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СТРАТЕГІЧНІ ВИКЛИКИ РОЗВИТКУ СУЧАСНОГО СВІТУ

Монографія

STRATEGIC CHALLENGES IN THE DEVELOPMENT OF THE CONTEMPORARY WORLD

Monograph

2026

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ОБИРАЙТЕ ПЕРШИХ! ДОВІРЯЙТЕ СПРАВЖНІМ! ЦІНУЙТЕ УНІКАЛЬНІСТЬ!

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6.1. Optimization of texturing procedures for relief surfaces in three-dimensional graphics software systems

The organization of calculations during the reproduction of relief from a height map is considered. The choice of the number of samples according to the length of the view ray projection, the use of a conservative depth hierarchy and the refinement of the localized section are justified. The requirements for the preparation of materials, the implementation of shaders and the verification of image quality are determined. Analytical cost estimates and the procedure for comparative testing are presented. Keywords: relief texturing, height map, three-dimensional graphics, shader, adaptive detailing, graphics processor.

The surface of stone, brickwork or machined metal is perceived as three-dimensional due to the change in the orientation of normals, mutual overlap of parts and their shading. Reproducing all irregularities with polygons increases the volume of geometric data and the cost of their processing. For interactive graphics, it is advisable to specify some of these properties with textures. The choice between imitation, geometric and combined representation of the relief is considered in [1]. This division determines the limits of the application of optimization: fast calculation of the texture displacement does not replace geometry when it is necessary to change the silhouette of the object.

In the relief texturing procedure, a significant part of the work falls on finding the intersection of the view ray with the height map. If all fragments are assigned the same number of steps, simple areas receive an excess budget, and complex ones may remain insufficiently detailed. Increasing the maximum number of iterations partially reduces the omission of small protrusions, but increases the load on the texture subsystem. Therefore, the optimization must take into account the observation conditions, the spatial structure of the map, and the permissible error of the coordinates.

The aim of the work is to substantiate a consistent method of organizing procedures for texturing relief surfaces in a three-dimensional graphics software system. The preparation of material data, selection of detail, traversal of the depth map, refinement of the section and evaluation of the resulting image are considered. The numerical examples given are analytical calculations for given conditions; they are not presented as the results of measurements performed on a graphics processor.

The material is specified by a consistent color map, normal map, and depth map. The coordinates of the corresponding details in these maps must match. The color map describes the basic optical properties, the normal map is used to calculate the lighting, and the depth map determines the position of the visible point inside the conditional relief layer. Various methods of giving surfaces texture are discussed in [2]. In this work, a unique depth field model is adopted: each pair of texture coordinates corresponds to one depth value.

This representation is suitable for depressions, scratches, seams, and irregularities without overhangs. It does not describe cavities that overlap each other along the normal, and does not provide automatic contour changes to the polygonal model. For such areas, geometric refinement or another surface representation is required. This limitation should be checked during material preparation, since increasing the number of tracing steps does not eliminate the error of the model itself.

Let the upper boundary of the relief layer correspond to zero depth, and the lower one to unity. The direction from the surface to the observer is given by a unit vector in the tangent coordinate system. For face fragments, its normal component is positive. The position of a point along the ray is described by the equation

$$\mathbf{q}(t) = \mathbf{q}_0 - t\mathbf{p}, \quad \mathbf{p} = s\frac{\mathbf{v}_{xy}}{\max(v_z,\varepsilon)}, \quad 0 \le t \le 1. \tag{1}$$

Here $\mathbf{q}_0$ – initial texture coordinates; s – relief scale; $\mathbf{v}_{xy}$ – tangential components of the observation direction; v_z – normal component; ε – positive threshold. Using a threshold limits the numerical increase in displacement near the sliding angle, but does not eliminate geometric distortions. For such angles, a separate material simplification mode or a transition to geometric representation is required.

Given a normalized depth map, d the difference function has the form

$$F(t) = t - d\big(\mathbf{q}(t)\big). \tag{2}$$

The first intersection, i.e. the smallest value of the parameter at which the ray reaches the surface, must be found. Sequentially reviewing the segment ensures the correct order of checks, but a discrete step may miss fine detail. Therefore, a change in the sign of the function is a condition for starting the refinement, and not proof that there was no other intersection before. This distinction is essential for small-width seams and high isolated protrusions.

