# Security aspects of commercially available dot matrix and image matrix origination systems<sup>1</sup>

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### ABSTRACT

This paper discusses the security aspects of a few commercially available hologram origination systems. Some of these compose an image by creating a matrix of laser beam interference dots, so called "dot matrix" origination systems. Others compose a matrix of microscopic images, in this paper referred to as "image matrix" origination systems. Samples of holograms originated with several commercially available origination systems were collected and their microscopic structures studied.

It is assessed that some hundred systems are currently sold worldwide, but an assessment of the number of privately built origination systems will probably be difficult. Such hologram origination systems allow composing an unlimited variety of high resolution diffractive images and the danger of abuse of these systems to imitate existing security features is obvious.

A discussion is devoted to the various security aspects of these origination systems and the means available to detect and trace these.

Keywords: document security, DOVID, dot matrix holography, image matrix holography, counterfeiting, Universal Hologram Scanner.

### **1** INTRODUCTION

Dot matrix holograms are Diffractive Optically Variable Image Devices (DOVIDs) that consist of an array of fine diffractive dots, together composing an optically variable image. Typical for dot oriented holograms is that the dots consist of a uniform diffraction pattern, of which the grating pitch and grating orientation may or may not vary from dot to dot, depending on the optical system applied. In contrast, image oriented holograms are composed of an array of microscopic images. Examples of dot matrix holograms are discussed in section 2, while examples of image matrix holograms are discussed in section 3. Various holographic origination systems of the dot matrix and image matrix type are commercially available. It is assessed that some hundred systems are currently sold worldwide, but the number of privately designed and built origination systems is unknown.

Since the invention of dot-matrix holography by Frank Davis in 1988 [1], the technology has mushroomed and various proprietary and commercially available systems have been developed. The first concept, filed by Davis in 1998, and shown in Figure 1, has three object beams to produce true color images but does not allow grating orientation and continuous pitch adjustment. In his 1996 filed patent [2], Davis proposes a rotating optical set-up (Figure 2), to realize continuous grating orientation. In that same patent Davis also proposes a set-up with translating mirrors in order to continuously vary the angle between both interfering beams (Figure 3). Continuous variation of grating pitch and grating orientation are the basis of modern holographic origination systems and they allow the design of kinematic animation, morphing, 2D/3D, 3D, kinematic animations and true color rendition.

Since, a variety of origination systems has been realized by different manufacturers, some of which are discussed in this paper. The system information presented in this paper was provided by the manufacturers or found on the internet. For complete information reference is made to the brochures provided by the manufacturers.

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Figure 1 – Optical set-up from Davis US 5,262,879 patent [1]. Three object beams for color rendition, no grating orientation, no variable pitch adjustment.

Figure 2 – Optical set-up from Davis US 5,822,092 patent [2]. Three object beams for color rendition, the optical system can be rotated for grating orientation; no variable pitch adjustment.



Figure 3 – Optical set-up from Frank Davis US 5,822,092 patent [2]. Grating orientation and pitch adjustment are proposed.

Apart from grating pitch and orientation, dot matrix holograms are characterized by properties such as resolution and cross talk. These properties are presented in Table 1, where an obvious distinction is made between quality and design properties. In a dot oriented matrix, the dot-resolution refers to the actual number of dots written per inch, while in an image oriented matrix the specified resolution refers to the resolution of the image in the matrix. Obviously, for a given spatial frequency of dots or images, the image resolution will need to be significantly higher than the dot resolution.

Table 1 – Properties of Dot and Image Matrix Hologram	IS
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Design properties	Quality properties
Dot/Image location	Dot/Image position jitter
• Image design	Dot/Image resolution
Grating orientation     Kinematic animation	Grating angle resolution
• Morphing	Filling factor
<ul> <li>2D/3D and 3D digital images</li> <li>Grating pitch</li> <li>True color rendition</li> </ul>	Diffraction efficiency
	Dot/Image shape
<ul><li>Color gamut</li><li>Viewing angle</li></ul>	Cross talk between dots

Many of these systems are commercially available, while some are proprietary. A few examples of these systems are presented in Table 2. The commercially available systems are of particular relevance in this context, because these may ultimately become available for counterfeiters. Abuse of proprietary systems seems less likely and, therefore, these are not discussed in this paper.

