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# Unsharp masking geometry improves 3D prints

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ABSTRACT

Mass market digital manufacturing devices are severely limited in accuracy and material, resulting in a significant gap between the appearance of the virtual and the real shape. In imaging as well as rendering of shapes, it is common to enhance features so that they are more apparent. We provide an approach for feature enhancement that directly operates on the geometry of a given shape, with particular focus on improving the visual appearance for 3D printing. The technique is based on unsharp masking, modified to handle arbitrary free-form geometry in a stable, efficient way, without causing large scale deformation. On a series of manufactured shapes we show how features are lost as size of the object decreases, and how our technique can compensate for this. We evaluate this effect in a human subject experiment and find significant preference for modified geometry.

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## 1. Introduction

With the recent proliferation of 3D printers, creating physical artifacts of free-form geometry has become much more common. Unfortunately, the manufactured artifact often looks different from a rendering – the most prominent effect is that the artifact seems to lack detail. This is likely due to several reasons: on one hand, manufacturing technology and materials are limited, and the artifact might simply miss fine features or subsurface scattering makes them less noticeable; on the other hand, renderings are usually not produced at the real size of an object, and the perception of an object changes with its size – smaller features require more contrast for the same effect.

This situation has a lot in common with intensity and contrast reproduction for images: the contrast of real-world images is much higher than that of printed images. Tone mapping operators are used to preserve features in the image while globally reducing the contrast so that it fits the output medium. Note that the tone-mapping operators, while motivated by human perception and technical properties of media, are neither accurately modeling human perception nor the printing process. Instead they provide fast and convenient ways to preserve features that would otherwise be lost. In particular, the quality of tone-mapping is subjectively judged and may differ among observers, making any attempt to find the “optimal” futile.

The goal of this work is to show that similar functionality for emphasizing shape features, by *directly modifying the geometry*, indeed improves the perceived quality of manufactured free-form shapes. Motivated by its effectiveness for perceptually meaningful manipulations of images [1–3], we develop an *unsharp masking* approach for emphasizing features geometrically. This general approach is not new [4,5], yet we put a particular focus on robustness and interactive parameter exploration. Our approach is based on the extraction of three frequency bands using Laplacian smoothing and then locally modulating their effect. This allows the interactive exploration of feature enhancement (see Section 3).

Our central contribution is a human subject experiment testing the hypothesis that emphasizing features for 3D printing would be deemed desirable by human observers. The main idea for the experimental design is to ask observers which of several artifacts generated with different parameters best resembles *larger but unmodified* artifacts. In this way we avoid measuring subjective categories such as personal preference among several versions of an artifact without reference. The idea is summarized in Fig. 1, showing a shape in different sizes, comparing the original geometry with the result of adaptive unsharp masking. The experiments reveal, as expected, that moderate feature enhancement is preferred over no or strong enhancement. Details of the experimental setup and the results are presented in Section 4 and an outlook is provided in Section 5.

## 2. Related work

We focus here on work that considers geometry – the literature on images is vast and beyond the scope of this paper.

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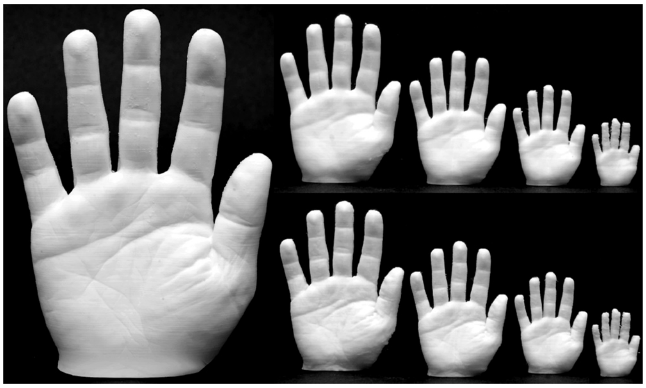

**Fig. 1.** A 3D print of the HAND model (left) and successively smaller prints based on the original geometry (upper row) or a modification based on adaptive unsharp masking (lower row). The apparent loss of features with decreasing size is compensated by the modification.

*Feature enhancement for rendering geometry.* There are a number of effective techniques for emphasizing features of 3D geometry in order to aid visual shape understanding. Most of these approaches target *rendering* and, unfortunately, make use of the possibility to alter the properties of the shape or the environment in ways that are physically impossible, e.g. changing the albedo or surface normals based on geometric analysis [6,7], or the light sources depending on surface location [8–10].

