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Color Enhancement for Rapid Prototyping

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Abstract

We propose to exploit the color capabilities of recent rapid prototyping hardware devices to enhance the visual appearance of reproduced objects. In particular, by carefully pre-computing surface shading, we are able to counterbalance the sub-surface scattering (SSS) effects that hinder the perception of fine surface details. As a practical result, we are able to reproduce small scale copies of cultural heritage artifacts with an increased readability of the tiniest features and particulars, without requiring manual post-reproduction interventions or hand painting.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]:

1. Introduction

Nowadays 3D scanning technologies have a well assessed impact in the Cultural Heritage (CH) field. The availability of digital 3D models opens a wide spectrum of uses which can improve our capabilities to study, analyze, recognize and compare the artwork with other heritage items. 3D models are the starting point for the design of a large number of applications based on visual encoding and communication, ranging from interactive and immersive (multimedia books, interactive navigation, immersive VR/AR systems, etc.) to more passive ones like still images, videos, computer animations and digital reproductions.

Rapid prototyping techniques exploit a wide variety of basic technologies to create a real world reproduction of a 3D digital model, ranging from additive techniques (like the classic stereolitograph polymerization, powder deposition, wax deposition) to subtractive, milling approaches. Rapid prototyping techniques have proved to be especially interesting in the specific field of CH for a number of reasons. First of all, when coupled with 3D scanning they provide a non-contact, safe alternative to the traditional plaster casting techniques, which can often cause degradation or have a significant impact on the condition of the original surface finishing. The capability to produce exact copies, whatever is the scale and the number of replicas, is often considered an important characteristic of the rapid reproduction technologies. Moreover, even if 3D graphics and interactive interfaces have incredibly evolved, the "real" feeling given by a solid object that can be manipulated and explored in a natural way is something that is still unsurpassed. This last consideration is particularly true in the CH context, where a large number of professionals lack the basic technical skills to successfully explore and interact with 3D digital models through a standard 3D interface.

On the other hand, we should keep in mind that rapid prototyping techniques have been created for the design industry, so the focus of these technologies was on precision of mechanical properties of the produced object (which was often required to validate design hypotheses) and the final finishing of the surface was not an issue for most applications. On the other hand, in CH this aspect is quite important and the typical ”plastic” look of many materials used in this field (e.g. the resins used by stereolitography) is usually disregarded by CH professionals, since they give to the replica a completely wrong visual aspect.

Luckily enough, rapid prototyping technologies exploit different materials with different properties; some of these materials are based on powder deposition and reconstruct objects with a diffuse opaque sandy texture grain that is well accepted in the CH field, since it resembles sand stone which is used for most of artworks. On the other hand, although these sand-like materials are appropriate for the reproduction of many 3D models, their optical properties (mostly the sub-surface scattering (SSS) characteristic) make it difficult to read fine details when the objects are printed on a small scale. Recently color painting capabilities have been added to rapid prototyping devices, allowing the direct creation of colored 3D objects and we propose in this paper to exploit this new capability to improve the visual/perceptive quality of the replicas.

The main contribution of this paper can be summarized as follows: we propose a technique to color the surface of an object in order to enhance the perception of its geometric shape once it has been printed. The technique is based on a counter shading approach that tries to overcome the drawbacks of SSS effects of the printing material, which usually blurs out the perception of the shades of the smallest details.

2. Related Work

The idea of changing the color of a real object surface by means of computer driven technologies has been well explored in the past. Probably the first experiments in this direction were done in the *Augmented Reality* domain, where, by means of digital projectors, new color and surface properties were projected onto real objects [BRF01, BF02]. In [BGW*02] the specific idea of enriching the displayed information on an existing object by means of projected images was exploited, even if the objective was to offer a new semantic description of surface portions rather than enhance its geometric shape.

With respect to these approaches, we focus on a different task: exploiting the color assigned to the object to automatically make its real shape more perceivable, enhancing the small geometric details that could disappear because of the optical properties of the manufacturing material. In a way, since we aim to enhance the shape perception by exploiting some knowledge of the shading process, we could say that our work is related to the field of *illustrative visualization* [VGH*05], which we exploit to enhance the information-effectiveness of the real printed model. On the other hand, from the point of view of the basic technologies exploited in our approach we strongly relate to previous work that has been done in shading techniques.

Therefore we are going to deal with two issues: choosing the proper shading environment to enhance small geometric details and taking into account the material behaviour regarding its appearence. In the following sections we show the work related to these two topics.