Table 2 – Examp	les of Dot M	atrix and Image	Matrix Hol	ographic systems
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	Dot Matrix Oriented	Image Matrix oriented
Commercially available systems	Dimensional Arts/HoloCom (USA) Light Machine	New Light Industries (USA) Holographic Imagesetter
	Spatial Imaging (UK) <i>LightGate</i>	Polish Holographic Systems (Poland) KineMax, HoloMax
	AHEAD Optoelectronics (Taiwan) Sparkle I, II	
Proprietary systems	ITW Holographics (USA) iScan	Pacific Holographics (USA) SecureText

## 2 DOT MATRIX HOLOGRAMS

### 2.1 Light Machine – Dimensional Arts

An example of a low-resolution (200 dpi) dot matrix hologram is given in Figure 4. It is written with an early Dimensional Arts' Light Machine at Light Impressions (UK), for producing diffractive patterns for decorative purposes. The dot size is 125  $\mu$ m, the dots show strong cross talk and significant positional jitter, while the filling factor is only limited. The dot-pattern does not allow incorporating fine security patterns such as microtext, and is typical for early dot-matrix holograms.



Figure 4 – Microphotograph of dot pattern, written with a 200 dpi Light Machine: dot size 125  $\mu$ m. Hologram sample made available by Light Impressions Int. (UK).





Figure 5 – Microphotographs of dot patterns written with a Light Machine at 400 dpi, 600 dpi and 1200 dpi, with average pixel sizes of 63  $\mu$ m, 42  $\mu$ m, and 21  $\mu$ m.

Hologram samples made available by Hueck Folien (Germany).

In Figure 5 Light Machine patterns of square dot are presented from holograms made available by Hueck Folien (Germany). This Light Machine model was built in 1999 and operates at 400, 600 and 1200 dpi. The photographs respectively illustrate cross talk between pixels, pixel size variations and loss of pixel resolution at high pixel frequencies. This Light Machine allows true color rendition by single (R, G, and B) and multiple grating pitch exposure of dots (Ye, Ma, Cy, and white dots). At the time, it was mentioned on the internet<sup>3</sup> that the Light Machine provides dot shape control to differentiate between machines and has three registered angle writing heads for color mixing, where each registered angle is unique to the machine with which it is sold.

<sup>&</sup>lt;sup>3</sup> http://www.holo.com/holo/cmpany/da.html of Dimensional Arts & HoloCom Inc. Last visited on September 2003; Internet source no longer available.

### 2.2 Lightgate - Spatial Imaging

Figure 6 shows a 1016 dpi pattern of 25  $\mu$ m diameter dots, written with Spatial Imaging's Lightgate V4. The filling factor is relatively high, yet the cross talk is only moderate. Pixel position jitter in the order of a few microns appears in this hologram. According to specifications, the Lightgate V4 system provides circular dots of sizes 50  $\mu$ m (508 dpi), 25  $\mu$ m (1016 dpi), 12.5  $\mu$ m (2032 dpi) and 8  $\mu$ m (3048 dpi), the dot size being manually controlled. True color rendition is provided by single and multiple beam dot exposure (R, G, B, Ye, Ma, Cy and white dots). The system also writes covert laser read images.<sup>4</sup>

An interesting optical set-up, depicted in Figure 7, is proposed by Robert Munday of Spatial Imaging [3]. The grating pitch and orientation are adjusted by a spinning aperture set, which, depending on the aperture orientation will create sets of two or more beams. The required apertures can also be displayed on a LCD, thus making the set-up even more versatile. Together with a pulse laser this set-up would allow for extremely fast exposure rates of dots with variable grating pitch and orientation, as well as allow double and triple dot exposure for true color rendition, as illustrated in Figure 7.



Figure 6 – Microphotographs of dot patterns written with the Light Gate V4. The dots are 25  $\mu$ m diameter (1016 dpi). The lower dot row in the bottom illustration is triple exposed.

Hologram sample made available by Spatial Imaging Ltd. (UK).

