# Explosive embossing of holographic structures: Computational simulation of procedural influences to the reconstructed hologram

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**ABSTRACT**

A new, fast and easy process for nanostructuring of hard surfaces is currently being developed: explosive embossing. The Institute for measurement and control engineering (IMR) of the Leibniz-University Hannover and the Fraunhofer-Institute for Chemical Technology (ICT) are currently presiding over the project which deals with the practicability of explosive embossing for nanostructures such as holographic structures. Within this project the IMR is concerned with the digital creation of holographic data and the numerical simulation and the evaluation of the transfer characteristics of the process.

## Introduction

Nowadays, the moulding of holographic structures is a relatively complex process: First a master-hologram has to be created in a very soft, possibly even near-liquid, medium. These however are usually too soft to be of interest for industrial structuring. Further stabilizing of the structures present in the master-hologram requires galvanic processing, which is both energy- and time-intensive as well as environmentally questionable, due to hazardous residues from the galvanic baths. As the medium used is usually relatively soft and hence not really dimensionally stable under stress as found in industrial processes, the master shims resulting from the first galvanic process are themselves duplicated by further galvanic processing to produce numerable and most importantly interchangeable daughter-shims. In contrast to this laborious process, explosive embossing requires moderate energy- and minimal time-resources, while not producing any hazardous waste. Additionally, the process of explosive embossing enables the use of relatively soft materials to structure hard materials, such as steel. Moreover, it also addresses the issue of forgery-immunity, as the original master structure is destroyed in the process, which is schematically displayed in Figure 1.

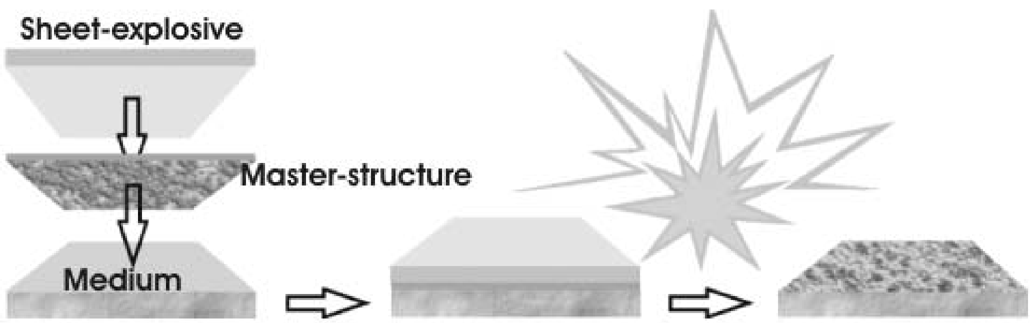


Figure 1. Schematic of the process of explosive embossing. (Source: Fraunhofer ICT [1,2])

As far as experimental results employing traditional holograms are concerned, research at the ICT has yielded more than hopeful signs for the practicability of explosive embossing of holograms into steel.

The process of explosive embossing will probably introduce some deviations into the final nanostructure (see figure 4); hence it is important to determine the transfer characteristics as accurately as possible in order to be able to adjust the master structure in such a way, that any possible deviations from the optimum case are minimized.

In order to determine said transfer characteristic we envisioned a computer-program to digitally analyse the differences between the holographic results yielded by the master structure and its explosive-embossing-result (see figures 5 and 6). Currently, the main focus is concerned with the complete digital processing of all data, including the generation, modification and reconstruction of holographic data.

## Holography

In order to describe holographic phenomena, complex wave-functions are the best choice. This section is simply intended to be a short reminder of the formulaic concepts behind holographic processing.

