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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.
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. Gusov 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 onlypronounces edges, the human visual cortex creates the illusion that complete features have been
altered, an effect called Cornsweet illusion (Fig. 2). A step edge in image luminance is amplified by unsharp masking, however, the perceived luminance is altered not only at the edge. We exploit the same effect for 3D geometry and amplify edges which will lead to more pronounced lighting locally and therefore perceptually exaggerate features.

Unfortunately, unsharp masking is prone to amplify noise, since it amplifies all high frequencies. Several authors [31,32] consider non-linear adaptive unsharp masking for 2D images as a way to reduce these artifacts. These approaches modulate the sharpening effect based on some local measure of noise. Öztireli and Gross [3] adaptively control the sharpening effect using the ratio of local variances of the input image and a filtered version. Thus image regions with high variance in a smoothed version of the image are sharpened less.

It is difficult to generalize techniques from image processing to meshes. The main difference is that images are graphs of a function with a clear separation between parameterization domain and signal. Any filter affects the signal but not the parameterization. A boundary representation, such as a triangle mesh, has no immediate parameter domain. Applying the filter to the vertex geometry of a triangle mesh affects both, signal and parameterization. The combined change of parameterization and signal commonly causes global deformation and the formation of singularities.

Moreover, numerical instabilities that would arise when using a quotient of measures as a weighting term akin to the one used in [3] are not easily fixed and will destroy the visual quality of the mesh. In the image domain clamping can be used to deal with these problems in an inconspicuous way.

Our approach is based on extracting frequency bands and then adaptively modulating their effect. This leads to an extremely efficient, practical and easy to implement algorithm.

3.2. Spectral mesh processing

For a mesh \( \mathcal{M} = (V, F) \) with \( V \in \mathbb{R}^{n \times 3} \) the matrices \( L, M \in \mathbb{R}^{n \times n} \) denote the cotan-Laplacian [33] and the lumped mass matrix respectively. We obtain smoothed versions of the geometry by using semi-implicit mean curvature flow [34]:

\[
(I - \delta M^{-1}L)V_\delta = V. \tag{1}
\]

The parameter \( \delta \) controls the step size of the implicit smoothing and therefore the smoothness of the result.

We interpret differences in vertex positions between different smoothed versions of the mesh as feature vectors. In order to convey meaningful geometric information, these vectors should be independent of the triangulation, in other words, smoothing should have no tangential effect – a planar region should be unaffected by the smoothing operator. This is in fact the defining property of geometric Laplacians [35] like the popular cotan-Laplacian which we use in our algorithm.

Because Laplacian smoothing moves vertices normal to the surface, it leads to shrinkage. A sharpening operator based on differences of smoothed versions of the geometry would cause undesirable shape deformations. We tackle this problem using locally adaptive weighting. Compared to smoothing techniques that directly address the undesired deformation we believe this approach is more stable and faster.

3.3. Unsharp masking meshes

Using smoothed meshes we can formulate a basic version of unsharp masking:

\[
\hat{V} = V + \lambda_1 (V - V_\delta). \tag{2}
\]

This naive approach has two problems: First, noise is amplified. For images this problem is solved by excluding small scale details from amplification. We use a similar technique to overcome this problem. The second problem is unique to geometry. Features may be significantly deformed (see Fig. 4), because of the shrinkage present in the smoothed shapes. The reason for this is that smoothing causes shrinking, and since the effect of smoothing is essentially reversed, naïve unsharp masking of geometry increases the local volume, which can appear as unnatural deformation.

