure 2: *An occluder shadow is used for fast rendering of urban environments. Note how the roof top of the shown building facade allows to determine whether an object is hidden from its occluder shadow footprint in the ground floor.*

A good occlusion algorithm should use all important occluders if possible, because any holes reduce the performance of the algorithm. However, identifying all important occluders analytically is a computationally costly process. Instead, a fast algorithm may simply use a larger set of potentially important occluders (according to some simple criterion such as size) to heuristically achieve the same degree of occlusion. Consequently, fast computation of occlusion is essential.

In this paper we introduce a new hybrid image based and geometrical culling algorithm for urban environments exhibiting the properties discussed above. We compute *occluder shadows* (Figure 2) to determine which parts of the environment are invisible from a given viewpoint. Occluder shadows are shadow frusta cast from selected occluders such as building fronts. The 2½D property of an urban environment allows us to generate and combine occluder shadows in a 2D bitmap using graphics hardware.

Our algorithm has the following properties:

- It uses a relatively large set of occluders (up to 600) that are automatically combined by the graphics hardware.
- The algorithm is fast to calculate (about 10ms on a mid-range workstation) and therefore also useful for scenes of moderate complexity and walkthroughs with over 20fps.
- We calculate the occlusion dynamically and do not rely on any visibility precalculation or occluder preselection.

Furthermore the algorithm is simple to understand and implement. These properties should make this algorithm suitable for many existing urban walkthrough implementations without introducing major drawbacks to existing systems.

After reviewing the previous work an overview of our algorithm is given and the various stages of our acceleration method are explained. After that we will describe our implementation and give the results of different tests made with our example environment. Then we will discuss the applicability of our algorithm and compare it to the other existing solutions. Finally we will give a preview of our future work in that field to achieve further optimizations.

2. Previous Work

Several methods were proposed to speedup the rendering of an interactive walkthrough application. General optimizations are implemented by rendering toolkits like Performer[10] that aim for an optimal usage of hardware resources. Level of Detail algorithms are very popular in urban simulation[9], because they don't need a lot of calculation during runtime. Heckbert[6] gives a good overview of recent LOD algorithms.

The idea of image based simplification approaches is to replace whole scene parts with an impostor. One impostor is usually only valid for a few frames and has to be updated frequently[11,13]. Other approaches use textured depth meshes[1,14], that incorporate depth information for efficient impostor update.

The idea of an efficient visibility culling algorithm is to calculate a conservative and fast estimation of those parts of the scene that are definitely invisible. The final hidden surface removal is done with the support of hardware, usually a Z-buffer. A simple and general culling method is View Frustum Culling[2], that is applicable to almost any model. General algorithms for occlusion culling were proposed that calculate the occlusion in image space. Green's hierarchical z-buffer[5] depends on special purpose hardware, which makes it impractical for real walkthrough systems. The hierarchical occlusion maps proposed by[17] are a more practical approach, that was implemented and tested on existing graphics hardware. A set of occluders in

the near field are rendered in the frame buffer and this image is used to calculate a hierarchy of occlusion maps, using mip mapping hardware. In a second pass the scene graph is traversed, and the bounding boxes of the scene graph nodes are tested against the occlusion hierarchy.

For building interiors most visibility algorithms decompose the model into cells connected by portals[15] and compute inter-cell visibility (potentially visible set, PVS). Luebke's algorithm[8] eliminates the precalculation of the PVS and calculates the PVS during runtime. Urban environments were stated as a possible application, but in practice one can not rely on a very dense building structure allowing a good cell partition of the model. A first try with a regular space division was proposed by Cohen-Or[3].

For urban environments the occlusion culling with a few large occluders was proposed by Coorg[4] and the research group at UNC[7]. They both select a small set of occluders for each frame, that are likely to occlude a big part of the model. Hudson takes the scene organized in a hierarchical data structure like an octree or k-d tree and clips it against the occluded region. Coorg calculates visibility events to make additional use of temporal coherency.