The wave-functions can usually be written in the following form:

$$\Psi_O = A_O(x,y,z) \cdot e^{i\varphi_O(x,y,z)} \tag{1}$$

where $A_O(x,y,z)$ = Modulus of the amplitude at a given position in space
$\varphi_O(x,y,z)$ = Phase at a given position in space

Introducing a reference wave R however does give the possibility to store a phase relative to the reference wave, as depicted in Figure 2.

$$\Psi_R = A_R(x,y,z) \cdot e^{i\varphi_R(x,y,z)} \tag{2}$$

$$I(\Psi_O + \Psi_R) = |\Psi_O|^2 + |\Psi_R|^2 + \Psi_O \cdot \Psi_R^* + \Psi_O^* \cdot \Psi_R \tag{3}$$

where * = Complex conjugate

The important part in equation (3) obviously being the two cross-terms we omit the constant terms and get:

$$\Psi_O \cdot \Psi_R^* + \Psi_O^* \cdot \Psi_R = A_O A_R \cdot \left(e^{i(\varphi_O - \varphi_R)} + e^{i(-\varphi_O + \varphi_R)}\right) = A_O A_R \cdot \left(e^{i\cdot\Delta\varphi} + e^{-i\cdot\Delta\varphi}\right) = A_O A_R \cdot 2\cos(\Delta\varphi) \tag{4}$$

where $\Delta\varphi = \varphi_O - \varphi_R$ = Phase difference between the two waves at a given point (x,y,z)