The viewing angle alone is not enough to determine the number of steps. The same surface orientation at different depth scales gives different lengths of movement in the texture. Similarly, changing the mip level changes the number of texels through which the ray projection passes. For a consistent choice of budget, it is advisable to use the length of this movement at the current level of detail:

$$L = \sqrt{(W_\ell p_x)^2 + \big(H_\ell p_y\big)^2}. \tag{3}$$

In the formula W_ℓ, and H_ℓ are the map dimensions at the selected mip level; p_x and p_y are the displacement components. The quantity L is measured in texels. It characterizes the search volume in texture space, but does not determine the complexity of the depth profile itself. On a nearly flat area, a long projection can be cheap for hierarchical traversal, while a short ray near a narrow ledge will require careful refinement.

The initial budget of sequential search is proposed to be defined as

$$N = \min\big(N_{\max}, \max(N_{\min}, \lceil L/\delta \rceil)\big). \tag{4}$$

Here δ, is the target displacement between samples in texels; $N_{\min}$ and $N_{\max}$ is the lower and upper budget bounds. If the upper bound is reached, the condition of the given step may be violated. Accordingly, the constraint $N_{\max}$ should be considered as a cost constraint, and not as a guarantee of accuracy. For complex materials, this mode should be supplemented with conservative acceleration data.

The rough pass is completed after detecting neighboring points between which the difference function changes sign. Subsequent calculations are performed only within this interval. Repeated pass of the entire layer thickness for refinement is impractical, since the already obtained information about the location of the intersection is lost. Bisection sequentially divides the interval in half and preserves that part of it in which the sign change remains.

If the initial length of the interval is equal to Δt, then after m steps its upper bound is

$$\Delta t_m = \frac{\Delta t}{2^m}, \qquad e_q \le L\Delta t_m. \tag{5}$$

The value e_q limits the uncertainty of the position along the ray projection in texels. The estimate is valid for an already localized root for a continuous function on the corresponding interval. When sampling the nearest texel, the map is discontinuous, therefore, for such refinement, it is advisable to use a consistent continuous reconstruction of values. In this case, its profile may differ from the initial discrete sample.

For a given permissible uncertainty, τ the required number of refinements is determined by the condition

$$m \geq \max\left(0, \lceil \log_2 \frac{L\Delta t}{\tau} \rceil\right), \qquad \tau > 0. \tag{6}$$

At zero offset, no refinement of texture coordinates is required. In other cases, the marginal refinement budget must be sufficient for the given error or the system must explicitly switch to a less accurate regime. Limiting the number of iterations by itself does not ensure that the inequality is satisfied. Separating the stopping criteria by accuracy and by cost makes the procedure behavior predictable.

For example, with a projection length of 24 texels and a localized interval width of 1/16, the initial uncertainty is 1.5 texels. Four bisections reduce it to 0.09375 texels. This estimate explains why a few local refinements may be preferable to many additional uniform samples. It does not account for errors that occurred before localization and does not account for missed protrusions.

Reducing the number of samples on smooth areas requires information about the region, not just about a single point. To do this, it is proposed to build a hierarchy in which each node contains the lower and upper bounds of the depths of the child elements. Unlike the usual averaged mip-level, such a pair preserves the range of possible values. A thin protrusion does not disappear from the boundaries just because it occupies a small part of the region.

For four child nodes, the construction of the parent node is determined by the relations

$$d_{\min}^{\ell+1} = \min_{j=1,\dots,4} d_{\min,j}^{\ell}, \qquad d_{\max}^{\ell+1} = \max_{j=1,\dots,4} d_{\max,j}^{\ell}. \tag{7}$$

The boundaries should also include the values of the reconstructed map at the transitions between texels. With bilinear interpolation, the values inside a cell are limited by its corner samples, but at the edges of a node, it is necessary to take into account neighboring samples that participate in the filtering. Therefore, the construction of the hierarchy depends on the adopted sampling rule. If the range of ray depths over the entire segment of the node's passage does not intersect with its boundaries, the section is skipped. If there is a possible intersection, the child nodes are checked in the order of the ray's movement. Checking only the starting point is not enough.