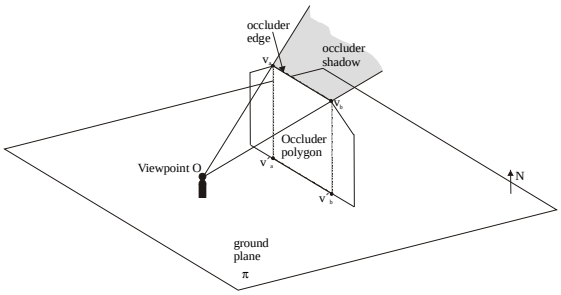

Figure 3: *This sketch shows the geometric relationship used for the occlusion culling. An occluder shadow is constructed from a given viewpoint and an occluder edge of an occluder polygon P.*

3. Overview of the approach

3.1 Occluder shadows

The concept of occluder shadows is based on the following observation: Given a viewpoint O, an occluder polygon P casts an occluder shadow that occludes an area of the scene that lies behind the occluder, as seen from the viewpoint. This area can be seen as a shadow frustum that is determined by the occluder and the viewpoint. Objects fully in this shadow frustum are invisible.

A more formal definition (compare Figure 3) of an occluder shadow is given in the following:

- The environment requires a *ground plane*[1] π with a normal vector N (up direction).
- An *occluder polygon* P is a (not necessarily convex) polygon with its normal vector parallel to the ground plane (i. e. P is standing upright). P is constructed from a set of vertices $V=\{v_1..v_k\}$, connected by a set of edges $E=\{e_1..e_k\}$. An edge e from v_a to v_b is written as $e = (v_a, v_b)$. At least one edge of P must lie *in* the ground plane (i. e. $\exists\, e\in E \mid e = (v_a, v_b) \wedge v_a\in\pi \wedge v_b\in\pi$).
- An *occluder edge* is an edge $e\in E$ with $e = (v_a, v_b)$ of P that does not lie in the ground plane (i. e. $v_a\notin\pi \vee v_b\notin\pi$). Let v_a' and v_b' denote the normal projection of v_a and v_b onto π, respectively. Then all points along the two line segments (v_a, v_a') and (v_b, v_b') must be completely *inside* P, i. e. every point along each of the two line segments must also be contained in P.
- An *occluder shadow* is a quadrilateral with one edge at infinity, constructed from an occluder edge $e = (v_a, v_b)$ and two rays: $v_a + t(v_a - O)$ and $v_b + u(v_b - O)$. When looking in -N direction, the occluder shadow covers all scene objects that are hidden by the associated occluder polygon when viewed from O.

We exploit this observation by rendering the occluder shadow with orthogonal projection into a bitmap coincident with the ground plane. The height information (z-buffer) from this rendering allows to determine whether a point in 3D space is hidden by the occluder polygon or not.

3.2 Algorithm outline

This section will explain how the concept of occluder shadows is used for rendering acceleration. For our algorithm we assume an urban model as described in the introduction. We rely on no special geometric features concerning the model. We need no expensive preprocessing and all needed data-structures are build on the fly at startup. For a completely arbitrary input scene, two tasks have to be solved that are not addressed in this paper: (1) The scene has to be decomposed into objects for the occlusion culling algorithm, which can be a semantic decomposition into buildings, trees and road segments or a plain geometric decomposition into polygon sets. (2) Useful occluders - mainly building fronts - must be identified. Details on the preprocessing are given in section 4.1.

The scene is structured in a regular 2D grid coincident with the ground plane and all objects are entered into one or more grid cells. During runtime we dynamically select a

[1] The definition is also valid if the urban environment is modeled on top of a height field, but this complicates the definition and is omitted here for brevity.

set of occluders for which occluder shadows are rendered into an auxiliary buffer - the *cull map* - using polygonal rendering hardware. Each pixel in the cull map (image space) corresponds to a grid of the scene-grid (object space). Therefore the cull map is an image plane parallel to the ground (xy) plane of the scene (see section 4.2). Visibility can be determined for each cell (or object) of the grid according to the values in the cull map. To calculate the occluded parts of the scene, we can compare for each cell the z value in the cull map to the z-value of the bounding boxes of the objects entered into the scene-grid at this cell (see section 4.3).