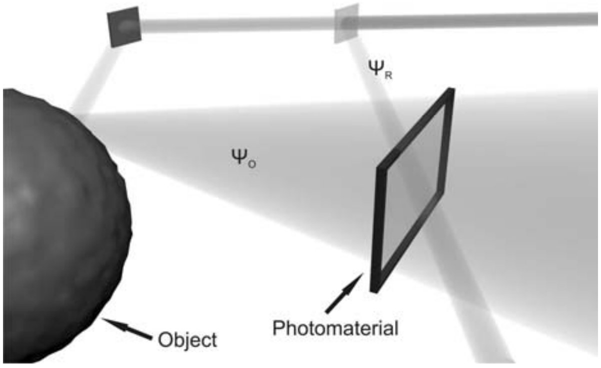


Figure 2. Traditional generation of a hologram

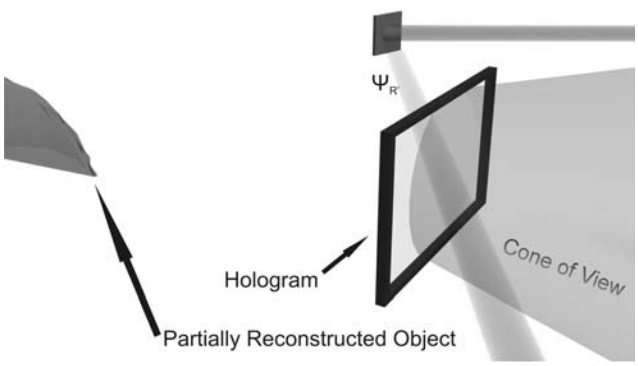


Figure 3. Traditional reconstruction of a holographic image

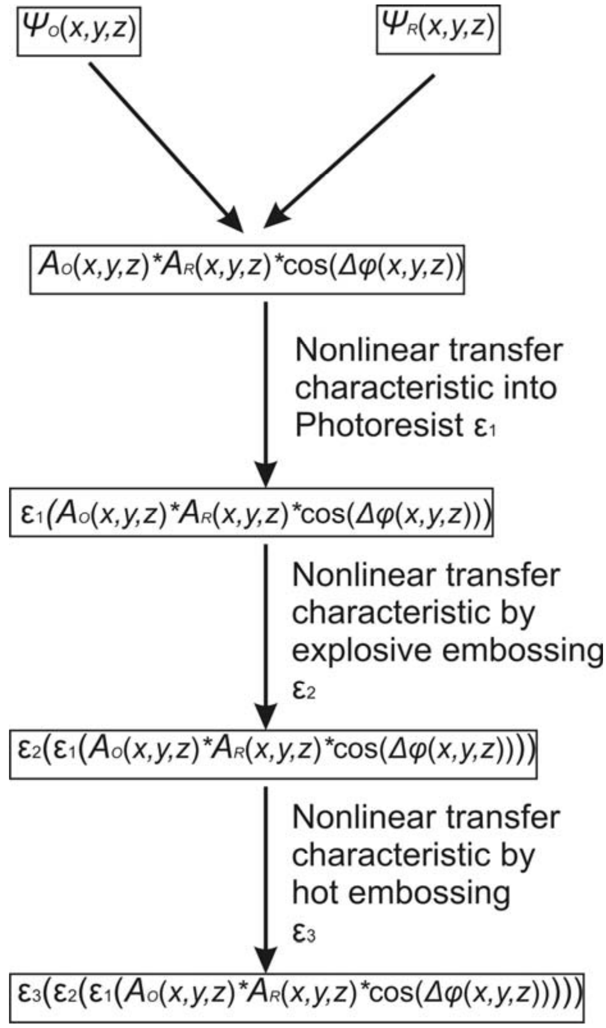


Figure 4. Formulaic schematic of the processes involved in manufacturing embossed holographic structures

Since only the difference of the phases $\Delta\varphi$ is stored in the intensity-picture, a reference wave R' is then required again to be able to reconstruct firstly the actual object wave O with an absolute phase and hence the three-dimensional picture of the original object. Taking $\varphi_{R'}$ as equal to $\varphi_R+d\varphi$, we get:

$$\begin{aligned} A_O A_R \cdot \left(e^{i\cdot\Delta\varphi}+e^{-i\cdot\Delta\varphi}\right)\cdot A_{R'}\cdot e^{i(\varphi_R+d\varphi)} &= A_0 A_R A_{R'}\cdot\left(e^{i\cdot(\varphi_O-\varphi_R+\varphi_R+d\varphi)}+e^{i\cdot(-\varphi_O+\varphi_R+\varphi_R+d\varphi)}\right) \\ &= A_0 A_R A_{R'}\cdot\left(e^{i\cdot(\varphi_O+d\varphi)}+e^{i\cdot(-\varphi_O+2\varphi_R+d\varphi)}\right) \end{aligned} \quad (5)$$

The two exponential terms give rise to two reconstructed images. The first one, containing only a dependency on $\varphi_O$ and the constant and hence irrelevant offset $d\varphi$ is the proper object wave we wish to recreate, the second term, which includes an additional dependency on $2\varphi_R$ is an artefact of the reconstruction method, which usually displays an inverted image of the original object.

Hence we get:

$$\psi_1 = A_0 A_R A_{R'}\cdot e^{i\cdot(\varphi_O+d\varphi)} \quad \text{and} \quad \psi_2 = A_0 A_R A_{R'}\cdot e^{i\cdot(-\varphi_O+2\varphi_R+d\varphi)} \quad (6)$$

$\Psi_2$ is obviously the inverted image, since the object phase $\varphi_O$ has a negative sign in this equation. For reasons of clarity only the partially reconstructed object wave $\Psi_1$ is shown in figure 3, while $\Psi_2$ is being omitted.

