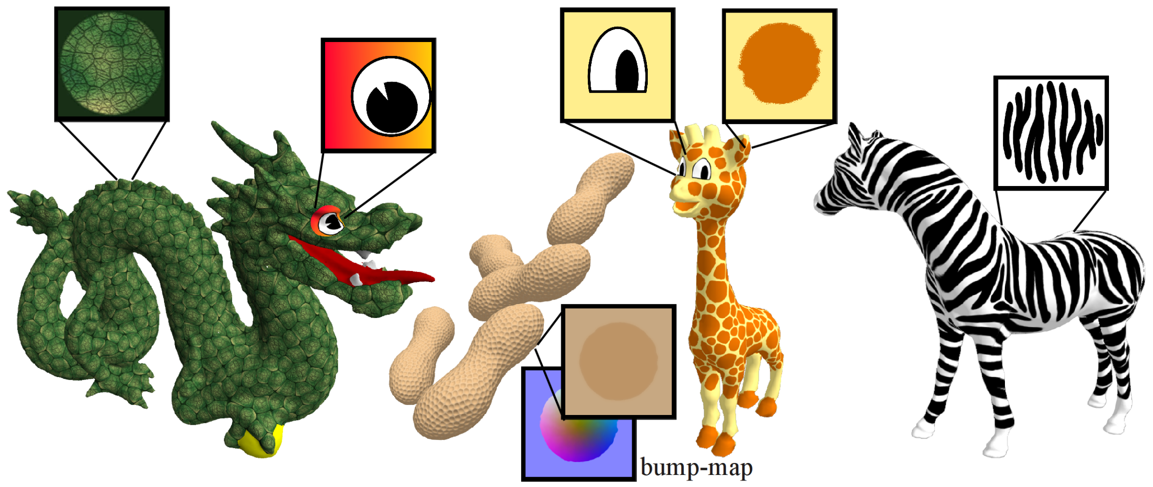
Implicit Decals: Interactive Editing of Repetitive Patterns on Surfaces

Erwin de Groot[1], Loïc Barthe[2], Brian Wyvill[3]

[1]University of Victoria (Canada), [2]IRIT, Université de Toulouse (France), [3]University of Bath (UK)



Abstract

Texture mapping is an essential component for creating 3D models and is widely used in both the game and the movie industries. Creating texture maps has always been a complex task and existing methods carefully balance flexibility with ease of use. One difficulty in using texturing is the repeated placement of individual textures over larger areas. In this paper we propose a method which uses decals to place images onto the model. Our method allows the decals to compete for space and to deform as they are being pushed by other decals. A spherical field function is used to determine the position and the size of each decal and the deformation applied to fit the decals. The decals may span multiple objects with heterogeneous representations. Our method does not require an explicit parameterization of the model. As such, varieties of patterns including repeated patterns like rocks, tiles, and scales can be mapped. We have implemented the method using the GPU where placement, size, and orientation of thousands of decals are manipulated in real time.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Computer Graphics—Three-Dimensional Graphics and Realism. Color, shading, shadowing, and texture

1. Introduction

For many computer graphics applications, such as interactive computer games and animation, the 3D objects appearance is defined by 2D textures [?, ?, ?]. Most texturing tools require the determination of an appropriate parameterization and atlas for polygonal or implicit surfaces where no natural parameterization exists [?, ?, ?, ?]. Creating such a parameterization by hand is very time consuming and automatic creation suffers restrictions or compromises the quality of the result, especially in the presence of large distortions. As a consequence, the editing and the placement of textures on arbitrary surfaces remains a tedious task requiring artists to spend much time to achieve a desired result.

While it is difficult to limit distortions in the parametrization for large textures, it becomes easier when they are composed of repetitive patterns such as dragon scales or giraffe freckles (see Teaser). Large textures are then decomposed in a set of small tiles, often called decals [**?**], that are individually positioned and mapped with a local parametrization on the surface. These small surface elements can be parametrized with very low distortions using exponential maps [**?**].

However, to be practical for the user, a very large number of decals must be positioned and displaced interactively, which is not feasible with current techniques. A second useful functionality would be the ability to define textures across multiple objects which may in addition use different representations (such as meshes, point-set-surfaces and implicit surfaces).

To this end, we propose the use of a decaling interface whose models are free of global parametrization, as suggested by Schmidt *et al.* [**?**]. However, our method for defining a local parameterization is not bound to the underlying geometry, typically meshes or parametric representations.

We use a particle system to automatically place cellular pattern elements (decals) over the surface of one or more objects. Subsequently, real-time interaction is possible to fine tune each element's deformation and placement. Fast local parametrization is obtained under the assumption that for small decals, fine distortion control is not required. The use of the Euclidean distance between a surface point and the associated decal center (i.e. the particle) is then sufficient, thus avoiding the far more expensive computation of the geodesic distance along the surface. This statement is validated by several examples illustrated in the Teaser and in Figures **??** and **??**. Very fast parametrization computation is then performed via the use of spherical field functions, centered on particles. This has also the advantage of enabling the application of field deformations and implicit composition operators in order to control the shape of decals and the way they cover the surface area. These field deformations allow the automatic adjustment of the textures when decals overlap such as the eyes of the dragon and the giraffe in the teaser, or when they compete for space as is the case for the dragon scales and the giraffe freckles. This is especially important in real-time interactive graphics applications, where decals representing pattern elements are mostly required to be similar but not identical, as shown in our examples.