The works devoted to the implementation of relief texturing on graphics processors [3] define the immediate context of the software implementation. In the proposed material organization, preparatory operations are performed during the import or loading of the resource. These include checking the depth range, forming the mip-chain, calculating conservative limits and recording scale parameters. Moving these operations from the frame construction cycle eliminates repeated work for immutable materials.

The color map and normal map are read after the intersection search is complete. If the search uses only depth, additional features do not need to be loaded at each step. A separate compact depth map reduces the data size per hit, but the benefit of this placement should be weighed against caching. Scale and format settings are stored with the material.

The choice of depth format determines the trade-off between accuracy and resource size. For uniform quantization of the normalized range per b bit, the maximum rounding error does not exceed

$$e_d \leq \frac{1}{2(2^b - 1)}. \tag{8}$$

This estimate is not an estimate of the final image error. Near a tangent intersection, a small change in depth can cause a large coordinate shift. Additional distortions occur when block compression, filtering, and rendering at lower levels of detail are applied. Therefore, the resource format should be tested on the materials with the narrowest details, not just the average profile.

For a conservative hierarchy, the quantization of the boundaries is done outwards: the lower boundary is rounded down, the upper boundary is rounded up. Conventional rounding to the nearest value can narrow the interval and create a false reason for skipping a cell. This requirement must be maintained at all levels and after format conversion. Special attention is required when re-compressing the auxiliary map during the assembly of the resource package.

The observation direction in the tangent basis, the displacement scale, and the initial coordinates are calculated once for a fragment. The only remaining steps in the loop are to update the ray parameter, sample the depth, and check the intersection condition. This separation facilitates cost analysis and reduces the number of repetitive operations. It is advisable to transfer parameters common to the material as immutable data, without restoring them from the textures in each fragment.

Early cycle termination reduces the logical number of steps of a single fragment. However, adjacent GPU threads may be executed together, and the completion of some of them does not always proportionally reduce the group time. To reduce the budget discrepancy, it is proposed to use several shader options: for short direct search, for a larger budget, and for hierarchical traversal. The option is selected before starting the processing of the corresponding group of objects.

For a fixed depth map, the preparation costs are distributed over many frames. In dynamic material, deformation, traces or procedural changes make the auxiliary structures obsolete. The topic of dynamic relief texturing is presented in [4]. For the proposed procedure, the key is the consistency of the map version with the hierarchy version used during the search. An outdated hierarchy may allow skipping an area in which a new detail has already appeared.

It is advisable to limit the update to the changed area and its ancestors in the hierarchy. If the edits are located far from each other, they should be grouped to avoid rebuilding the same node multiple times. After the update is complete, the resource is passed to the texturing pass, observing the synchronization rules. Until the auxiliary data is ready, a direct search on the current map is possible without using outdated boundaries.

The total feasibility of training can be estimated by the number of frames during which the resource remains unchanged. If the time to build the structure is equal to T_p, and the savings per frame is ΔT, the payback condition has the form

$$K\Delta T > T_p, \qquad \Delta T > 0. \tag{9}$$

The count K represents the number of times the material is reused. The estimate is a simplified one: it does not take into account computational overlap, memory contention, and changes in the visible area of the object. However, it helps to separate static resources for which pre-training is justified from materials with frequent changes. The final decision is made by measuring the full frame pass.

Optimization by the number of memory accesses does not guarantee the preservation of acceptable quality. The most noticeable defects occur during camera movement: small details appear and disappear, the edges of the recesses fluctuate, and the transition between levels of detail becomes visible. Further development of relief texturing procedures is considered in [5].

For distant surfaces, it is advisable to gradually reduce the amplitude of the parallax shift and switch to a normal map. The transition is determined by the screen size of the details. The normals must be coordinated with the reduction of the visible relief, otherwise the lighting will remain excessively contrasting. The hysteresis of the mode selection prevents frequent switching on the border of two states during small camera fluctuations.

Self-shading of terrain creates an additional search pass towards the light source. Its cost should be calculated separately from the search for the visible point. For a large number of sources, independent tracing for each of them may outweigh the gain of the main optimization. Therefore, it is advisable to relate the self-shading budget to the source's contribution to the lighting and the area of the material on the screen, keeping the same rules when comparing options.