When we render a shadow with the graphics hardware we obtain z-values and color-buffer entries that more or less correspond to a sample in the middle of the pixel. This is not satisfying for a conservative occlusion calculation. For a correct solution we have to guarantee, that (1) only fully occluded cells are marked as invisible and (2) that the z-values in the z-buffer correspond to the lowest z-value of the occluder shadow in the grid cell and not a sample in the middle. How this is achieved is detailed in section 4.4.

The advantage of our images based approach over geometric occlusion computation is that the whole scene is not clipped against each shadow frustum separately. The calculation time depends only on the number of pixels and the number of occluders. For reasonable sizes of the cull map the overhead through the copying of the frame buffer and the visibility traversal is small and the algorithm runs always fast independent of the scene complexity.

Furthermore we can use a larger number of occluder shadows, that are automatically combined by the graphics hardware. This *occluder fusion*[17] is very efficient, so that only a few invisible objects are overlooked by our culling algorithm.

To summarize, during runtime the following calculations have to be performed for each frame of the walkthrough:

- **Occluder selection**: For each frame a certain number of occluders has to be selected, that have a high chance to occlude the most parts of the invisible portion of the scene. The input to this selection is the viewpoint and the viewing direction.
- **Draw Occluder Shadows:** The selected occluders are taken to calculate an occluder shadow that is rendered into the cull map using graphics hardware.
- **Visibility calculation**: The cull map is traversed to collect all the visible objects in the scene. Objects that are not visible are omitted in the final rendering traversal.
- **Hidden Surface Removal:** The remaining geometry is potentially visible and is passed to a hidden surface removal algorithm (z-buffer hardware).

4. Culling algorithm

4.1 Preprocessing

At startup we have to build two auxiliary data-structures: The scene grid and the occluder grid. To construct the scene grid we have to organize all objects in a regular grid covering the whole environment. All objects are entered into one[2] cell, so that we store a list of objects for each grid cell. As occlusion is computed on a cell basis, the complexity and size of the environment influence the choice of the grid size.

Among the objects in the scene, candidates for occluder polygons are identified. An occluder polygon should have good potential for occlusion - it should be fully opaque and large enough to possibly occlude other parts of the scene. An occluder polygon does not necessarily have to be a scene polygon. Polygons extracted from objects like trees, bushes, vehicles, or roads violate one or more of these properties, which leaves mainly building fronts as useful occluders. Other possible candidates are walls, roofs and large trucks. The occluders are marked in the grid data structure for fast retrieval at runtime.

These tasks can be done very fast and take a time comparable to the loading of the scene.

4.2 Cull map creation

Once an occluder polygon is selected, the associated occluder shadow quadrilateral is rendered into the frame buffer. Since a quadrilateral with points at infinity cannot be rendered, we simply assume very large values for the t and u parameters from section 3.1, so that the edge in question lies fully outside the cull map. When the quadrilateral is rasterized, the z-values of the covered pixels in the cull map describe the minimal visible height of the corresponding cell in the scene-grid. The graphics hardware automatically fuses multiple occluder polygons rendered in sequence (Figure 4 and Figure 10).

When occluder shadows intersect, the z-buffer automatically stores the z-value, which provides the best occlusion.

Previous approaches selected a set of occluders, that are likely to occlude a large part of the scene, according to a heuristic depending on the distance from the viewpoint, the area and the angle between the viewing direction and the occluder-normal[4]. This is a necessary step if only a small number of occluders can be considered, but it has the disadvantage that the selection has to be precalculated, which makes it more difficult to add occlusion culling to an existing visualization system. In our approach, the number of occluders is large enough, that we use only the

[2] Note that usually objects span more than one cell.

distance from the viewpoint as a criterion for a dynamic selection during runtime (Figure 11).