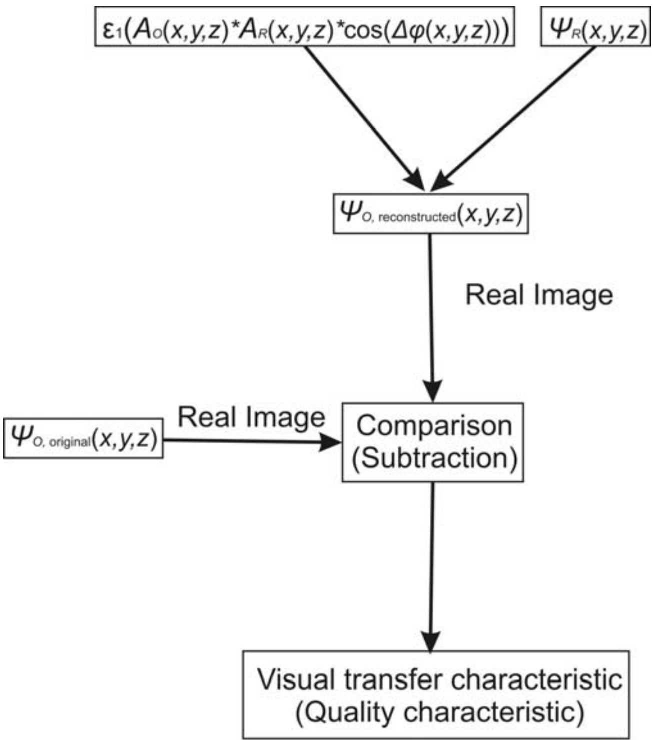


Figure 5. Formulaic schematic of the determination process of the transfer characteristic involved in explosive embossing by Intensity-comparison

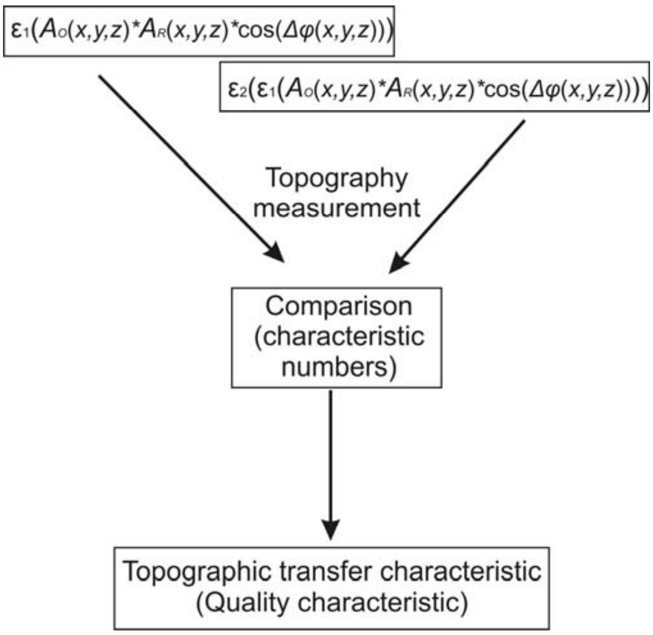


Figure 6. Formulaic schematic of the determination process of the transfer characteristic involved in explosive embossing by Topography-comparison

## Holo-Gen

Holo-Gen is the current name of the program currently being used and developed at the same time in order to generate digital holographic images. In order to do this, an existing image is loaded by the program, which is then converted into a greyscale-image which is used as height map to generate the three-dimensional object. The aspect ratio of the image is used as aspect ratio for the holographic data as well, while the width in µm can be manually defined. Optionally, if the image-format supports an Alpha- or Transparency-channel, such as with *.png's, this information can be used to generate partially transparent objects. The actual height, which the object is to have in the end can be set manually, however since only 256 different initial height-levels exist and the initial image will almost certainly be of a lower resolution than the final holographic image, it is usually preferable to use the in-built cubic interpolation-function in order to smoothen edges and increase the local accuracy of the height-information, as steps larger than the wavelength result in ambiguity of the reconstructed height-information later on. This means that without the benefit of interpolation, the maximum height for the whole object would be only 255 / 4 ≈ 64 times the wavelength used for the generation of the hologram (e.g. ~32 µm for green light at 513 nm).
The three-dimensional angle of the plane reference wave with respect to the object wave can be set either by typing it directly into the graphical user interface or by clicking on the custom-made controls.

Another little feature of this program is the possibility to save the complex wave front data and superpose further wave fronts at different wavelengths, giving the possibility to create "pseudo-white-light-holograms". The prefix "pseudo" refers to the fact that although it would be theoretically possible to add wave fronts for each and every wavelength in the visible spectrum, the amount of computation required for this is simply paramount and hence more than just impracticable.