<sup>&</sup>lt;sup>4</sup> Spatial Imaging communicates (21 May 2004) that an origination system, based on their new Lightspeed Technology, will be launched soon. This system is essentially different from the Lightgate V4 system and can write any shape dots with very high speed (1500 dots/s) and resolution (> 3000 dpi), with 100 nm dot location precision.



Figure 7 – Optical set-up from Munday patent WO 98/29767 [3].

A variable aperture for triple exposure of dots is illustrated.

#### 2.3 Sparkle – Ahead Optoelectronics

Figure 8 shows various dot patterns written with a Sparkle II from Ahead Optoelectronics (Taiwan). All dots are well resolved and placed in a close packing. A slight vertical dot jitter can be observed in Figure 8 top left. No noticeable cross talk exists between dots of different grating orientation (Figure 8 bottom left), but strong cross talk is found for the Sparkle I. Obviously, dots of 6 µm size can only contain about 6 fringes and are near the lower useful limit of dot size. The Sparkle I system writes circular dots, variable in size from 150 to 1,300 dpi. The Sparkle II optical system writes variable dot sizes from 400-4,000 dpi and allows shape control (round, Gaussian and square) on the fly. Both the Sparkle

I and II systems provide true color rendition by writing R, G, and B dots.

The optical set-up of the Sparkle I system is presented in Figure 9 [4]. The system allows continuous size adjustment of round dots by lens translation. The grating orientation is adjusted by rotating the optical head, while the grating pitch can be continuously adjusted by translating two reflecting prisms. The optical principle of the Sparkle II is similar, but its configuration allows the choice between round and square dots and additionally provides direct laser writing microscopic features with line widths under 1  $\mu$ m, (resolution specified as over 43,000 dpi) as illustrated in Figure 10. The Sparkle systems also write covert laser read images and moiré type hidden images.



Figure 8 – Microphotographs of Sparkle II dot-patterns. Top left: Microtext 0.24 mm high, consisting of 10  $\mu$ m dots and 60  $\mu$ m dots showing a slight jitter. Top right: 6  $\mu$ m dots at 2,400 dpi. Bottom left: 10.5  $\mu$ m dots at 2,400 dpi and bottom right 6  $\mu$ m dots at 4,000 dpi. Hologram and photograph of 4,000 dpi pattern made available by Ahead Optoelectronics (Taiwan).



Figure 9 – General optical set-up of the Sparkle system [4]. Dot size, grating orientation and grating pitch can be continuously adjusted by the respective translation of a lens, the rotation of the optical head and the translation of reflecting prisms.



Figure 10 – Microscopic details of a Sparkle II dot matrix hologram. Left:  $65 \mu m$  pixels incorporating characters "H" created by direct laser writing. Right: detail of characters "H",  $15 \mu m$  high. Hologram made available by Ahead Optoelectronics (Taiwan).

### **3 IMAGE MATRIX HOLOGRAMS**

#### 3.1 Imagesetter – New Light Industries

An example of a commercially available image matrix oriented system is the Holographic Imagesetter of New Light Industries (USA). Two types are available: the HI-600 and the HI-1200, respectively providing dot resolutions of 600 dpi and 1200 dpi. The HI-600 prints round and square dots with a single grating frequency. The HI-1200 prints dots of any shape with continuous frequency variation and thus provides full color rendition. The image resolution is specified as up to 20,000 dpi. Optional are on the fly dot shape and image content control, covert laser read images and moiré type

hidden images. No information is available on the optical set-up of the Imagesetter<sup>5</sup>.

Figure 11 left gives an example of an image matrix written by the Imagesetter. The 50  $\mu$ m size images contain the New Light Industries company logo, while the 25  $\mu$ m images (1016 dpi) contain a 6 x 6  $\mu$ m marker, of which the location in the dot varies with the location of the dot in the hologram. Figure 11 right shows that there is no appreciable cross talk between dots of different fringe orientation. Microscopic inspection reveals no appreciable image jitter.



Figure 11 – Left: image matrix with 50  $\mu$ m square dots containing the New Light Industries logo, and 25  $\mu$ m dots containing a 6  $\mu$ m marker. Right: 25  $\mu$ m square dots of different fringe orientation without cross talk.

