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# Fragment-based Surface Inpainting

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**Abstract**

*Inpainting is a well-known technique in the context of image and art restoration, where paint losses are filled up to the level of the surrounding paint and then coloured to match. Analogue tasks can be found in 3D geometry processing, as digital representations of real-world objects often contain holes, due to hindrances during data acquisition or as a consequence of interactive modelling operations. We present a novel approach to automatically fill-in holes in structured surfaces where smooth hole filling is not sufficient. Previous approaches inspired by texture synthesis algorithms require specific spatial structures to identify holes and possible candidate fragments to be copied to defective regions. Consequently, the results depend heavily on the choice and location of these auxiliary structures, such that for instance symmetries are not reconstructed faithfully. In contrast, our approach is based on local neighbourhoods and therefore insensitive with respect to similarity transformations. We use so-called guidance surfaces to guide and prioritise the atomic filling operations, such that even non-trivial and larger holes can be filled consistently. The guidance surfaces are automatically computed and iteratively updated during the filling process, but can also incorporate any additional information about the surface, if available.*

## 1. Introduction

The goal of our algorithm is to fill holes in point set surfaces *plausibly*, i.e. we want to restore or extrapolate the (unknown, yet assumed) basic and detail geometry. Inspired by successful 2D texture synthesis and disocclusion techniques, our approach is based on the observation, that real-life objects often exhibit a high degree of coherence in the sense that for missing parts one can find similar regions on the object. As a consequence, our surface inpainting method analyses the neighbourhood of a hole, and identifies and copies into the hole region appropriate local neighbourhood patches represented in local frames (the 3D analogue to what is called a *fragment* in image processing). By finding best matches hierarchically on several scales, the hole is filled in conformance with the context with respect to all considered scales.

## 2. Surface Fragments

Suppose we are given a point set $\mathcal{P} = \{\mathbf{p}_1, \ldots, \mathbf{p}_n\} \subset \mathbb{R}^3$. Following the notion from 2D-image synthesis, we define for every point $\mathbf{p} \in \mathcal{P}$ and a radius $\rho$ a corresponding *surface fragment* $\mathcal{N}_\rho(\mathbf{p}) \subset \mathcal{P}$ as $\mathcal{N}_\rho(\mathbf{p}) = \{\, \mathbf{p}_i \in \mathcal{P} \mid d(\mathbf{p}, \mathbf{p}_i)) \leq \rho \,\}$, where $d(\mathbf{p}, \mathbf{p}_i)$ is the distance between $\mathbf{p}$ and $\mathbf{p}_i$, evaluated using the point set's proximity graph, as recently suggested in [KZ04]. In our hierarchical multi-scale approach, the fragment size $\rho$ is naturally determined by the kernel size of the filtering operation used to construct the point set hierarchy. Therefore, (in the spirit of [BDW*04]) the surface fragments are the scale-equipped atoms of our filling operation.

In order to be able to measure the alikeness of surface fragments, we define a 2-Layer-Descriptor as illustrated in fig. 3.

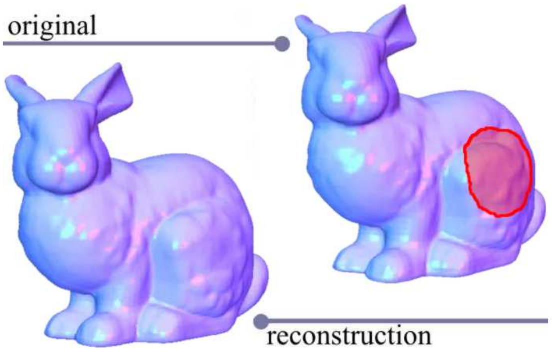

**Figure 1:** *Reconstruction of the Stanford Bunny. The hole (indicated in red on the right) is filled hierarchically, leading to the visually plausible reconstruction (left).*