2.1. Shading Environment

The idea of shading the surface according to its local geometric shape in order to enhance the presence of small pits and details was already explored with a different purpose in various papers, which focused on the idea of finding fast approximation of global lighting effects. An example is [Ste03], where the use of a *vicinity shading*, a variant of the obscurance term proposed in [ZIK98], was proposed to enhance the visualization of volumetric datasets. Similarly, in [Mil94] the so called *accessibility shading* approach was introduced, where the geometric local (and global) accessibility of a point is used to modify the Lambertian shading of the surface in order to darken deep, difficult to access areas. Among all these methods, our choice of using ambient occlusion as a basic shading environment was motivated by a previous work [LB99], where the authors report the results of perceptual experiments showing that depth discrimination under diffuse lighting is superior to that predicted by a classical sunny day/direct lighting model, and by a model in which perceived luminance varies with depth. Generally, in local shading models the light effect which does not come directly from the primary light source has to be approximated. Otherwise, the portion of the scene that is not directly lit will come out entirely dark. Even without resorting to more correct (and complex) global illumination solutions, shortcuts are possible. The commonest and cheapest solution [Pho75] is to use a simple per-scene constant term, but this approach leads to a notable flatness in the portions of the scene that are not directly lit. The approach has been improved by the *ambient occlusion* technique, by explicitly computing the accessibility value for each point of the surface; this value is the percentage of the hemisphere above each surface point not occluded by geometry [Lan02]. This method is used in many production environments to add an approximation of the shadowing of diffuse objects lit with environment lighting. For example, ambient occlusion is precomputed in the interactive visualization system described in [BCS01, CPCS08]. Furthermore, various interesting methods for efficiently computing an ambient occlusion term using GPU have been proposed (e.g. [PHA04]). Some of these methods were extended to compute a first bounce of the diffuse interreflection of light ([Bun05]).

2.2. Sub-surface Scattering Effect

The other purpose of our work is to counterbalance a drawback of 3D printing physical models that depends on material properties. In particular, we deal with the blurring effect that SSS causes during the shading and that makes it more difficult to perceive the surface details. There is a large bibliography on theoretical and practical methods for efficient computing BSSRDF [LGB*03, JB02], which includes subsurface (multiple diffuse) scattering. From our point of view any technique could be used without affecting our approach. We have implemented the approach of [HBV03] for computing a simple and fast approximation of sub-surface scattering effects.

3. Color Enhancing

We start from the simple observation that most of real world materials are not perfectly opaque, and therefore their appearance is scale dependent. In other words, people are able to guess the size of an object simply by looking at its appearance. One of the most prominent cause of this behavior

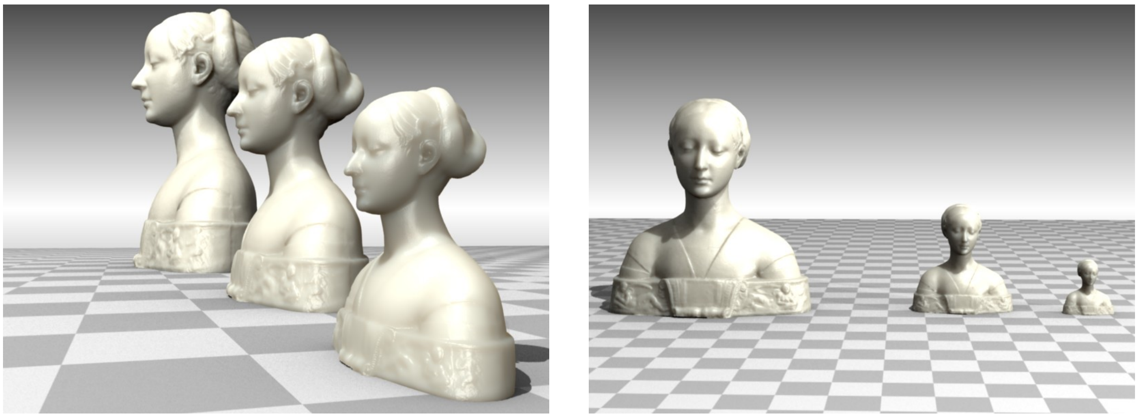

Figure 1: *Sub-surface scattering (SSS) properties of a material affect the perception of object surface details in a scale dependent way. These three busts are represented by the same detailed 3D model, and rendered using the same material. The scale-dependent SSS effects of the material are much more evident on the small-sized model where most of the tiniest details are blurred. The right image helps to better perceive the relative size of the three busts. In the two images, object size configuration, material and lighting settings are the same, only the camera position is changed.*