The main contributions of our method are:

- The very fast computation of local parameterizations based on the Euclidean distance over a model. This local parametrization can be computed at arbitrary resolution and is independent of the underlying geometric representation.
- The technique is simple enough to implement in a pixel shader, without modifying the graphics pipeline nor limiting the use of other shaders, and it allows thousands of decals to be placed and edited interactively.
- Our decals can compete for space and deform when they interact with nearby decals.
- Surface connectivity is not required thus a decal can be placed across multiple objects or across gaps in an object without changing the object representation.

This paper is organized as follow. After presenting the related works on texturing with decals (section **??**), we explain how decals can be distributed over surfaces and their position edited (section **??**). We then present our local parametrization system with its deformations when it populates a surface (section **??**), before detailing implementation (section **??**) and discussing our results (sections **??** and **??**).

2. Previous work

A standard way of defining object appearance, or material information, is the creation of a single texture or a set of large textures. Textures are in general 2D or 3D. When 3D textures are used, the material is defined for all points in the 3D space in which the object is embedded. Each point of a surface is directly parametrized by its coordinates and while textures can be defined by repeated features, as done by Du et al. [**?**], the direct control of the texture appearance on the surface remains very difficult. We rather focus on 2D textures that are directly defined over the surface.

There are several approaches to texture design but interactive painting tools [**?**, **?**] have steered texture design interfaces. In these approaches the parameter space is either already explicit in the object representation, or is piece-wise approximated as necessary to maintain detail in the image as it is painted incrementally.

Solid procedural textures [**?**, **?**, **?**] are generated using noise functions or other texture basis functions. They can create many patterns, but it can be time consuming to find the right parameters and it is not possible to manipulate local features.

Another type of texture mapping interface is constrained parameterization [**?**], [**?**]. Here a set of constraints are manually specified between the desired texture image and the surface. Global optimization algorithms are then applied to map the image onto the surface such as to satisfy the constraints and minimize a given distortion metric [**?**]. Recent advances support point sets [**?**], and atlas generation from multiple images [**?**]. These systems do not address the general problem of texture design, as the desired 2D images are assumed to already exist.

A visually related area of work, though very different in implementation, is the field of texture synthesis. Wei and Levoy's work exemplifies this approach [**?**]. Starting from examplar textures, they synthesize a new texture over a given object by searching for the best-pixel fit in local neighborhoods. Similar techniques are presented by Turk [?], Efros and Freeman [?] and Lefebvre and Hoppe [?]. These techniques must all maintain a local or global parameterization for the object as well as the full-size generated texture, making the techniques applicable to pre-processing more than interactive editing. In fairness, these methods are expected to be used when a regular tiling of decals is inadequate to capture the desired variation in the semi-tiled textures. Turk [?] proposes a technique synthesizing a texture with repeated patterns from points regularly sampled over the surface and a reaction-diffusion mechanism. Even though no parametrization is required, this approach does not support interactive editing and it is limited in the variety of patterns it can produce.

The direct manipulation over the surface we are looking for is efficiently done using a texturing interface introduced by Pedersen [?], called a 'decaling interface', which combines aspects of both painting and constraint tools. In this approach the metaphor is that of 2D images affixed to the surface. Pedersen dubs these 'patchinos', but they are now more usually called decals. Decals are treated as independent scene elements which are constrained to lie on a surface, but may otherwise be interactively manipulated. Because a simple mapping exists between the image and the surface, 2D image processing tools can be trivially implemented. Decals are composited in real-time, mimicking 2D image compositing [?] and vector graphics interfaces. This approach allows artists to interact with surface texture directly, using familiar 2D methods and tools. One of the biggest benefits of decaling is that it allows for easy re-use of 2D images in texture design. When combined with a digital camera or image database, realistic textures can be created very quickly. Constrained parameterization can also be used to apply decals, however the human interface of [?] is difficult to implement because of the problem of simultaneously moving all of the constraints across the surface.

An interactive decaling system based on hardware-accelerated octree textures is described in [?]. Basic interactive positioning and blending composition is supported. Like 3D painting, decals are applied using planar projection. In this method image sprites can be combined to produce blended sprites (decals). In our work we use the implicit field to apply more complex operations such as deforming decals so that, for example, a snake's scales are not uniform but compete for space. Similarly, Autodesk Alias products also supports application of decals using planar projection, as well as conformal decals that rely on the surface geometry [?].

Schmidt *et al.* [?] build on the decaling idea and address many of the problems of Pedersen's interface. In this work a local exponential map parameterization is generated from a single point and geodesic radius, that serves to simplify the user interface and support automatic creation of decals. The system can be applied to any point set, and provides a nice tool for texturing animated implicit surfaces. It can preserve texturing even in the presence of topological changes. Our 'implicit decal' approach described here is similar in spirit but instead of deriving the local parameterization from an exponential map that is based on the geometry of the surface, we introduce an implicit support surface. This gives us most of the properties of Schmidt's system plus the advantages listed above.

Tiletrees [?] solve the problem of texturing onto arbitrary surfaces but the octree must be regenerated if there is a small change in the model. In our system if a small change is made to the model, decals can be projected back onto the surface and may change position but the general appearance of the decal will not change.