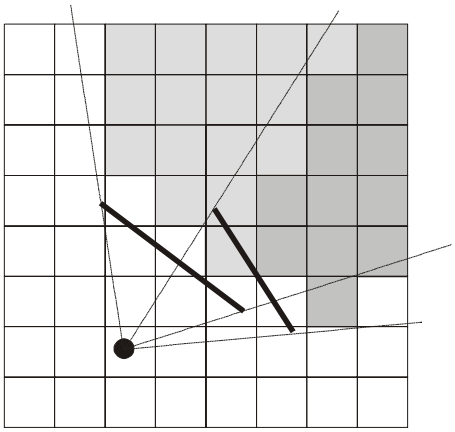

Figure 4: *The cull map is created by drawing occluder shadows as polygons using graphics hardware. Overlapping occluders are correctly fused by standard rasterization and z-buffer comparison.*

Our experiences have shown that a more sophisticated precomputed occluder selection does not improve the occlusion performance of our implementation. However, we perform a simple backface culling test on all occluder candidates. As the building fronts we consider are generally closed loops of polygons, and it is sufficient to consider only frontfacing polygons.

For each of the occluders we render the frustum in the cull map. The resulting cull map is passed to the next step, the actual visibility calculation.

4.3 Visibility calculation

To determine the visible objects that should be passed to the final rendering traversal, we have two options: We can either traverse the cull map or we can traverse the scene graph to determine which objects are visible. While traversing the scene graph would make a hierarchical traversal possible, we found that a fast scan through the cull map is not only simpler, but also faster.

Our algorithm therefore visits each cell that intersects the viewing frustum and checks the z-value in the cull map against the height of the objects stored in that cell. We use a two-level bounding box hierarchy to quickly perform that test: first, the z-value from the cull map is tested against the z-value of the bounding box enclosing all objects associated with the cell to quickly reject cells where all objects are occluded. If the test for rejection fails, the bounding boxes of all individual objects are tested against the cull map. Only those objects that pass the second test must be considered for rendering.

In pseudo code, the algorithm looks like this:

```
for each cell C(i,j) in the grid do
  if C(i,j).z > cullmap(i,j)
    for each object O(k) in C(i,j) do
      if O(k).z > cullmap(i,j).z
      and O(k) not already rendered
        render O(k)
```

4.4 Cull map sampling correction

As stated in the previous section, the simple rendering of the occluder shadows generally produce a non conservative estimation of occlusion in the cull map because of undersampling. For (I) correct z-values in the cull map and (II) to avoid the rendering of occluder shadows over pixels that are only partially occluded, we have to shrink the occluder shadow depending on the grid size and the rasterization rules of the graphics hardware.

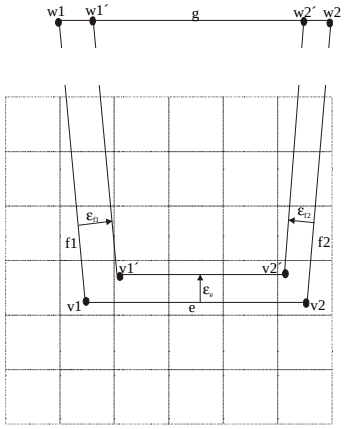

Figure 5: *Sampling correction is performed by moving three edges of the occluder shadow inwards so that no invalid pixels can accidentally be covered.*

Our method to overcome these sampling problems requires information about the exact position used for sampling within one pixel. Current image generators usually take a sample in the middle of a pixel. For example the OpenGL[12] specification requires that (1) the computed z-value corresponds to the height in the middle of a pixel, (2) a pixel fragment is generated when the middle of a pixel is covered by the polygon and (3) For two triangles, that share a common edge (defined by the same endpoints), that crosses a pixel center, exactly one has to generate the fragment.

Given these sampling constraints, a conservative solution for both stated problems is to geometrically shrink the occluder shadow (Figure 5). Consider an occluder shadow quadrilateral constructed from the vertices v_1, v_2, w_1, and w_2, defining the occluder edge $e = (v_1, v_2)$ and three other edges $f_1 = (v_1, w_2)$, $f_2 = (v_2, w_2)$ and $g = (w_1, w_2)$. By moving e, f_1, and f_2 towards the interior of the polygon along the normal vector by distances ε_e, ε_{f1}, and ε_{f2}, respectively, we obtain a new smaller quadrilateral with edges e', f_1', f_2' and g', that does not suffer from the

mentioned sampling problems. g is outside the viewing frustum and need not be corrected, it is only shortened.