is the SSS effect, i.e. the light transport effect that happens when light penetrates the surface of a non-perfectly opaque, translucent object, is scattered by interacting with the material, and exits the surface at a point that is different from the entrance one (see Fig. 2). In this section we explain that the amount of light that moves around under the surface of an object depends on its scale. Therefore, if a given shape is manufactured in the same material but at different scales, the way the light interacts with the surface can significantly change. Particulary SSS effects have the annoying property of making it difficult to perceive the fine scale details of a given object. A practical example is presented in figure 1, where the same bust is rendered in the same material at three different sizes. Even when looking at the smaller bust from a close distance it is difficult to perceive the surface details. SSS effects cancel out shadows from small bumps, making small surface variations almost invisible.

Our objective is to change the surface basic color in order to counterbalance the shading effects due exclusively to subsurface shading behavior. In practice, we darken those surface regions that were lightened by the subsurface component of the lighting, making again evident those tiny details that were washed out by the SSS properties of the surface.

3.1. Counterbalancing SSS

In order to achieve this result, we compute a static shading of the object as a purely diffuse surface, lit by a uniform sky lighting environment. In this computed lighting model, we use the very simple approximation proposed by Hao et al [HBV03] to compute a SSS lighting of the mesh surface. The main idea presented in this paper is that once you have computed a per-vertex scattering term (e.g. the quantity of light back-scattered from each point of the surface) you can simulate the SSS effect by simply blending this term on the surface. The blending is done by a simple Laplacian diffusion iterative approach, where we iteratively substitute the scatter term with an average of the scattering on the adjacent vertices:

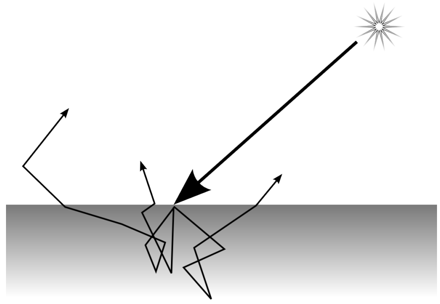

Figure 2: *SSS light transport effect. A fraction of the light entering at a point can emerge at a close different point after traversing a random path inside the object.*

$$L(v) = \frac{1}{|Adj(v)|} \sum_{v_i \in Adj(v)} L(v_i) \quad (1)$$

While this approach has some limitations, the produced results are convincing enough to be used for our purposes. Better and more accurate approaches could be easily substituted in our pipeline without affecting the rest of the proposed approach.

We used this method to create a counter-shading effect. The basic insight is that we can slightly change the original surface color in order to simulate a shading behaviour that is different from the original one. In particular, we want to counterbalance the blurring effect of SSS that makes it difficult to perceive small details. In practice, we code back into the mesh color the shading difference between the current object and the object as it would appear if it had no SSS behaviour.

3.2. Ambient Occlusion

In a general setting, computing this difference would imply that you have to choose both a particular lighting environment and a particular viewpoint, simply because the resulting surface shading depends on them. A good solution/approximation is to choose a purely diffusive surface being viewpoint independent. It allows us to avoid the choice of a particular vantage point. On the other hand, we have to introduce some approximations concerning the lighting environment. Assuming that we want to compute a general solution, a reasonable approach is to use ambient occlusion as an approximation of general lighting environment.

Ambient occlusion can be seen as the *average* lighting under all the possible lighting directions. Let us consider a point p on the surface with surface normal n_p. According to [Kaj86] we can define the *irradiance*, E, arriving at p as:

$$E(p) = \int_{\Omega} n_p \cdot \omega L(\omega) d\omega \tag{2}$$

where $L(\omega)$ is a scalar with magnitude equal to the radiance arriving from direction ω, and Ω is the set of directions above the surface, i.e. the directions for which $n_p \cdot \omega > 0$. This can be approximately evaluated by discretizing the domain Ω into k sectors $\overline{\omega_i}$ with a possibly uniform solid angle measure $|\overline{\omega_i}|$, and, for each sector, evaluating the radiance L only for a sample direction ω_i:

$$E(p) = \sum_{i=1}^{k} n_p \cdot \omega_i L(\omega_i) |\overline{\omega_i}| \tag{3}$$

The above equation becomes simpler if we consider a uniform lighting environment (where light comes uniformly from every direction, as under a cloudy sky). In this case, if we discard diffuse interreflection effects and therefore we only take into account direct lighting, $L(\omega)$ can be substituted by a simple binary function $O(\omega)$, valued 0 if the ray shoot from p along ω intersects our surface (and therefore the light coming from the sky is obscured) and 1 otherwise. The result can be considered as a simple first order approximation of the whole rendering equation.