Currently, the Holo-Gen program mainly generates the holographic data at one specific depth, since full scale wave-front-propagation, in order to give the possibility of shifting the image plane within which the object will be reconstructed, takes very long, as for every pixel present in the final wave-front, a spherical wave has to be propagated. These spherical waves easily affect many thousands of pixels and hence increase the processing time accordingly. The possibility of shifting the image plane means, that a real hologram, created with the output-data, may display the reconstructed object in front of, behind, or within the plane of the photo-materials surface.

As the sheer amount of data required to create a mere 10.0 x 7.5 mm wave-front (4.24 GB) was too large for the RAM of an up-to-date PC, a method was implemented to allow for multi-million-pixel-per-picture-support. In other words, the program was restructured in a way, which allows for the holographic data to be cut into smaller chunks or areas, which are saved to the computers hard disk and can then be processed separately, as long as no full scale wave-front-propagation is effected.

## Preliminary Results

First tests of the Holo-Gen program without using spherical-wave-propagation have led to results such as Figure 7, which is part of the result of a sine-wave image. The part of the original image represented holographically by Figure 7 is shown in Figure 8.

The mathematical angle of the sine-wave with respect to the horizontal is approximately 30° in the original image, as can be deduced from the holographic image as well.

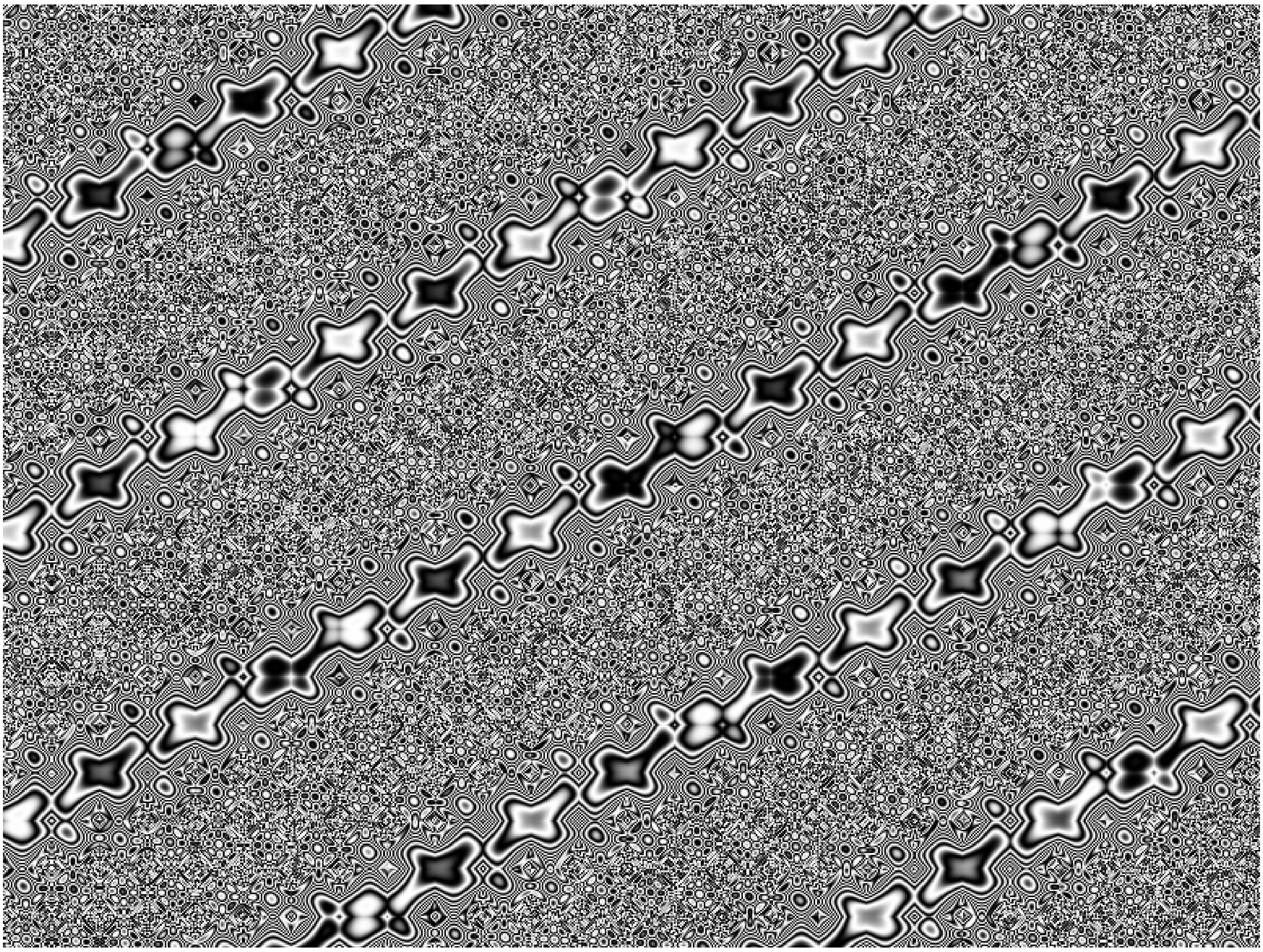

Figure 7. Partial (800 x 600 Pixel) preliminary result of a sine-wave image

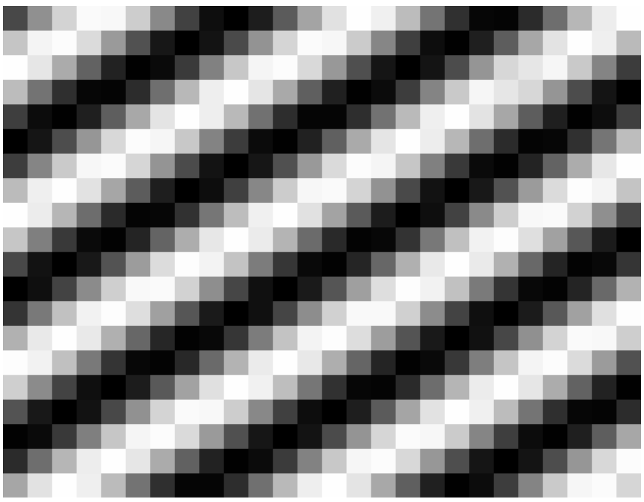

Figure 8. Partial original topography for Figure 7