The correction terms ε_e, ε_{f1}, and ε_{f2} are dependent on the slope of e, f_1, and f_2, respectively. An upper bound for them is $d/\sqrt{2}$, where d is the length of one grid cell (for the worst case of a diagonal line). However, it is sufficient to take $(|n_x|+|n_y|) / \|n\|^2 \cdot d/\sqrt{2}$, where n is the normal vector on an edge that should be corrected. This term describes the furthest normal distance within a pixel to the cell minimum.

If the occluder or the angle between the occluder and the viewing direction is small, fl_1' and fl_2' may intersect on the opposite side of e as seen from e'. In this case, the occluder shadow quadrilateral degenerates into a triangle, but this degeneration does not affect the validity of the occlusion.

5. Implementation

We implemented our algorithm on an SGI platform using Open Inventor (OIV) as high-level toolkit for the navigation in and rendering of the urban environment. The cull map handling is done with native OpenGL (which also guarantees as conservative occlusion) in an off screen buffer (pbuffer). OIV allows good control over the rendering and navigation and is also available on different platforms. In our cull map implementation we use only simple OpenGL calls, which should be well supported and optimized on almost any hardware platform. The most crucial hardware operation is fast copying of the frame buffer and the rasterization of large triangles with z-buffer comparison. Hardware accelerated geometry transformation is not an important factor for our algorithm.

We tested and analyzed our implementation on two different hardware architectures: an SGI Indigo2 Maximum Impact representing medium range workstations and an O2 as a low end machine. Where the implementation of most tasks met our estimated time frames, the copying of the cull map showed significantly different behavior on various hardware platforms and for different pixel transfer paths. Where the time to copy the red channel of an 250x250 wide frame buffer area on our maximum impact took about 3ms, this step takes over 20 times as long on the O2, where only the copying of the whole frame buffer (red, green, blue and alpha values) is fast. These differences have to be considered in the implementation. Furthermore, the copying of the z-buffer values on an O2 is more time-consuming and not efficient enough for our real-time algorithm.

Due to the fact that fast copying of the z-buffer is not possible (which is also stated by [17]), we had to resort to a variation of the algorithm that needs only to copy the frame buffer:

1. At the beginning of each frame, each value of the z-buffer is initialized with the maximum z-value from the objects in the corresponding grid cell. z-buffer writing is disabled, but not z-comparison. Next the color buffer is cleared and the viewing frustum is rendered with a key color meaning *visible*. The cells without any objects are initialized to have very high z-values, so that they are not marked visible by rendering the viewing frustum.
2. Each occluder shadow is then written with a key color meaning *invisible* and overwrites all pixels (= grid cells) that are fully occluded.
3. Finally, the resulting frame buffer is copied to memory for inspection of the occlusion.

The sampling correction for the occluder shadows makes it necessary to keep information of directly connected occluders. All connected occluders are stored as poly-lines. For our implementation we use an extension of the described sampling correction algorithm to a set of connected occluders, where the most parts of the calculation are precalculated at startup.

Furthermore all occluders that come from building fronts have an oriented normal-vector that is used for backface culling. This helps to reduce the number of occluders of about 50%.

6. Results

To evaluate the performance of our algorithm we performed several tests using a model of the city of Vienna. We started with the basic data of building footprints and building heights and used a procedural modeling program to create a three dimensional model of the environment. This made it possible to control the size and scene complexity of the test scene. We modeled each building with a few hundred polygons. For the first test we created a smaller model with 227355 polygons, which covers an area of about a square kilometer.

We recorded a camera path through the environment where we split the path in two parts. In the first part (until frame number 250) the camera moves along closed streets and places. This is a scenario typically seen by a car driver navigating through the city. In the second part the viewer moves at a wide open area (In the real city of Vienna there is a river crossing the city).