We tackle both problems by considering three frequency bands. With the original geometry \( V_0 \) and three progressively smoother versions \( V_{\delta_1}, V_{\delta_2}\) and \( V_{\delta_3}\) we build the differences

\[
\Delta_1 = V_0 - V_{\delta_1}, \quad \Delta_2 = V_0 - V_{\delta_2}, \quad \Delta_3 = V_0 - V_{\delta_3}. \tag{3}
\]

Note that these differences only roughly correspond to a frequency band representation, as their spectral components are overlapping. The exaggerated geometry is computed as

\[
\hat{V} = V_{\delta_3} + \lambda_2 W \Delta_2 + \lambda_3 \Delta_1
\]

with \( W_{ii} = \exp(-\mu ||(\Delta_1)_i||^2) \). \tag{4}

with a diagonal matrix \( W \). Using the parameter \( \lambda_1 \), we can reduce the influence of very high frequency content that we attribute to noise. If the mesh is free from noise (because it has been generated synthetically, or it has been processed after scanning) this parameter can be set to one. In the context of 3D printing, we have found it convenient to set \( \lambda_1 = 0 \) for all our experiments. The additional smoothing is irrelevant for the coarse approximation with a real world artifact, and we safely avoid boosting noise in the process of sharpening. Fig. 3 illustrates the effect of noise reduction. Using unmodified unsharp masking (Eq. (2)) results in severe artifacts Fig. 3, which can be partly suppressed by excluding the highest frequency band Fig. 3.

The second parameter \( \lambda_2 \) controls the amount of exaggeration for features in the frequency band \( \Delta_2 \). This effect is modulated by...
a weight function to counteract the shrinking in the smoothed geometries. The motivation for this weighting term is that regions that exhibit shrinking during smoothing will do so in all frequency bands. However, this effect will become even stronger for larger smoothing values $\delta$ and we can use the length of the difference vectors in $\Delta_3$ as an indicator for the amount of large scale shrinkage. Based on this value we modulate the sharpening effect and obtain a filter that approximately preserves the local volume and primarily acts on a specific frequency band, since lower frequencies are dampened. Fig. 4 illustrates the weights $W_i$. Note, how the extremities, e.g. bunny ears and finger tips, carry a low weight value indicating difference vectors of relatively large norm in the lowest frequency band $\Delta_3$.

Fig. 3 demonstrates the effect of adaptive unsharp masking as compared to standard unsharp masking. For comparability $\lambda_2$ is set to the geometric mean of the vector $W$ in the non-adaptive version. The adaptive version preserves the shape much better while still exaggerating mid-frequency details. The insets on the right hand side of Fig. 3 demonstrate the capability of our algorithm to preserve the shape of smooth features.

It is difficult to quantify the effect of shape preservation. We decided to measure the Hausdorff distance between the original and modified geometry. Because the goal of the procedure is to modify the geometry we cannot expect the Hausdorff distance to be zero. But we might want to interpret the idea of preserving shape as having a bound on the maximal distance between original and modified geometry, which is precisely what Hausdorff distance measures. We find that the adaptive approach results in about 50% smaller Hausdorff distance compared to standard unsharp masking (see Table 1, distances measured with Metro [36]) or, in other words, shapes exaggerated with our technique are typically much closer to the original.

### 3.4. Parameters

While it would be possible to adjust the frequency parameters $\delta_1$, $\delta_2$ and $\delta_3$ for each mesh, we believe it is more convenient to select them a-priori. To choose reasonable values we investigate the effect of the parameter $\delta$ on smoothness in terms of the Dirichlet energy for a set of example meshes. We start by scaling each model so that it fits into a unit bounding sphere. Then we use

$$E_\delta(V_\delta) = \|\text{diag}(V_\delta^T L_{V_\delta} V_\delta)\|$$

(5)
to measure smoothness of shapes where small values of $E_\delta$ indicate smoother meshes (see Fig. 5). We observe that the shape of the curves are roughly similar and that most mid-scale detail is preserved until $\delta = 1 \times 10^{-4}$. Larger values aggressively smooth the mesh and lead to results exhibiting extreme local volume loss and ultimately singularities. Because of the choice of a geometric Laplacian this behavior is independent of combinatorics and mesh resolution.

Based on these observations, we suggest to set the smoothing parameters to $\delta_1 = 0.5 \times 10^{-5}$, $\delta_2 = 10^{-3}$, $\delta_3 = 10^{-4}$. These parameters tend to select a frequency band of mid scale features that are well separated from noise while also not resulting in aggressive smoothing. All examples in this paper are generated with this choice of parameters. If necessary, they could be changed and we would suggest to use analysis based on Dirichlet energy as explained above.