3. Decal placement

Decal placement consists of positioning particles over the surface whose center point will serve as center for the field functions $f_i : \mathbb{R}^3 \to [0,1]$ from which a local parametrization is derived for the decal. Two strategies can be used: manual or automatic placement. Manual placement of particles is done by selecting positions on the surface of the model (see left image of Figure ??). Even though this an easy task, it takes a long time to texture complex surfaces or surfaces that require a large number of decals. A tool to automatically texture the whole surface greatly reduces the modeling time. With our texturing method such tools are easily created. All our method needs for input is a list of particles (position, size and orientation). In our system this input is generated by scattering particles [?] onto the surface of the model and have them repel each other. The radius s_i of each particle is calculated by taking the maximum distance to neighboring particles in the local Delaunay triangulation. These local triangulations can be simply computed from the local Voronoi regions surrounding the particle centers [?, ?]. The orientation, i.e. local 2D frame $(u_i, v_i) \in [0,1]^2$ tangent to the surface and of origin the particle center p_i, is either random or aligned to some surface field such as minimum or maximum curvature direction fields [?, ?] or as done by Turk [?].

Fleischer *et al.*'s Cellular Texture Generation work [?] offers a method to generate seed locations for our particles, evolving a system of partial differential equations to generate seed points and surface-based field values on object surfaces. We implemented a simplified version of this work, and instead of placing a geometric primitive at each particle, we place one of our decals.

The right image of Figure ?? shows 1000 decals distributed over the surface of a model using a particle system. It should be noted that the user can interactively edit the decals after the initial placement.

We use a particle system because it has the double advantage of being both easy to implement and flexible for integrating

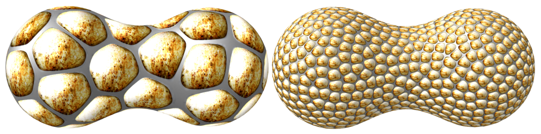


Figure 1: *Left:50 decals positioned manually in under a minute. Right:1000 decals positioned using a particle system.*

decal editing operations. For example, after automatically positioning decals on a model, the user can interactively edit a group of decals while the particle system repositions surrounding decals. For instance, particle position, orientation and radius can be directly modified and the system automatically and interactively adjusts the position of surrounding particles. That way, textures can be translated over the surface, rotated and scaled. Instead of a particle system, remeshing algorithms [?] could be used to generate a coarse mesh. The positions of the vertices of this mesh would be the positions of the particles.

Once particles cover the surface, they are likely to overlap and in that case, a strategy has to be chosen in order to define how the textures coming from each overlapping decal are combined. Different solutions can be adopted. One decal can be dominant and only its texture is applied, resulting in an overlapping feature (as the eye of the dragon in the teaser). Textures can be blended (blurred) as presented by Schmidt et al. [?]. A new behavior, presented in the following sections, is deformation in contact, which replaces overlapping texture by texture deformations so that they are in contact but do not overlap. This generates useful results as those illustrated in the teaser and in Figure **??**.

4. Local parametrization

Once particles are distributed over the surface, we have as input their center p_i, radius s_i and local frame (u_i, v_i) illustrated in Figure **??** and computed as explained in Section **??**. Particles center p_i and radius s_i are used to compute an isotropic spherical field functions $f_i : \mathbb{R}^3 \to [0,1]$ which together with the local frame (u_i, v_i) allows us to derive the local parametrization (section **??**). Deformations produced by contact between neighboring decals are presented in section **??** and the way field functions can be modified to produce parametrization adapted to decals of different shapes is explained in section **??**.

4.1. Isotropic parametrization

We define isotropic spherical field functions f_i, of minimal value 0 at radius distance s_i, and maximal value 1 at their center p_i, as illustrated in Figure **??**. Field functions f_i evaluated at a point $q \in \mathbb{R}^3$ are mapped to $[0,1]$ by scaling the Euclidean distance between q and p_i and then composing

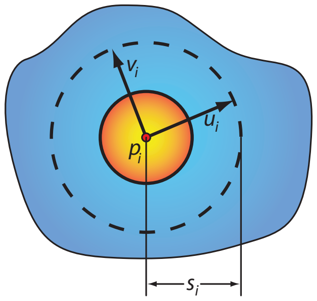


Figure 2: *Spherical field function f_i placed on the surface of a model. p_i is its center, s_i its radius, and u_i and v_i are the tangent vectors defining its orientation.*

this scaled distance by a so called Filter Fall off Function (*FFF*) [?] $g : \mathbb{R} \to \mathbb{R}$ whose graph is given in Figure **??**:

$$f_i(q) = g\left(\frac{\|q - p_i\|}{s_i}\right), \tag{1}$$

with

$$g(d) = \begin{cases} (1-d^2)^3 & \text{if } d \le 1 \\ 0 & \text{if } d > 1 \end{cases} . \tag{2}$$

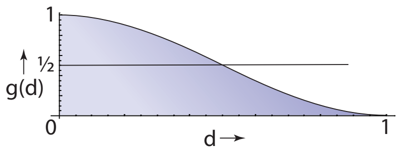


Figure 3: *The filter fall off function g*

As our particle system tends to organize particle centers over the surface in a close to triangularly regular manner (i.e. each particle tends to have six regularly distributed neighbors), only the part of the field with values equal or higher than $\frac{1}{2}$ (orange area in Figure **??**) generates texture coordinates, as the outer area (blue area in Figure **??**) overlaps with other spherical field functions in this initial setting. The dashed line in Figure **??** indicates the boundary of the field around the particle center and this part will only be used to calculate the amount of deformation of nearby decals (see section **??**). Note that different *FFF* g function (possibly with a different parametrization boundaries) could be used to achieve slightly different deformation effects, but we use the *FFF* from equation **??** for its high smoothness and its suitability for contact deformations (see section **??**).