For our walkthroughs we configured our system with a grid size of 8m and we selected all occluders up to 800 meter (which is on the secure side). In the most frames we select between 400 and 1000 occluders and drop about half of them through backface culling. The construction of the auxiliary data structures and occluder preprocessing does not take longer than 10 seconds, also for larger scenes, while the loading of the geometry takes sometimes over a minute.

Figure 6 shows the frame rate for the walkthrough on the Indigo2. We see that we have good occlusion and that the algorithm is fast to compute. We have a speedup of 3.7 for the indigo 2. Furthermore the frame rate stayed over 20 fps. The frame rates in the second part are also high, because the model is structured in a way that little additional geometry comes into sight.

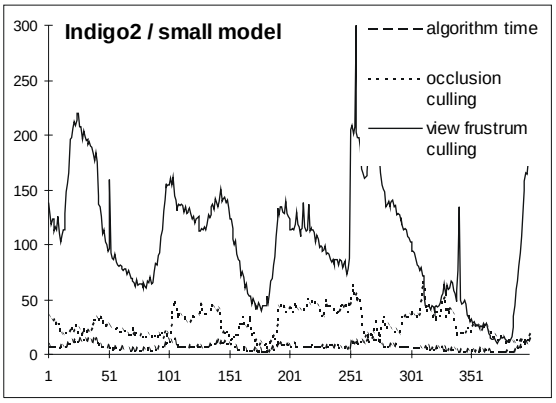

Figure 6: *The frame times for walkthrough of a model consisting of 227355 polygons on an Indigo2 (frame times on y-axis in ms).*

For the second test we took the same walkthrough embedded in a larger city of about 1,300,000 Polygons with a size of 4km^2 to test the quality of the occlusion (compare Figure 9). To be able to compare the results we used the same camera path in the larger environment. The first part of the walkthrough has high occlusion and shows a performance similar to the smaller city model, which demonstrates how independence of scene complexity is possible.

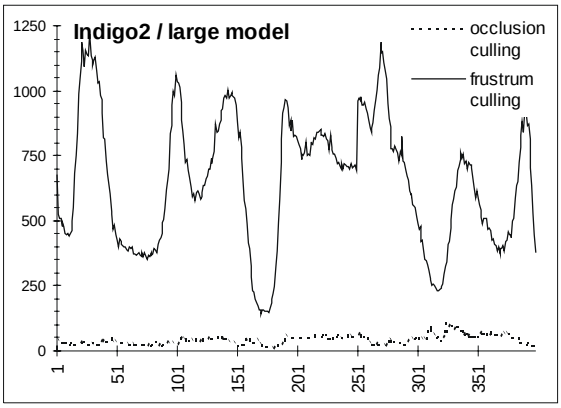

Figure 7: *The frame times for walkthrough of a model consisting of 1,300,000 polygons on an Indigo2 (frame times on y-axis in ms).*

In the second part of the walkthrough, however, because, the field of view is not fully occluded for several hundred meters (sometimes up to 700). This situation violates the assumption of dense occlusion and can not be handled without additional measures (see proposed future work).

The results for the Indigo2 are shown in Figure 7 and a summary of all results is given in Figure 8.

Indigo2	**Model 1**	**Model 2**
Frustum Culling	103 ms	653 ms
Occlusion Culling	28 ms	42 ms
algorithm	7 ms	14 ms
part 1	29 ms	37 ms
part 2	27 ms	51 ms
Speedup	3,7	15,4

O2	**Model 1**	**Model 2**
Frustum Culling	312 ms	2029 ms
Occlusion culling	76 ms	120 ms
algorithm	12 ms	26 ms
part 1	75 ms	90 ms
part 2	77 ms	26 ms
Speedup	4,1	16,9

Figure 8: *Summary of all measurements for the two walthrough sequences. Speedup factors between 4 and 17 could be obtained.*

It can be seen that the frame rate in the first part is almost the same as in the smaller model. Moreover, almost the same set of occluders were selected for both city models. Longer frame times are only due to higher algorithm computation time and Inventor overhead.

This evaluation demonstrates that the occlusion is efficient and that our algorithm generally does not leave unoccluded portions in the field of view if suitable occluders are present. Even the low-end O2 workstation could sustain a frame time of 120 ms.