The parameters $\lambda_1$, $\lambda_2$, and $\mu$ are exposed to the user and can be used to interactively find a suitable result. For larger sharpening effects we found that more aggressive modulation is necessary in order to avoid artifacts. In order to reduce the number of parameters to one we found empirically that the combination $\mu = 0.1 \lambda_2 / \|\Delta_3\|$ and $\lambda_1 = 0$ gives consistently good results. Fig. 6 shows renderings of progressively sharper models, generated using different values for $\lambda_2$. Even for very high feature amplification the results remain noise free and maintain the overall shape. The main computational burden of the algorithm lies in solving the linear systems in Eq. (1), however, this can be done in a preprocessing step. The parameter $\lambda_2$ can then be used to explore different exaggeration levels interactively. We systematically explored the parameter space of all exposed parameters $\lambda_1$, $\lambda_2$, and $\mu$. Even though one can achieve more artistic effects by adjusting all parameters, our experiments have shown that for accentuating features and preserving details this is not necessary.

### 4. Validation

Our hypothesis is that light exaggeration of features helps to compensate for the deficiencies of 3D printed artifacts as well as perceptual effects: 3D printers are limited in resolution and material, and the human visual system has decreasing contrast sensitivity for small spatial frequencies. These effects together suggest that smaller prints would appear to have less pronounced features for the same geometry. And indeed this is what we observe (see Fig. 1).

Note that it would be difficult to disentangle these different effects. Instead, we wish to demonstrate that the particular geometric modification we propose here is good enough to provide better 3D prints. Yet, it is not easy to provide experimental evidence for this, as the question ‘Which 3D print looks best?’ is too subjective and leaves too much room for interpretation for experimental validation. Our solution to this is to provide a reference object. This
reference artifact is printed significantly larger, so appears to have more features. Based on the reference object we can ask for perceptual resemblance – a question that is much clearer.

We begin with generating a collection of 3D printed objects and their brief visual inspection. Then we provide the details of our experiment and discuss the outcome.

4.1. Objects and qualitative analysis

We restrict the experiment to a small set of variants: each shape is printed based on its original geometry at large scale, and then 4 different versions at a smaller scale. One of the 4 versions is based on the unmodified geometry, and the other 3 are modified using adaptive unsharp masking with $\lambda_2 = \{10, 20, 40\}$ and the other parameter set as explained in Section 3.4. For future reference we term the three parameter settings as light, medium, and strong exaggeration of features. All shapes have been manufactured on a common fused-deposition modeling device (an Ultimaker2) using Verbatim White PLA. Large versions of the unmodified geometry are shown in Fig. 7.

A simple visual inspection of the resulting prints aims at a qualitative analysis of our statements that smaller scales appear to have less detail and that unsharp masking can compensate for this.

Fig. 7. Photographs of the large versions of 3D printed shapes. From left to right: Golfball, Hand, Bunny, Gargoyle, Icega.

4.2. Experimental validation

The experiment is based on our basic idea to provide a large object as reference and then let observers decide which smaller reproduction they believe better fits the larger one. In this sense, the large model serves as ‘ground truth’. We decided to have more trials and present only two possible alternatives, rather than having observers choose between all four simultaneously. This not just
makes the task simpler for participants, the experiment also has a simpler underlying probability distribution for the null hypothesis, i.e. similar to a coin flip. The details of the experiment are as follows.

Setup. Object material was white, and presented on black cloth, normal indirect room lighting was used. In each condition, two of the four variants were presented in front of the large physical version. See Fig. 8 for an image showing the setup.

A total of 10 conditions were shown: all possible 6 pairs of the 4 variants, and 4 randomly chosen pairs with the left/right placement reversed to exclude effects of the placement. The order of presentation for the conditions was independently randomized for each shape.

Participants. There were 19 participants (age 27–45, 6 female). The degree of familiarity with ‘3D printing’ varied, with 8 having been professionally (academically) involved with the technique. In a short introduction we made all participants familiar with common defects of fused-deposition model printing (see Fig. 10), and showed the possible maximal range of variation among the variants on a shape not used for the experiment. Participants were minimally compensated for their effort.