With the assumption of a uniform sampling of the ω directions,

$$E(p) = \frac{1}{4\pi} \sum_{i=1}^{k} n_p \cdot \omega_i O(\omega_i) \tag{4}$$

3.3. Color Enhancing Algorithm

Given a 3D model, the entire algorithm to enhance the details perception of a printed object using a modified surface color consists in computing the color difference between the shading resulting from a purely diffuse opaque white surface and a diffuse white surface that is not perfectly opaque with a simulation of a SSS behavior. Figure 3 depicts this process. Starting from a simple diffuse shading under a fixed lighting environment, we store this resulting shading for each vertex(Fig. 3.left). Exploiting surface connectivity, we perform a simple laplacian smoothing of the computed shading color (Fig. 3.center). After this step, most of the finest details have been washed out by blending the shade. The difference between the shading color of the first two models is shown in Fig. 3.right; this shading color difference is normalized and centered around 50% gray, because it can be negative or positive according to whether the SSS has lightened or darkened a given portion of the mesh. Please note that the models in Figure 3 are directly rendered with the computed per-vertex color without any additional shading (i.e. technically speaking, we rendered them in OpenGL with no light enabled). The displayed shading is the one stored (*cooked* using the game engine terminology) onto the vertices.

3.4. Color enhancement and unsharp masking

This approach could be seen as closely related to the unsharp masking technique, where a given signal is processed in a way that enhances the discontinuities: the given original signal is smoothed and then the difference between the original signal and the smoothed one is added back onto the original signal (Fig. 4). This approach has been used for a long time as an image sharpening technique and recently it has been used both to enhance the surface shading by blending the normal of the surface [CST05] and to enhance local scene contrast by unsharp masking over arbitrary surfaces under any form of illumination [RSI*08]. The similarity between the unsharp masking approach and our color enhancement for printing is due to the fact that the SSS effect is quite close to a low pass filtering of the shading, so trying to counterbalance the SSS effects has some similarities with approaches that try to enhance high frequencies.

In our case we do not perform the last step of the classical unsharp masking process (the mix of the difference and of the original signal), but we directly use that difference itself to color the mesh. In practice we rely on the real world shading to mix in the difference color.

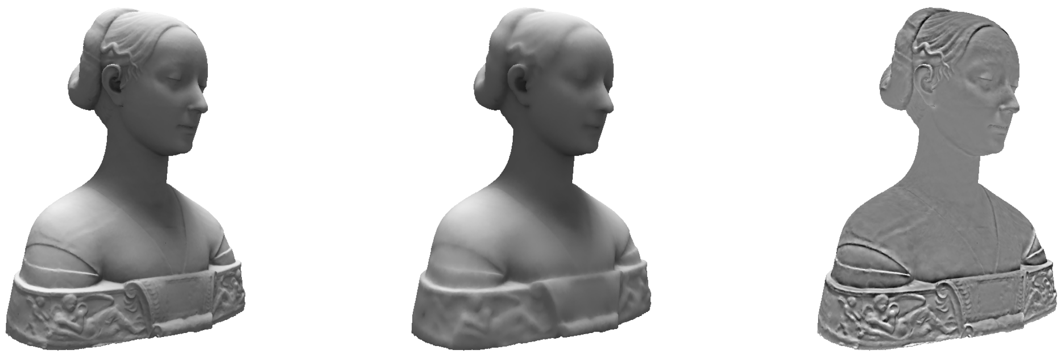

Figure 3: *Computing the shading difference between the purely opaque and the approximated SSS version of a 3D model. Left: simple diffuse shading. Center: SSS simulation by diffusing the lighting over the surface. Right: the difference between the shading of the first two models.*

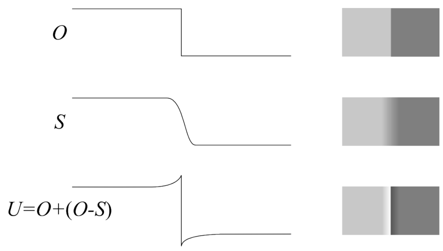

Figure 4: *The unsharp masking technique to enhance the color discontinuities. The original signal is smoothed, and then the difference between the original signal and the smoothed one is added back onto the original signal.*

4. Results

The whole pipeline for computing the enhanced color described in the previous section was implemented inside MeshLab [CCR08], an open source mesh processing tool, which, among many other functionalities, offers tools for computing an ambient occlusion term, for smoothing that term, for computing the difference between these signals, and mapping them back into gray levels. By combining these pieces it is possible to easily implement the described pipeline.