From field function f_i and the local frame (u_i, v_i) we derive the local texture coordinates as a polar 2D coordinate system $(r(q), \theta(q))$ as follows. To calculate the radius $r(q)$ at a surface point q, we first evaluate the field value $f_i(q)$ to which we apply the inverse of g. We then scale it by $g^{-1}(1/2)$ to get the radius $r(q) \in [0,1]$:

$$r(q) = \frac{g^{-1}(F(q))}{g^{-1}\left(\frac{1}{2}\right)}, \tag{3}$$

where $F = f_i$ if only a single field function covers the point q. We use equation **??** instead of the simpler scaled distance $r(q) = \frac{\|q-p_i\|}{s_i}$ in order to support the different definition of F presented in Section **??** where decals are deformed when they are in contact as illustrated in Figure **??**.

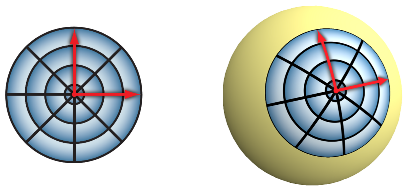


Figure 4: *Illustration of the local parametrization (left) on a plane and (right) on a sphere.*

The computation of the second texture coordinate $\theta(q)$ is performed using the two perpendicular vectors u_i and v_i of our local frame. If q^* is the projection of q onto the plane formed by u_i and v_i, the value of $\theta(q)$ is the angle between u_i and the vector $(q^* - p_i)$:

$$\theta(q) = \arctan\left(\frac{v_i \cdot (q-p_i)}{u_i \cdot (q-p_i)}\right). \tag{4}$$

Figure **??** shows an example of a our local parametrization on a plane and on a sphere. The vectors u_i and v_i are calculated from the surface normal at p_i (using cross product) and a user defined orientation angle.

4.2. Contact deformations

When decals are in collision, overlapping is avoided and contact decal deformations are performed as illustrated in Figure **??**. As our local parametrization is directly derived from field functions $f_i : \mathbb{R}^3 \to [0,1]$, they support the set operators produced for combining implicit surfaces defined by compactly supported field functions [?].

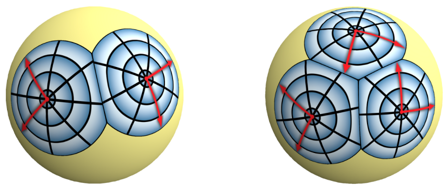


Figure 5: *A decal (left) placed on a sphere once, twice and three times*

We need a deformation modeling contact between n field functions, avoiding gaps and discontinuities while maintaining r in $[0,1]$ with $r(q) = 1$ for all surface point q in the deformed field function boundary (see Figure **??**). Following the procedure suggested by Cani [?], we compute a field function F as a deformation of the function f_k having the highest field value at a point q:

$$F(q) = \frac{1}{2} + \left(f_k(q) - \frac{1}{2}\right)\prod_{j\neq k} h\left(f_j(q), f_k(q)\right), \tag{5}$$

where

$$h(s,t) = \begin{cases} 1 - \left(\frac{s+t-1}{2s-1}\right)^{\frac{1}{1-t}} & \text{if } s+t \geq 1 \\ 1 & \text{if } s+t < 1 \end{cases}.$$

In this formulation, when a point q only lies in the field of one field function, the product part of equation **??** yields 1 and the whole equation equals f_i. When other field functions overlap in q, equation **??** adapts $f_i(q)$ to make the decal touch but not overlap the nearby decals. This behavior is obtained when function F reproduces the graph presented in Figure **??**, illustrating the combination of two field functions (including contact). This graph has been constructed following the properties and the procedures presented by Barthe et al. [?], Bernhardt et al. [?] and Gourmel et al. [?]. Even though several equations matching this graph could be proposed, our formulation has the advantage of being both n-ary, i.e. it is able to combine any number of decals at once, and efficient to compute.

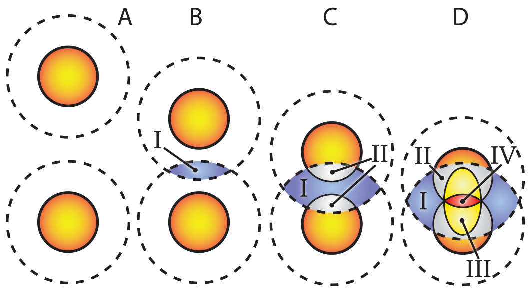


Figure 6: *4 possible situations when using only 2 decals*

Equation **??** can be understood by looking at the interactions between two field functions, f_0 and f_1, illustrated in Figure **??**. Four situations are to be considered. In situation A, the fields are not overlapping each other and no deformation is needed. In situation B and C, the fields are overlapping but the parametrized areas are not, so again, no deformation is needed. Only in situation D where the parametrized areas overlap, is deformation required.

