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# Geometric plane shapes for computer-generated holographic engraving codes

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ABSTRACT

We report a new theoretical and experimental study on hologravures, as holographic computer-generated laser-engravings. A geometric theory of images based on the general principles of light ray behaviour is shown. The models used are also applicable for similar engravings obtained by any non-laser method, and the solutions allow for the analysis of particular situations, not only in the case of light reflection mode, but also in transmission mode geometry. This approach is a novel perspective allowing the three-dimensional (3D) design of engraved images for specific ends. We prove theoretically that plane curves of very general geometric shapes can be used to encode image information onto a two-dimensional (2D) engraving, showing notable influence on the behaviour of reconstructed images that appears as an exciting investigation topic, extending its applications. Several cases of code using particular curvilinear shapes are experimentally studied. The computer-generated objects are coded by using the chosen curve type, and engraved by a laser on a plane surface of suitable material. All images are recovered optically by adequate illumination. The pseudoscopic or orthoscopic character of these images is considered, and an appropriate interpretation is presented.

## 1. Introduction

Thin scratches on surfaces have interesting optical properties. In 1992, Plummer and Gardner [1] reported the discovery of holographic behaviour in lap abrasion, with three-dimensional effects; mechanically produced scratches acted as a reflection hologram.

Different approaches to a technique for obtaining images from regular scratches were reported in 1995 by Beaty [2], referring to some previous works mentioning the synthesis of 3D images [3–5]. Beaty developed the circular-scratch technique into a method for creating three-dimensional images. *Scratch holography* has been the usual name for describing these displays. In [6], Abramson affirms that for the first time, these 3D displays by scratch techniques were obtained by Weil, who introduced its patent in December 1934 in the UK [7], and referred to the technique as incoherent holography [8,9]. Others similar techniques in copper or aluminum metal are described in [10,11].

Some elements of the theory for such a “scratch” technique, and how scratches work in the formation of 3D images, have been discussed and explained from different particular viewpoints by Plummer and Gardner [1], Eichler et al. [12], and also by Beaty [13]. These theoretical analyses consider only the circular geometry of scratches. More recently, Brand [14] analysed geometrically, in a more general way, the shape of the surfaces for constructing specular holograms to be formed by fabrication techniques such as milling, grinding, stamping, ablation, etc. Duke [15] used hand-made and mechanical engraves of some particular curvilinear geometries to form abrasive holograms on aluminum plates and by an etching press.

Hologravures as computer-generated holographic laser-engravings using circular-arcs as code curves were presented by Augier and Sánchez [16–18]. This approach is a generalisation of the scratch-holographic record. Engravings and technology were created in order to allow the competitive use of these displays and to widen its applications, scope and quality by making computer-generated engravings directly by a laser. This technique allows reproduction of hologravures from an original computerised design. As in [16], we have conserved the general use of the term “holography” when referring to this technique of “scratches”, able to encode three-dimensional information, and to the corresponding reconstructed images. Although these displays are not holographic in the strict and original sense of that term, they possess a group of optical properties in common with conventional holograms [1,2,8,13]. Consequently, a

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hologravure is also considered as a holographic-engraving process to record directly by laser an encoded "virtual-scene" from a 3D computer-generated world onto a 2D engraving, and to recover optically the original scene as a 3D reconstructed image from the real world, by means of appropriate illumination. Thus, for a determined size of the plate, undistorted stereo images can be observed for a wide range of viewpoints under an adequate position of the light source. Hologravures have been exhibited in public art exhibits, in conditions of standard gallery illumination. An example in the transmitted light mode, showing photographs of appropriate quality, can be found in [19].

In these engravings, two-dimensional representations on the recording material are considered as a 2D code that allows the corresponding 3D object image to be recovered. When the engravings are recorded in transparent materials, the reconstructed images can be observed in both the transmitted and reflected illumination modes. Some interesting applications are shown in [16–18].

Considerations about the internal shape of scratches, as grooves, are not usually found in the thematic literature, although in isolated cases we can find some remark. For example, in [1] the circular scratches made by a lap on nickel plated aluminum piece was analised as curved line-scatterers reflecting the light equally in all radial directions, where each incoming ray is scattered as a hollow cone of rays. The line-scatterer is represented in [13] as a bent rod, and each ray from the point source produces conical sets of scattered rays. It is shown not rigorously how the images are formed; the circular line-scatterer produces both a reflection-mode image sent to one side of reference plane, and a transmission-mode image sent to the other. In [12] the intensity distribution of the fan beam produced by circular scratches is considered experimentally. This paper shows photographs from positions of a possible observer, of a single circular broad scratch with a semicircular profile produced by a turning lathe, illuminated by a light point-source in transmission mode. From each position, one can see two light spots at opposite sites on the scratch. In [16] the quality of the lines traced by the $CO_2$ laser on some materials, as acrylic, polycarbonate, acetate and glass was considered. Microphotographs of the scratches drawn by steel point or laser traces on these materials and measurements of scratch average width are shown. Except in the case of engravings on common glass sheets, where can be observed that the grooves are broken, the reconstructed images from hologravures on other materials were qualitatively satisfactory.