In the second part of the walkthrough performance dropped as expected because of insufficient occlusion. Nevertheless, the frame time of the Indigo2 does not exceed 107ms (the maximum frame time) and the average frame time for the second part is almost 50ms. The overall improvement for the whole path (compared to simple view frustum culling) equals a factor of about 16.

7. Discussion

For the applicability of an algorithm we found that fast calculation times are an important feature, that strongly determine the applicability of an algorithm. If we assume the goal of 20 fps for a fluent walkthrough, we have only 50ms per frame. If 30 ms are spent on the occlusion algorithm, little is left for other tasks like rendering, LOD selection, or image based simplifications. Such an algorithm may accelerate from 2 to 10 frames per second, but not from 4 to 20 fps, which is a fundamental difference. We therefore found it more important to have an algorithm that is robust and does not degenerate under

worst case conditions rather than an algorithm that occludes as much as possible.

An expensive algorithm depends on strongly occluded scenarios to compensate for its calculation time, whereas a fast algorithm can also result in speedups for slightly occluded environments. Consider HOMs[17] used for the UNC walkthrough system, for which the calculation times of the occlusion algorithm itself on mid-range machines are relatively high. The pure construction time of HOMs on an SGI Indigo2 Maximum Impact is about 9 ms, which is the time for one complete frame (including rendering) of our algorithm on the same machine. However, it must be stressed that HOMs provide a framework that is suitable for far more general scenes which cannot be handled by our algorithm.

The geometrical algorithms of [4] and [7] operate on a similar idea, where former appears superior because it makes additional use of temporal coherency, and the presented implementation is faster.

Coorg's algorithm however is a complex geometric algorithm and the paper indicates, that the fast implementation is very complicated. We still can give a rough comparison based on the presented results in the paper. Both algorithms operate on the same idea, of culling objects, that lie in the shadow frustum of selected occluders. To summarize the comparison, Coorg's algorithm provides a better solution in the following areas:

- Independence from graphics hardware makes a multi-processor implementation simpler.
- The algorithm's scalability is not constrained by a fixed size cull map.

In contrast, our algorithm has the following advantages:

- It is faster to compute and we can handle an order of magnitude more occluders.
- The calculated occlusion is better because the algorithm can deal with connected occluders. Most important we use the effect of connected occluder chains, that are extracted from one building.

8. Conclusions and future work

We have presented a new algorithm for fast walkthroughs of urban environments based on occluder shadows. The algorithm has proven to be fast, robust, and useful even for scenes of medium complexity and low-end graphics workstation. It is capable of accelerating up to one order of magnitude, depending mostly on support for fast frame buffer copying, which hopefully will be available also on low-cost hardware in the near future.

For very large scale urban environments, occlusion culling alone is not sufficient if views with open view corridors into a far field with huge geometric complexity are possible. To overcome this restriction, we are currently working towards the integration of occluder shadows and a raycasting/image cache algorithm for far field rendering[16], which should eliminate the mentioned restriction. We hope to be able to present a true 20fps walk through a very large scale (10 million polygons) urban environment in the near future.