The different areas numbered from I to IV in which the final function F is computed with a specific expected result are illustrated in Figure **??**. In this figure, the values of function f_1 are taken as abscissa and those of function f_0 as ordinate. On the upper-left part of the diagonal line $f_0 = f_1$, the field

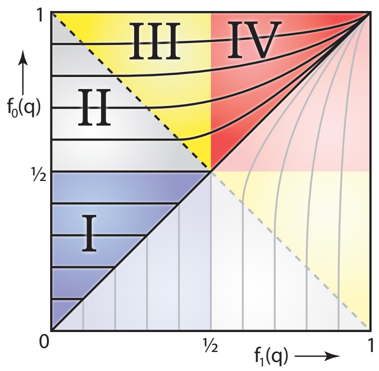


Figure 7: *Graph of our function F when two field functions are involved. Field functions f_1 and f_0 give the values for respectively the abscissa and the ordinate.*

function with the highest value is f_0 and F is the result of the deformation of f_0 while in the lower-right part of this line, the highest value is the one of f_1 and F is the result of its deformation. As we expect the same deformation behavior on both decals, the one parametrized from f_0 and the one parametrized from f_1, these two parts are symmetric and we propose to only focus on the upper-left part. The black lines in Figure **??** are the iso-lines of the resulting decal for $F = \frac{1}{10}$, $F = \frac{2}{10}$, etc. Where these iso-lines are horizontal, it means that they reproduce the values of f_0, $F = f_0$ and no deformation is performed. Otherwise, they represent the way the iso-values of f_0 are deformed by F, i.e. the way the decal is deformed. The contact is where $f_0 = f_1$ and we see in red area of Figure **??** how the function F deforms the iso-curves at its vicinity. We refer to the implicit extrusion fields [**?**] for a detailed explanation of how to link the graph of the composition operator (here function F) with the deformed objects (here the decals).

In other words, no deformation is to be performed in situations A, B and C (Figure **??**), which is guaranteed as in areas I and II, $F = f_0$. In fact, deformation must hold in areas that only exist in situation D, which correspond to areas III and IV. These areas are where contact and field deformations are thus to be performed. Formally, they correspond to field values where $f_0(q) + f_1(q) > 1$. In area IV, contact deformations at parametrization boundaries are performed by ensuring that if $f_0 = f_1$, then $F = \frac{1}{2}$. The rest of area IV and area III are used to build a function F performing smooth field deformations between the contact at boundaries and areas I and II where no deformation are required.

The resulting deformation in contact performed on our parametrization when this definition of F is used in equation **??** is illustrated with two and three field functions in Figure **??**.

4.3. Anisotropic parametrization

Non-circular decals are easily supported by slightly adapting the technique presented in [**?**]. In the computation of the field function in equation **??**, rather than scaling the Euclidean distance between a point q and the particle center p_i with a constant radius s_i, this distance is scaled by the distance between p_i and the point $b_i(q)$ of intersection of a ray launched from p_i and the decal boundary (see Figure **??**-left). This scaling is done so that for all point q lying on the decal boundary, $f_i(q) = \frac{1}{2}$.

$$f_i(q) = g\left(\frac{\|q-p_i\|}{b_i(q)}\right) g^{-1}\left(\frac{1}{2}\right). \tag{6}$$

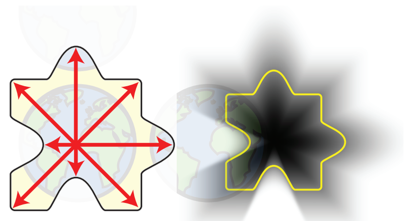


Figure 8: *Storing the field function f_i in a 2D texture for the puzzle piece decal. Left: computing b_i. Right: the field values in the texture (the yellow line marks the $\frac{1}{2}$ contour).*

In this case, function f_i can be directly precomputed and stored in a 2D texture (Figure **??**-right) or computed from an analytical function $b_i : \mathbb{R}^2 \to \mathbb{R}^+$ giving the radial distance between the decal center and its boundary for all point q.

The puzzle piece used in Figure **??** is mapped on the bunny in Figure **??** along with some other non-circular decals.

5. Implementation

Implicit decals require texture mapping on a per-pixel basis which can be done in pixel shaders. The definition of decals by 3D field functions allows a computation of the pixel color using only its 3D coordinates as input (as for 3D textures). The requirement for an efficient evaluation is the fast access to decals enclosing the pixel. Once this is done, contact deformation, overlapping or any invertible transformation can be applied to derive the texture coordinates and compute the final material information. In our system the pixel shader of the GPU is used, because it can achieve interactive frame rates. To render a number of implicit decals on the surface of a model, the decal information (position, size and tangent vectors) is loaded into the graphics card memory. The pixel shader program queries the decal information to calculate texture coordinates. To increase performance and allow a large number of decals to be rendered, we implemented an octree structure similar to the one described in [**?**]. An octree data structure as described in [**?**] could also be used.