It is advisable to separate the search costs from the final color and lighting calculations. For a direct pass, the approximate depth map access count consists of the initial read, coarse steps, and local refinements. For the hierarchical version, accesses to node boundaries are additionally taken into account. Comparing only the number of coarse steps can create a false impression of the overall gain.

With the same agreement on the initial sample, we denote the basic budget by B_0, and the optimized budget by B_1. The relative reduction in the number of requests is equal to

$$R_B = \left(1 - \frac{B_1}{B_0}\right) \cdot 100\%. \tag{10}$$

If the basic procedure uses 32 rough samples and 5 refinements, and the adaptive procedure uses 12 rough samples and the same 5 refinements, then without separately accounting for the common initial sample, the budgets are 37 and 17 applications. The reduction is approximately 54.1%. By adding one common initial sample, we get 38 and 18 applications and about 52.6%. Therefore, the calculation method must be explicitly specified.

The calculated reduction in requests does not equal acceleration: additional checks and flow divergence change the execution time. The equivalence of quality under the two budgets requires a separate check.

If the optimized procedure takes a fraction of f the original frame time and is speeded up by S_p a factor of , a simplified estimate of the overall speedup is

$$S_{\text{frame}} = \frac{1}{(1-f)+f/S_p}. \tag{11}$$

For example, for $f = 0{,}4$ and $S_p = 2$ the score is 1.25. Even a two-fold acceleration of a single pass in this case means only a 25% gain in frame time. If another stage remains the bottleneck, the actual effect may be smaller. The need for complex indicators is consistent with the approach to metric evaluation of rendering considered in [6].

The baseline and optimized procedures should be run on identical scenes, maps, camera trajectories, and lighting settings. Frame resolution, depth format, filtering rules, and number of light sources are recorded separately. After warming up the resources, the processing time on the GPU is measured, not just the duration of the commands from the CPU. Repeated runs are required to assess the spread of results.

The detailed standard is formed by a procedure with a significantly smaller step and a larger refinement budget. However, it should not be considered absolutely accurate just because of the large number of samples. For individual simple profiles, it is necessary to check the coordinates analytically. Such control cases help to identify the common error of the basic and optimized implementations. Comparing two implementations with the same error does not confirm correctness.

In addition to time, the average and maximum number of samples, the proportion of fragments with the maximum budget achieved, and the coordinate error are recorded. The lack of information about the worst cases can hide local omissions of details. For the image, it is advisable to save a difference map and mark the areas where the terrain visibility has changed. The final indicators should be associated with specific angles and material parameters.

Analytical metrics should be supplemented by expert image evaluation [7], including viewing sequences with camera movement. Acceptance criteria include a given time budget, limited error, and no omission of critical details.

In the software, it is advisable to separate the material preparation module, the mode selection procedure, the shader search and the profiling module. The preparation module checks the resources and creates auxiliary maps. The mode selection procedure uses the visible scale and material parameters. The shader calculates the intersection coordinates, and the profiling accumulates indicators for comparing configurations. This separation allows you to change the traversal procedure without rebuilding the entire material system.

For texture seams, the coincidence of depths and directions of the tangent basis is checked separately. Mismatched map edges create a relief gap that cannot be eliminated by increasing the number of search iterations.

Conclusions.

The adaptive selection of the number of samples by the length of the ray projection in texels is justified. The criterion takes into account the scale of the relief, the direction of observation and the resolution of the map. Local refinement limits the uncertainty of the coordinates after finding the intersection interval, but does not eliminate previously missed details.

Conservative depth hierarchy is suitable for skipping regions that are guaranteed not to contain an intersection on the tested segment. Its correctness depends on the map reconstruction rule, the method of quantizing the boundaries, and the timely updating of dynamic resources. Direct adaptive search should be kept as an alternative for materials where the cost of traversing the hierarchy is not remunerative. The choice between modes should be based on profiling.

Analytical examples justify the reduction of a given budget of appeals, but require verification of frame time and quality. Control scenes should contain narrow details, sliding angles and camera movement. The practical result is a consistent order of data preparation, intersection search and error control.

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