The physical reproductions presented in this paper were printed with a ZCorp Z450 3D Printer [ZC], which uses a mix of powder, binder and color to create physical objects from 3D models. It builds the replica (max. 203x254x204 mm) by the deposition of the powder and the colored binder one layer at a time. Its resolution along the X and Y axes is 300 x 450 dpi, while along the Z axis it may be set to 0.102 or 0.089 mm. The time required to print a model depends on its height along the z-axis and on the selected layer thickness. On the other hand, the printing time varies only slightly as a result of model size variations along x and y. It is straightforward that the thinner the layer, the longer it takes to print it. For example, given that the printing speed is about 2-4 layers per minute, the time required to print a model 10 mm in height with a layer thickness of 0.102 mm is about 30 minutes. Once the printing process is completed, it is necessary to wait about an hour and a half before extracting the object from the chamber in order to let the binder dry off perfectly. The next step is to remove all the excess powder from the object surface with compressed air. Due to the physical properties of the powder, the resulting surface is very friable; therefore, the model needs to be strengthened by covering it in a special glue provided by the manufacturer.

Figures 5, 6, 7 and 8, show some examples of the proposed technique in action.

Figure 5 shows two views (front and back) of the Laurana bust model without and with color enhancement. The model without color enhancement (on the left) has been printed using uniform color. The model on the right in both views is the one with enhancement; many small details, whose shading is canceled by the SSS, are now clearly visible (as an example, look to the line of the eyes, of the mouth and many chiselled details on the hair).

Since most of the blurring effects that cause the disappearence of small scale detail shadows are due to SSS, we show in figure 6 a comparison with a printed model that has been painted with a white opaque paint. Even in this case our models are more readable; in fact while the painting process significantly reduces the SSS effects, the thickness of the paint layer decreases the sharpness of the geometric features, making them less evident.

The color-enhancing technique is also applied to two models that were reconstructed from data produced with a Scanning Electron Microscope (SEM) (see figure 7). In this case a directionally biased ambient occlusion term allows to start from a lighting that is similar to the standard ”grazing light” approach that is used to better see tiny details raising from a surface. When starting from such a shading, our counter-shading approach tries to recover most of the details lost by the SSS effect when the shading is a highly directional/grazing.

Finally, we show in figure 8 some variations in the strength with which we can apply our color-enhancing technique. In the left pair (the gargoyle model), the enhancement has been applied in a very evident and strong way in order to achieve a "exaggerated" shading effect. Many features of the object are very evident and the result is a more dramatic appearance. In this case, in order to enhance the shading effect we have chosen to use an ambient occlusion term computed in a non-uniform way to simulate a lighting environment where most of the light came from above. The pair of images on the right of figure 8 show a color enhancement that has been applied in a rather subtle and much more *natural* looking way on a portion of the st. Matthew statue. Even if the enhancement is very slight and delicate, it allows to clearly see the tiny chisel marks on the unfinished sculpture surface.

4.1. Models References

- The 3D model presented in figure 8 is a detail of the Michelangelo’s unfinished apostle "St. Matthew" from the Digital Michelangelo Project [Sta03].
- The red circular box in figure 6 is a model acquired by INRIA in 2006 using a minolta Vivid 910 laser scanner. It is downloadable from [Aim03].
- The gargoyle and Laurana meshes were acquired by the Visual Computing Lab - ISTI -CNR and are available from the AIM@SHAPE repository [Aim03]
- The vitruvian man model (a detail of an Italian Euro coin) and the finger print in figure 7 were acquired with the Photometric Stereo method applied to Scanning Electron Microscope (SEM) images [PPV08]. The vitruvian face is about 2 mm in diameter, while the fingerprint model is a detail of a silicone cast of a human fingerprint.

5. Conclusions

We have proposed a simple and effective technique to color an object surface in order to enhance the perception of its geometric shape once the object is printed using recent rapid prototyping techinques. The proposed approach is based on a counter shading approach that tries to remove the downsides of SSS effects on the printing material that usually blur the perception of the shades of the smallest details. We have shown that the proposed approach allows to see the smallest details of a printed object in a clearer way, by testing it on a variety of 3D scanned and reproduced models.