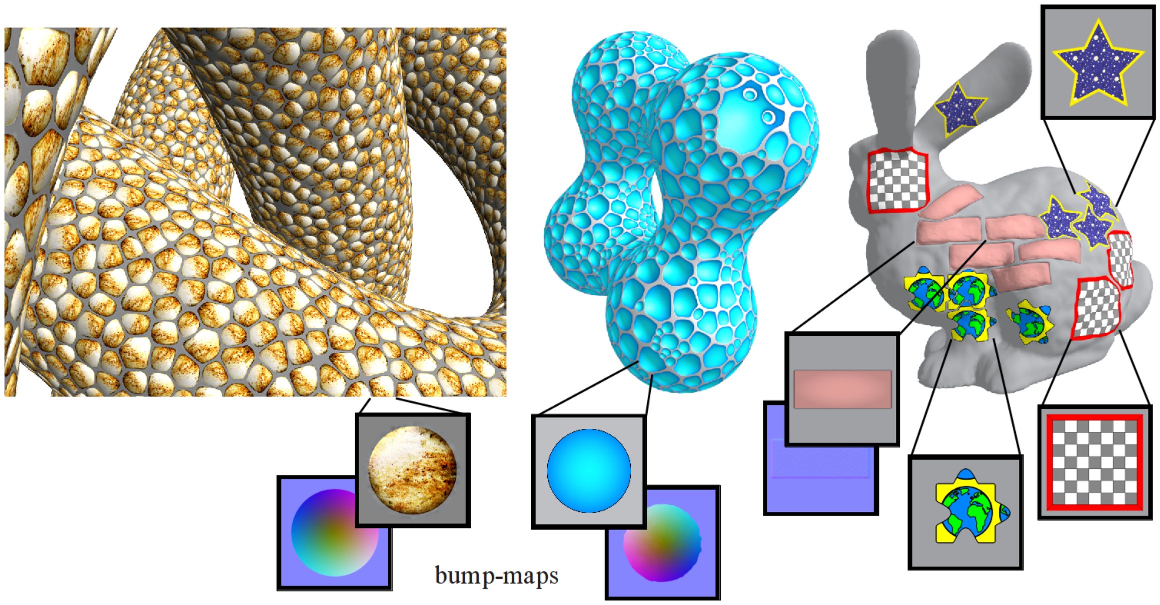


Figure 9: *3 models textured using Implicit Decals: the knot, implicit spheres, and the bunny*

Before the decals are loaded into the GPU memory, an octree is constructed containing the decals. Each non empty voxel contains either 8 references to other voxels or a maximum of 8 references to decals that intersect with the voxel. A voxel is subdivided when it overlaps with more than 8 decals. The list of voxels is loaded into GPU memory together with the list of decals. Our implementation of the pixel shader contains an octree lookup function which typically uses between 4 and 10 repetitions to traverse the octree and retrieve the needed voxel from the octree. With this implementation the pixel shader performs a maximum of 10 octree lookup repetitions and includes a maximum of 8 decals in the calculation of the final texture coordinates. Without an octree, all decals would have to be included in the calculation of the final texture coordinates This would greatly increase computation times and at present would limit the maximum number of decals to approximately 20 (in a single pass) due to GPU limitations.

Decals can be removed from the octree by removing them from the decal list in the GPU memory. Adding and moving decals however, would normally require a new construction of the octree. To prevent rebuilding the octree while the user is editing a small set of decals, the pixel shader implementation allows for a small number of decals to be added in addition to the ones in the octree. These decals will always be included in the calculation of the final texture coordinates. Rebuilding the octree will only be necessary when the user starts editing (adding, removing, moving) a different set of decals. After the rebuild (which usually is nearly instant, but can take up to a second when thousands of decals are used), editing operations can be performed interactively.

6. Filtering

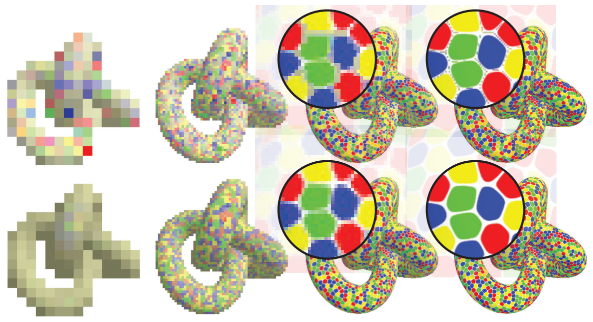


Figure 10: *Filtering at different resolutions. Top row: standard Mipmaps and anisotropic filtering. Bottom row: adapted Mipmaps and anisotropic filtering.*

In general, existing techniques like trilinear or anisotropic filtering with Mipmapping can be used. However, problems can occur on the borders of the decals. Some of these problems can be avoided by using a uniform color for the borders of the decal texture images. This creates a smooth transition between touching decals. When the decals do not cover the whole surface, the border color can be chosen to be transparent to create a smooth transition with the surface color. Still some problems remain as can be seen in the top row of Figure **??**:

1. When the decals cover no more than a few pixels (first two columns of Figure **??**) standard Mipmap generation produces incorrect colors. This is caused by the use of

low resolution Mipmaps which contain color information from all pixels in the texture and not just the pixels used for the decal.

2. When the decal sizes approach pixel level (first column of Figure **??**), the decal colors do not necessary converge towards the same solid color when different texture images are used. This can result in seemingly random pixel colors and flickering of the pixels in animation.
3. There are artifacts in between the decals (last two columns of Figure **??**). In the situation where two filtering samples cover different decals, the sample texture coordinates are close to the edge of the circular texture image (see Figure **??**). The texture coordinates should result in the same color (because the edge of each decal has a uniform color) even though the texture coordinates are very different. With standard graphics hardware the difference between the texture coordinates will result in the use of a very low resolution Mipmap giving in the wrong color.