Unsharp masking has been used in the context of feature enhancement for rendering. Luft et al. [11] apply unsharp masking to the depth buffer of a scene. Ritschel et al. [2] improve on this idea by unsharp masking the image function using the geometry as the parameter domain. This avoids artifacts near disocclusions. Even though our approach aims to achieve similar results, our domain (i.e. geometry) is different and this causes problems not present in rendering (see Section 3).

*Reliefs.* Generating reliefs from geometry is a problem that is similar to the image domain: the depths of the relief is a signal that needs to be compressed, while the ground plane of the relief serves as a parameter domain. Consequently, techniques for the generation of reliefs are similar to tone-mapping methods [12]. Schüller et al. [13] generalize relief generation by considering other parameter domains and handling the case of discontinuities in depths.

*Feature enhancement.* A common idea for feature enhancement is to decompose the geometry into frequency bands and then amplify the band corresponding to the desired features. This can be done based on spectral decompositions [14,15], which is unfortunately quite expensive. Guskov et al. [16] suggest that a multi-resolution decomposition could be used.

Instead of using a frequency decomposition other filters similarly allow defining (and then enhancing) features. Kim and Varshney [4] base their definition on mesh saliency [17], while Miao et al. [18] develop their own measure. The mesh is then modified such that saliency increases. It has recently been shown that common measure of geometric saliency fail to predict where humans fixate on the actual 3D print [19], so the advantage of basing feature enhancement on such measures (over other differential quantities) is unclear.

A particular goal of ours is the enhancement of features while preserving the overall shape as much as possible. This is a challenge that is not directly addressed in these approaches.

*Optimization for 3D printing.* Recently, optimizing the perceptual quality of 3D prints has gained attention. Zhang et al. [20] focus on the reduction of artifact caused by support structures and use perceptual models to minimize them. Pintus et al. [5] modify the geometry of the shape to counter the effects of a particular printing technology, in their case powder-based 3D printing. Their goal is similar to ours in that the dominant problem of this technology is loss of resolution. Our approach differs in that it is agnostic to the printing technology and rather provides a technique that is easily adapted to different settings.

Besides the methods that optimize the perceived quality of a print, there are also approaches that optimize the print quality by addressing problems of a specific printing technology. Alexa et al. [21] achieve higher accuracy prints by optimally adapting the layer thickness of FDM and SLA prints. Zhou and Chen [22] increase the accuracy and resolution of SLA prints by finding the optimal mask image for each printed layer. In comparison, our approach does not aim at improving the objective quality but rather the perceived quality of prints. It is therefore agnostic the actual printing technology and much simpler to realize.

*Shape-preserving geometry processing.* As mentioned, one of our goals is to preserve the geometry as much as possible while enhancing the features. This goal of shape preservation has also been considered in smoothing, which is related as unsharp masking is based on reversing a smoothing operator. Smoothing methods usually minimize the surface area (i.e. mean curvature flow) so the shape tends to shrink. While it is easy to adjust the global volume (by scaling) it is more difficult to preserve the shape. Available methods incorporate a term for local volume loss [23–25] that requires an iterative solution even for moderate levels of smoothing. In contrast, our approach is based on simple implicit Laplacian smoothing.

Compared to gradient domain techniques [26] our approach allows exploring different parameter settings without the need for repeatedly optimizing or solving a system of equations, thus enabling interactive exploration on very large meshes. Work on anisotropic smoothing [27–29] aims at smoothing surfaces while retaining defining features. Using these enhanced smoothing operators to define frequency bands is potentially useful in our context and constitutes a promising direction for future work.

Our main contribution lies in utilizing established methods to enable intuitive and fast improvement of 3D prints. The conducted human subject experiment shows that the approach is an appropriate solution for this purpose.

## 3. Adaptive unsharp masking

The goal of our method is to modify the geometry of free-form shapes so that 3D prints of the shape are visually closer to the result expected from the virtual version of the shape. In particular when printing in small size, features will be lost due to the limited resolution of common manufacturing devices as well as subsurface scattering.

We strongly believe that any method can only be of practical relevance if it is robust with respect to the quality and size of the input mesh. In addition, the effect should depend only on few parameters and it should be possible to explore this parameter space interactively. Our proposed approach that provides these desirable properties is a locally adaptive filter based on the idea of unsharp masking.

### 3.1. Unsharp masking background

In its simplest form unsharp masking of 2D images can be implemented as a linear filter that boosts high frequencies of the signal. Even though the filter only pronounces edges, the human visual cortex creates the illusion that complete features have been

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