Task. For each condition, we asked which of the two presented small shapes “better provides the visual impression” of the presented larger physical version. Participants were able to move freely to inspect the objects, but they were not supposed to touch them. They were asked to come to a conclusion within 10 seconds, yet there was no time limit enforced.

Analysis. We analyzed the collected data and provide further interpretation of the results based on post-experiment interviews.

Fig. 9 shows the preference of the 4 different small version compared to the large object. In this illustration, icons right of the midpoint mean that more than half of the participants preferred the row category over the column category. We see that strong exaggeration was universally disliked in comparison to any of the other categories. There is a trend in favor of light or medium exaggeration compared to the original, but the results vary with shape. And there seems to be no difference between light and medium exaggeration.

Based on the last observation (and a cluster analysis) we combined light and medium exaggeration into one category. Then we find significant differences at the $p < 0.05$ level between all classes: light/medium is preferred over strong ($p < 0.001$) and over original ($p = 0.025$), original is preferred over strong ($p = 0.046$).

It is worthwhile to discuss the trends in the data: one observes a relatively high noise level, and a clear separation of preference between the shapes Golfball, Hand, Bunny compared to Igea. While the former three behave consistently with the significant preference mentioned above, the latter does not. In fact, we find that Igea is always preferred in the original version (statistically significant at the $p = 0.05$ level). Post experiment interviews revealed that participants preferred smoother surfaces for the Igea model (see Fig. 10). Here, the ‘features’ in the original shape were perceived as defects that were better be suppressed in a reproduction. In retrospect it might be obvious that not all geometric features, no matter at what scale, should be emphasized to make them stand out. Yet, this is a semantic issue, and probably also depends on the application (for example, archaeologists might be interested in making such marks visible [37]).

The interviews also hinted at a potential reason for the high noise level: participants reported that, in general, they found the shapes to be quite similar (consistent with our goal not to distort the shape), so they looked for elements they disliked. This was often the ‘roughness’ of the surfaces (see Fig. 10). From their

Fig. 9. The results of pairwise comparisons for each of the shapes. The position of the icons shows the relative number of preferences of row category over column category. So icons left of the midpoint imply a preference for the category named in the column, while icons right of the midpoint imply preference for the category in the row. See main text for discussion.

Fig. 10. Upper row: original Igea model with smooth surface and 3 exaggerated models. Bottom row: Detailed views of the marked regions. It becomes visible that the roughness of the surface increases from left to right with the level of feature exaggeration. Additionally, some models (especially the second and last) show layer defects due to the low-cost FDM printing process. These defects are dependent on various parameters such as the material and printer calibration. As we printed small scale models, the defects were about the same scale as the smallest accentuated features. Even though we printed multiple series of objects and carefully selected the ones with the least defects, an effect on the human subject experiment was difficult to avoid.
description, roughness referred to typical manufacturing defects as well as feature exaggeration. We speculate that defects due to FDM manufacturing were not negligible relative to the modification we performed, thus likely increasing the noise level of the result.

5. Discussion

We have provided a simple, stable, and fast way to exaggerate features in geometric models. We believe the results generated with this technique are at least as good as other comparable techniques dedicated for improved 3D printing [5], general geometry feature enhancement [4,18], or as part of general purpose mesh processing [14,16,38]. A detailed comparison between these techniques is difficult, because there is no quantitative measure of performance.

The main contribution of our work is that we are the first to validate experimentally that moderate feature exaggeration is preferred by human observers in 3D printed shapes. More specifically if features are deemed semantically important, they should be exaggerated. Our experimental validation may or may not extend to the alternative mesh processing techniques referenced above – an experiment including all these techniques was beyond our possibilities. We would be curious to see our experiment replicated for other approaches.

The most obvious lesson learned in all our experiments is that the visual impression of the virtual shape yields very little
information regarding the visual impression of the real shape – so screen based experiments are not very helpful in analyzing the usefulness of geometry processing methods for 3D printing.

References