The first problem can simply be solved by using a filter to create the Mipmaps which determines which pixels should be used. To solve the second problem, the low resolution Mipmaps need to be adjusted so that they converge towards the same color. To do this, for each resolution a new image is constructed (the target image) which is the average of all Mipmaps of that resolution. If some textures are used more than others, a weighted average can be used. Next, new Mipmaps are created which are weighted blends between the respective old Mipmap and the target image. The lower the resolution of the Mipmap, the more the weights will shift towards the target image. At the lowest resolution (1×1 pixels) all Mipmaps will contain the same color which is the (weighted) average of all textures.

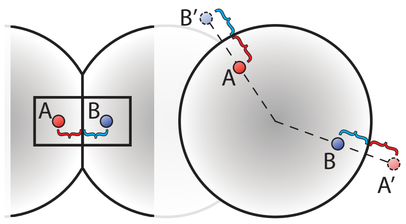


Figure 11: *Correcting sampling across decals. Left: model space. Right: texture space.*

The third problem can be solved in two steps. First, the pixel shader detects whether two filtering samples lie in different decals. This is be done by comparing the positions of the decals used in each sample. Figure **??** depicts the situation when these positions are different. In texture space the texture coordinates A of one sample and the texture coordinates B of the other lie farther apart than what one would expect looking at the positions in model space. This causes the filtering technique to select a Mipmap with the wrong resolution. Instead of using the distance between A and B in texture space to determine the pixel resolution and select the appropriate Mipmap, the distance between A and B' is used. As can be seen in the right image of Figure **??** B' lies on the other side of the decal edge from A at the same distance from the edge as B (this distance is indicated by the blue curly bracket). The distance between A and B' in texture space is a far better representation of the actual distance between A and B in model space.

The combined solutions for the 3 problems above result in the images shown in the bottom row of Figure **??**.

7. Results

Figure **??** shows how our decals handle sharp edges, holes in the geometry and bumps on the surface. Figure **??** shows how a single implicit decal can texture more than one surface at the same time. This can be useful in games, where stains or gunshot holes need to be applied in real time.

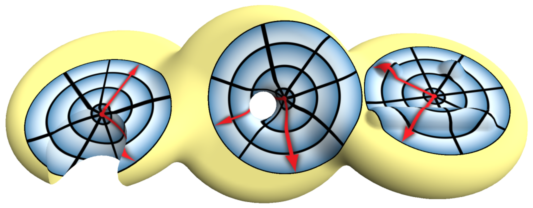


Figure 12: *Our decals are stable when placed on sharp edges, holes in the geometry or bumps (and other areas of high curvature)*

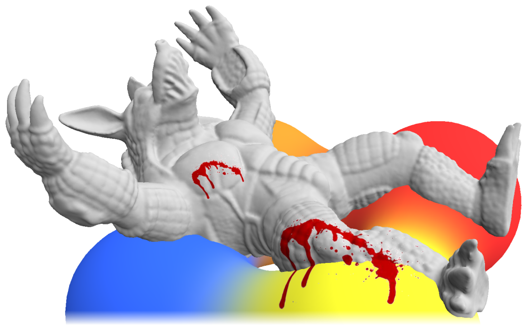


Figure 13: *Each blood stain is a decal which can cover different models*

The dragon model shown on the Teaser-left has been textured using our method. The green scales were automatically placed using a particle system. The user manually added the (non-deforming) eye decals, and gave the decals on the ball, the tongue, and the teeth a solid color. Some decals were slightly moved to fit the boundaries of the colored parts of the model (ball, teeth and tongue). The whole texturing process took about 15 minutes.

The left image of Figure **??** shows a closeup of the knot model. This image shows that our method supports high resolution textures: the texture resolution of the decals in the front is the same as the resolution of the decals in the back.

The middle image of Figure **??** shows the interaction of decals with different sizes and even shows the special case of Figure **??**D where a decal is placed completely inside a larger decal. The right image demonstrates several non-circular decals.

Model	Decals	Voxels	Octree	ms/ frm	Mem
Dragon	100	697	0.02s	25	12KB
Dragon	1K	5753	0.06s	30	116KB
Dragon	10K	58905	0.78s	32	1.14MB
Knot	100	897	0.02s	25	14KB
Knot	1K	8657	0.09s	25	127KB
Knot	10K	56217	0.80s	26	1.13MB
Horse	100	48121	0.02s	25	197KB
Horse	1K	130833	1.23s	25	605KB
Horse	10K	261561	2.58s	26	1.91MB
Spheres	100	921	0.02s	25	13KB
Spheres	1K	7393	0.16s	26	123KB
Spheres	10K	69889	1.28s	26	1.18MB

Table 1: *Rendering times and memory consumption of our method. The "Voxels" column shows the number of voxels that was needed to construct a suitable octree. The "Octree" column shows the amount of time needed to construct the octree on the CPU. The "ms/frame" column shows the rendering time of one frame in milliseconds and the "Mem" column indicates the amount of video memory allocated for storing the decals and the octree (this does not include the texture images).*

All results were obtained using a machine with an Intel® Core^{TM}2 Quad CPU at 2.66GHz and a GeForce 8800 Ultra graphics card. The resolution of the output window was 1600x1200 pixels. The CPU part of our implementation (constructing the octree) only uses one thread.