5.1. Acknowledgments

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Figure 5: *The color-enhancing technique in action on the Laurana model. Represented objects are less than 10 cm tall (crosshairs are 1 cm spaced). In each pair of images, the left model is a standard uniform color reproduction, while on the right the same 3D model have been printed with enhanced color: many small details whose shading is canceled by the SSS are again visible in the model on the right.*

Figure 6: *The color-enhancing technique compared with a white painted version of the "Red Circular Box" model. In the left pair the comparison between the plain version and the version with the color enhancement. In the right pair the color enhanced version compared with a model that have been painted with a very opaque diffuse white paint that should remove most of the SSS optical effects.*

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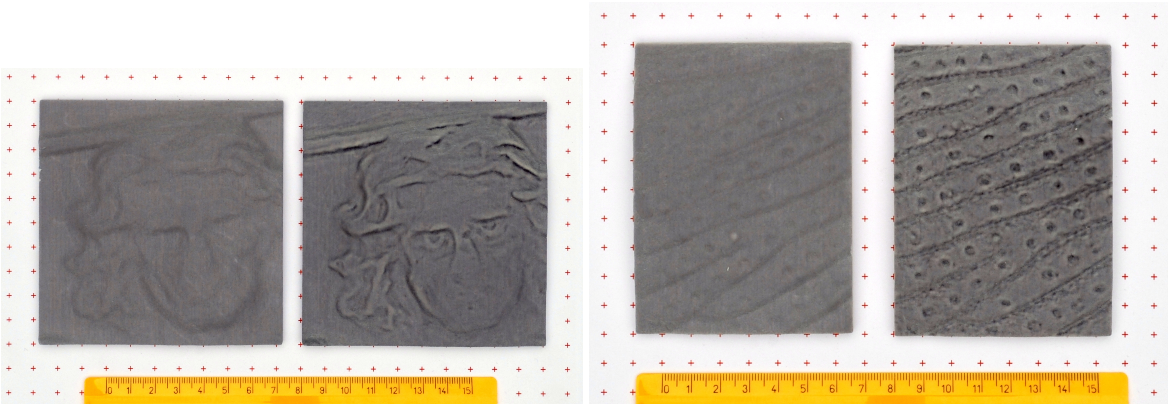

Figure 7: *The color-enhancing technique applied to two models that were reconstructed from SEM data. In this case a directionally biased ambient occlusion term allows to start from a lighting that was similar to the standard 'grazing light' approach that is used to better see tiny details raising from a surface.*

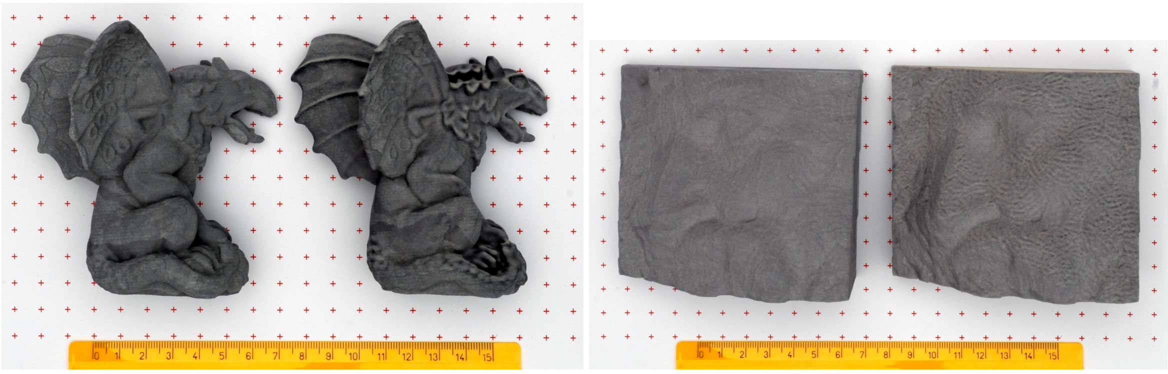

Figure 8: *The color-enhancing technique applied with different strength. In the left pair, the gargoyle model, the enhancement has been applied in a very evident and strong way in order to achieve a "exaggerated" shading effects. In this case, moreover, the ambient occlusion term was computed in a non-uniform way to simulate a lighting environment where most of the light came from top. On the right a color enhancement that has been applied in a rather subtle and more 'natural' looking way on a piece of the st. Matthew statue. The enhancing allows us to clearly see the chisel marks on the unfinished sculpture surface.*

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