It is important to note however, that the actual width of the whole holographic image (19494 x 14620 Pixel), of which Figure 7 is only a small portion, should be around 10.0 mm only.

## Planned developments

The Holo-Gen-program in its current state might possibly enable the implementation of multiple worker threads, leading to a better and fuller usage of the capabilities of state-of-the-art multi-core processors or multi-processor systems and hence a valuable acceleration of the whole hologram-generation process. This possibility still has to be verified.

In addition to these necessary changes to the existing program, two more programs or extensions are required in order to be able to determine the transfer characteristics of the process of explosive embossing:
Firstly, a program to simulate the errors expected in the process, such as random noise due to imperfect planarity of the medium, loss of resolution by conversion to a binary black and white image or localised errors due to the structure of the holographic master-topography. The actual type and localisation-criteria for the last type of errors mentioned are however still to be determined.

The second program required is one to reconstruct the original object and compare it with the original data in order to determine the actual impact of the various types of errors either created numerically or found by experimental means. As far as possible, this program is also meant to give hints as to how to modify the master-topography in order to minimise the errors in the final hologram.

Since the project is obviously also concerned with the creation of actual holograms, the possibilities for transferring the holographic image data from computer into photosensitive material, which can then be processed into a holographic nano-topography are also to be ascertained and performed.

## Acknowledgments

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