The results in table **??** show that our method supports interactive visualization and editing as the frame rates are between 30 and 40 frames per second even for more complex models with thousands of decals at a high window resolution. Note that these frame rates apply to our test cases where the model covers a large part of the screen. In practice Implicit Decals would only be used on some parts of the whole scene which would result in higher frame rates. Editing large groups of decals is still possible, but then the octree construction time becomes the bottleneck. To reduce the octree construction time in future implementations, a multi threaded algorithm could be implemented.

8. Discussion

Since the decal is mapped using a 3D field function, any part of the surface intersecting this field function where it is greater than $\frac{1}{2}$ is textured. This is the desired effect when the whole surface is textured as our field function contact deformations guarantee the local influence of each decal. This naturally avoids the case shown in Figure **??**-middle where a decal "bleed" through a thin part of the model. This situation can only happen if some parts of the surface are not textured and it is thus easily avoided by using an "empty" decal defined by transparent texture images. This user interaction can also be avoided by using thinner ellipsoid field functions f_i.

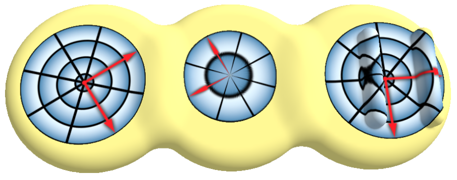


Figure 14: *Left: a decal placed on the front. Middle: undesired texturing produced by a decal placed on the back side which bleeds through to the front. Right: A decal folding over itself due to large extrusions.*

In general our parametrization behaves well when placed on bumps, ripples or other high curvature features. But in areas with large distortions, some parts of the texture image could be mapped onto the surface more than once which results in the texture folding over itself (see Figure **??**-right). This problem is actually inherent to our parametrization as no specific treatment is done to minimize distortions. The natural solution is to use more smaller decals in these areas but if this is not desired, the field function f_i will have to be computed from a more sophisticated procedure taking into account the local surface distortions.

Our technique is mainly prescribed for a lot of small decals, that are interactively placed and manipulated over the surface. When decals become large, depending on the pattern to be repeated and on the nature of the object itself, it is more likely that undesired distortions appear. In this case, implicit decals may fail to provide a satisfactory result and it would be better to use a more elaborate technique such as the decals proposed by Schmidt et al. [**?**].

It is also difficult to maintain a consistent surface covering if it is animated. Decals may change of shape and gaps may appear. The texturing of dynamic objects with implicit decals remains an open problem.

Current graphics hardware still limits the number of decals that can be edited simultaneously to approximately 20. When small groups of decals are being edited, they will be removed from the octree and added to the list of editable decals. The octree needs to be recomputed whenever the number of decals in this list exceeds the hardware limit. When ten thousands of decals are used, this can result in an occasional delay of approximately one second (see table **??**). Editing operations that involve large groups of decals, always require the octree to be rebuild and will be significantly slower.

9. Conclusion and Future Work

The main contribution of this research is an efficient method for placing and editing surface decals that can interact with one another. The surface does not require an existing parameterization. Since the method lends itself to implementation on the GPU, thousands of decals can be placed and edited. Traditional techniques would require excessively large textures to achieve a reasonable resolution, making these techniques infeasible for real-time applications.

An earlier decaling method [**?**] uses an arc length approximation (exponential map) to find a local parameterization on the surface, whereas our method uses an implicit field that is independent of the geometry. Our mplicit technique has several advantages demonstrated in section **??**:

- Implicit decals are independent of the underlying geometry making them applicable to multi-resolution meshes.
- The bulk of the computations can be done in the pixel shader making interactive editing of thousands of decals possible.
- Contact deformation can be used to make the decals appear to compete for space.
- An implicit decal can be made to span several objects without duplicating the decal or merging the objects.

Our method is similar to Cellular Texture Generation [**?**], in which a geometric primitive is placed at each particle, whereas we place a texture primitive instead. In this way many similar effects can be achieved, but at low-cost in a pixel shader. As future work, we could couple our implicit decals with a GPU-shader based displacement map method, to allow for a large set of Fleischer *et al.*'s images to be generated in hardware.

Section **??** shows how contact deformation can be used to shape the decals. Future work includes investigating how other implicit operations like blending can be used to achieve different effects. Also, different distance metrics like manhattan or anisotropic distance could be used to produce a wider variety of results.

A larger number of patterns could also be generated by creating two or more layers of decals. The final pattern is created by combining the layers, for example by using transparency to uncover deeper layers or some other function which combines the colors of each layer. Future work can also include designing functions to combine layers; how should layers be positioned in relation to each other to create interesting patterns.

To incorporate implicit decals more easily into existing modeling systems, a conversion between an implicit decal texture and more conventional textures can be written. When an atlas is in place, the model space positions of each texel of the atlas can simply be evaluated to get the corresponding colors. Future research can be done to create converters for other texture systems and incorporate better filtering.

Other future work includes better tools for decal positioning and editing. If a Poisson-disk sampling method [**?**] could be adapted to curved closed surfaces of any topology, this would significantly reduce the computation time of an initial decal distribution. Also, the system would greatly benefit from editing tools like a decal spray paint tool and brush tools that change the size or orientation of the decals. Automatic determination of the orientation of the decals could be done by using the gradient field or other properties of the model. Finally, decals with different behaviors could be added. For example decals which deform other decals, but do not deform themselves.

Acknowledgments

This work has been partially funded by the IM&M project (ANR-11-JS02-007).