9. Acknowledgments

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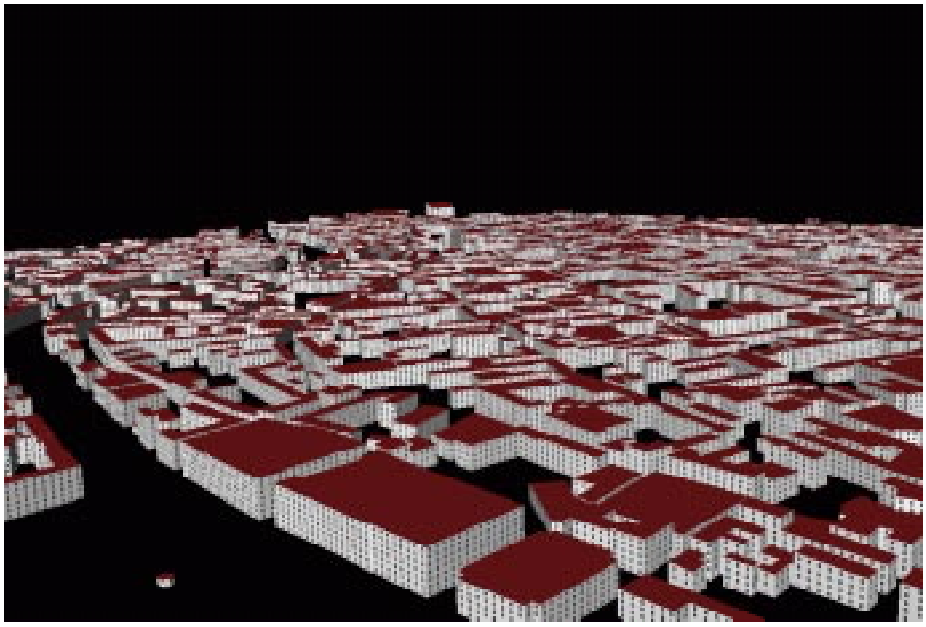

Figure 9: *This model of the city of Vienna with approximately 1.3M polygons was used for our experiments*

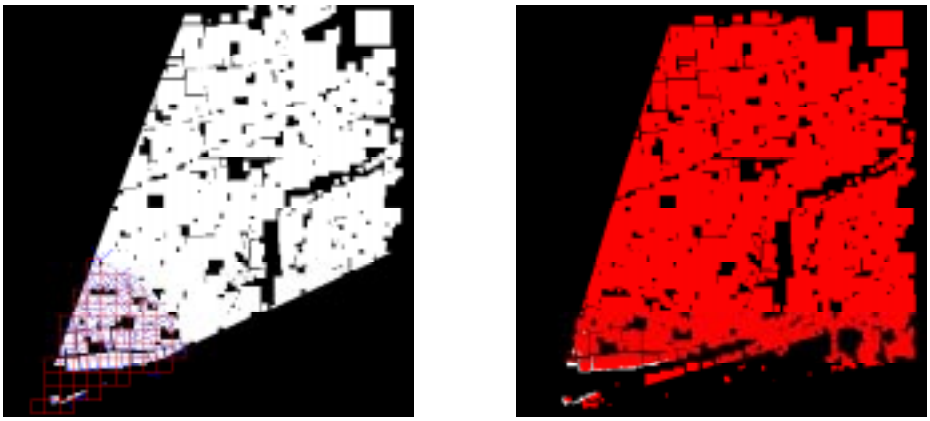

Figure 10: *Two views of the cull map used for the occlusion culling. The left view shows the grid cells inspected for suitable occluders (in red) and selected occluders near the viewpoint (in blue). The right view shows the culled portion of the model (in red), and the remaining geometry after culling (in white).*

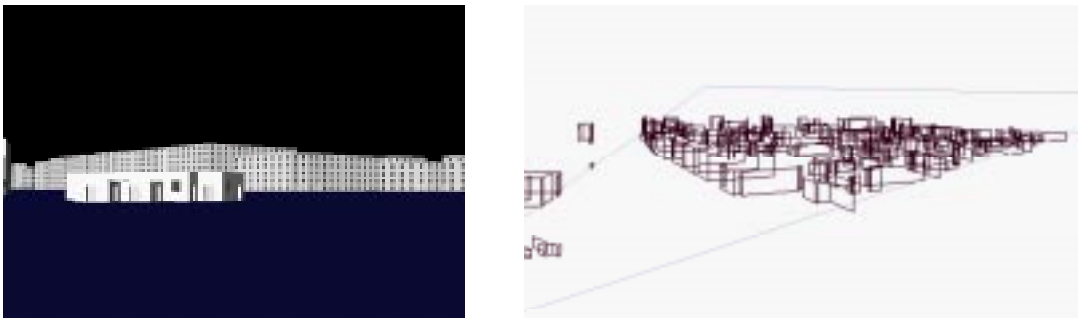

Figure 11: *For the viewpoint used in Figure* 10*, the resulting image is given on the left. The right view shows a wireframe rendering of the occluders only to give an impression of occluder density.*