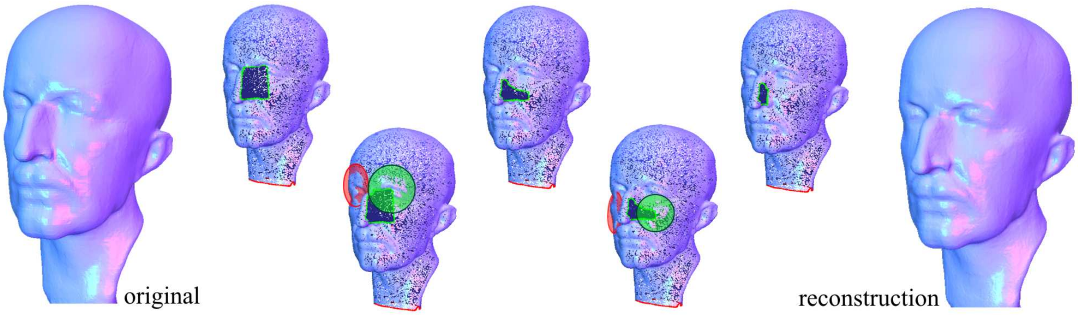

**Figure 2:** *The eye region is reconstructed by successive copying best matching candidates to target regions.*

## 3. Hierarchical Inpainting

Geometric properties of the hole region might be represented in different scales, and in many cases similarity relations present in different scales correspond to very different regions on the object. To exploit coherence and similarity between the region of interest and appropriate candidate regions, it is therefore important to allow candidates to stem from the optimal object region *per scale*, such that for instance the bunny's missing left knee (see fig. 1) is reconstructed on coarse levels by copying the bunny's right knee, whereas for the fur structure, exhibiting different similarity relations, various other locations are used as source. Consequently, the first step of our algorithm is to construct a scale space approximation of the input data by Laplacian smoothing and (optionally) subsampling. With this point set hierarchy our algorithm reads in pseudo-code:

```
Fill (Point Set Hierarchy $\mathcal{P}^H,\dots,\mathcal{P}^0$)
compute initial guidance surface $\mathcal{G}^H$
for all $h = H,\dots,0$ do
    $\mathcal{B}^h \leftarrow$ find boundary points in $\mathcal{P}^h$
    $\mathcal{C}^h \leftarrow$ find candidate points in $\mathcal{P}^h$
    compute descriptors $\chi(\mathcal{C}^h)$ and $\chi(\mathcal{B}^h)$ using $\mathcal{G}^h$
    $\mathcal{Q} \leftarrow$ prioritise $\mathcal{B}^h$
    while $\mathcal{Q}$ not empty do
        $b \leftarrow$ top($\mathcal{Q}$)
        find best matching candidate $c \in \mathcal{C}^h$
        copy $\mathcal{N}(c)$ to $\mathcal{N}(b)$
        update $\mathcal{B}^h$ and $\mathcal{Q}$
    end while
    $\mathcal{G}^{h-1} \leftarrow$ MLS($\mathcal{P}^h$)
end for
```

The multiscale aspect is incorporated into our algorithm by reconstructing the surface in the hole region on coarse scales first. Hole filling on finer scales then exploits the results on finer scales in form of guidance surfaces by evaluating them in the coarser level of the two-layer descriptor (fig. 3).

## 4. Ordering of the Filling Operations

Following ideas from [CPT03], we prioritise the atomic filling operations to propagate also highly irregular surface structures into the hole region. To this end, we order the atomic filling operations such that on the one hand the most expressive and discriminative and on the other hand the most confident target fragments are processed first.

## 5. Results

We applied our fragment-based inpainting algorithm to various data sets exhibiting holes in structured surface regions and are in addition to this comparably large in size. Traditional smooth hole filling algorithms would have lead to disturbing visual artifacts in these cases. In fig. 2, the basic workflow of our algorithm can be seen. For target fragments (illustrated as green disc) an optimal candidate fragment (red disc) is identified. The points corresponding to invalid target regions are pasted into the point set after the according transformations (translation, rotation, optional mirroring), which are deduced from the descriptor comparisons, are applied.

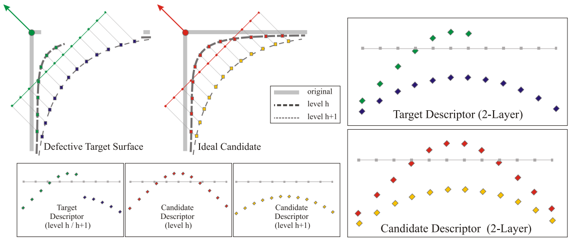

**Figure 3:** *Defective target surface and an ideal candidate (bold), together with two levels from the scale space representation (dashed, level h+1 filled, level h incomplete). Completing invalid descriptors (on level h) using $\mathcal{G}^{h+1}$ leads to a descriptor (bottom left) that is not well comparable with either of the candidate descriptors (bottom centre). We therefore use the 2-Layer-Descriptor depicted to the right.*

## References

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