The purpose of this work is to construct a basic theory of hologravures founded on general principles of the light ray behaviour. This approach is a new theoretical and experimental study on general curvilinear-encoding of image information as a novel perspective, allowing the design of engraved images for specific ends. Curves of very general geometric shapes can be used for encoding 3D image information from virtual models onto a 2D engraving. The experimental study of particular cases of curvilinear codes, showing their influence on the 3D reconstructed images, is developed by means of the same $CO_2$ laser-engraver used in [16]. This technique allows an adequate comparison with theoretical analysis.

A sufficiently broad theory allowing the analysis of general curvilinear scratch-codes and its influence on the 3D images obtained from a holographic engraving has not been previously available in the thematic literature. This work contributes to a more complete background of this theory.

## 2. Hologravures as computer-generated laser-engravings

According to Caulfield [20], the first computer-generated hologram known was made by Kozma and Kelly in 1965. Indeed, it was not used as a hologram, but as a complex spatial filter [21]. Pioneering work in this direction was also developed by Lohmann et al. [22].

Standard computer-generated holograms are usually of reduced dimensions and their use mostly restricted to work as diffractive optical elements in optical information processing. In other types of digital holography, information is typically recorded and recovered by a computer, with applications in areas like interferometry, microscopy, and data encryption [23]. Ordinary techniques for making computer-generated holograms [24] use a mathematical description of a virtual transparency. Typically, the calculated diffraction pattern first has to be plotted on an expanded scale and later photographically reduced. Other non-standard techniques, supporting computerised models and colour integral-holograms have been developed, including integral or stereographic holography, or similar technologies, and large format pieces, as for example in [25]. We will not mention here the numerous non-holographic computerised techniques to obtain 3D images that can be found in the Web.

Unlike the aforementioned techniques, a hologravure [16–18] is an engraving and an image reconstruction process. In the first step, by using a laser-engraver, an encoded 3D computer-generated virtual scene is recorded on a suitable 2D medium, recovering later optically, in a second step, the original scene as a three-dimensional image. The light source is required to have very limited spatial extension. These processes are schematically shown in Fig. 1.

However, by using the same type of computer-generated code a similar holographic-engraving could be obtained by another process, able to record it on the medium, and obtaining the same 3D image by using the appropriate illumination. As the computer-generated scene is directly encoded, and reconstructed later optically, neither complex mathematical description, nor elements of standard computer-generated techniques are needed, and no characteristic technology of the integral stereographic holograms is used. The maximum size of these engravings is limited only by the dimensions of the work space of the laser engraver; therefore, it can generate pieces of large format. This technique also allows 3D images to be obtained by means of engravings, requiring very low resolution. The typical spatial frequency of the laser traces on the material is on the order of one or two lines per millimetre, although this number can be increased, depending on the application, the recording medium, and the characteristics of images and laser used to engrave.

Next we show, for circular scratch encoding, the basic correspondence between the points of the 3D model and the points of the hologravure in the 2D plane. It was established in a very simple way in [16]. Note that these basic rules are contained in Fig. 1.

- Each point of the 3D model is coded as a segment of a circular curve in the hologram plane. The top of the curve matches the respective object point projection on that plane. (Observe 2D-encoded image from 3D model, to the left in Fig. 1a).
- For all the points of the 3D model that are at equal distance from the hologram plane, all the circular curve segments have the same radius.
- The distance between each point of the 3D model and the hologram plane is directly proportional to the radius of the corresponding coded circular curved segment. In this way, information about object depth is recorded.

Any available 3D virtual model computer generated could be represented in a 2D code by using some adequate encoding software and a $CO_2$ or other type of laser, as a tool for directly drawing the calculated scratch-codes on the suitable material. The power of the focused laser beam and its speed of movement on the material should be carefully adjusted.

Since the virtual depth of an image-point is proportional to the scratch radius, then the aperture angle of the circumference-arc is like the limit of a certain viewing angle, so that image only becomes visible at viewing angles.

Here, to appreciate the effects of depth, we show photographic stereoscopic pairs obtained from reconstructed 3D images. We use the illumination modes by either reflection or transmission. All images