#### 3.2 KineMax and HoloMax – Polish Holographic Systems

Two other image matrix systems discussed in this paper are the KineMax and HoloMax of Polish Holographic systems. The KineMax system writes image pixels of any shape. Examples of KineMax image matrices are given in Figure 12. Each image in the matrix can consist of a homogeneous grating or be composed of an arbitrary set of distinct gratings with different orientations and pitches. Together, these matrix images pattern the total image content of the hologram, although they can also incorporate complete micro-images. The image resolution is specified as 6,000 dpi (12,000 dpi optional). Figure 12 shows no appreciable jitter between images, while Figure 12 bottom left shows that there is no cross talk between image elements of different fringe orientation.

The principle of the KineMax optical set-up is given in Figure 13 [5]. It utilizes a diode laser, which expanded beam illuminates a transparent spatial light modulator (SLM), for instance a liquid crystal display. An image is displayed on the SLM that is subsequently reduced to microscopic size by a second lens system and recorded in photoresist on an XY-stage. Each separate matrix image, displayed on the SLM, contains a set of gratings with grating pitch and orientation adjusted to requirements. In the Fourier plane behind the SLM spatial filters can be positioned, for instance to block the zero order and orders higher than both first orders. An important advantage of such set-ups is that these do not require vibration damping.

The HoloMax system writes a matrix of microscopic images, each being a computer generated hologram (CGH) with a resolution of 2,000-10,000 dpi. The individual images are calculated to diffract light such that plus and minus first order are different. The following is an account of the HoloMax system derived of a 2000 paper by Stepien [6]. The term "computer generated hologram" (CGH) is sometimes used for stereograms and dot matrix DOVIDs, where computers control the mastering process. However, the authentic connotation of the term CGH is restricted to a diffractive structure that is calculated and recorded to diffract light in specified directions. The cross section profile of a CGH or its spatial

<sup>&</sup>lt;sup>5</sup> New Light Industries communicates (8 May 2004) that a new Imagesetter, the HI-2400, is expectedly available by August 2004. It works on a different optical principle than the HI-600 and HI-1200. It will be faster than the HI-600 and HI-1200, and it will provide 3D imagery as well as 2D/3D and gratings. The 3D components will be real 3D, not a matrix of tipped gratings.

transmission is a result of wavefront calculation rather than the interference of two or more laser beams or an analytic description of an array of diffraction gratings. The HoloMax mastering of CGHs involves calculating a holographic pattern using a special form of the Fourier transform iterative algorithm [7]. A grayscale map of the CGH structure is subsequently displayed on a SLM in an optical set -up, optically reduced and recorded on a photoresist as illustrated in Figure 13. However, due to the diffraction limit of the optical recording system, which only transmits the plus and minus first diffraction order, the recorded fringe profile is sinusoidal. Nevertheless, the result displays all optical effects required by DOVID designers and the image resolution amounts up to 20,000 dpi.

CGHs are calculated with submicron accuracy and their full potential can be only exploited once sufficiently high resolution recording technologies are utilized, such as electron beam microlithography. Amongst others, this will allow making CGHs with asymmetric fringe profiles, displaying different plus and minus first orders [8]. Such CGHs require an enormous amount of computational capacity and handling of a far greater amount of data than in standard microelectronic circuit mask recording systems. This means that such origination systems will be extremely expensive and their use restricted to top security applications.



Figure 12 – Image matrix patterns written with the KineMax system of Polish Holographic systems. Top left: matrix of 65 x 87  $\mu$ m images together forming an "H". Hologram provided by Light Impressions (UK). Top right: matrix of 155 x 210  $\mu$ m images incorporating small rectangles of 13 $\mu$ m width. Hologram provided by Polish Holographic Systems. Bottom left: detail of 13  $\mu$ m wide rectangles. Bottom right: matrix of 165 x 220  $\mu$ m cross-shaped images. Hologram provided by Optical Verification Components (Denmark).



Figure 13 – Principle of the optical set-up of the KineMax and HoloMax systems [5].

#### 4 SECURITY CONSIDERATIONS

#### 4.1 Additional Security Features

The examples presented in Section 2 demonstrate the considerable differences existing between dot matrix systems available from different manufacturers. But, because systems continuously evolve, significant differences also exist between different origination system versions of the same manufacturer. A good example of the differences within a system series is depicted in Figure 4 and Figure 5. The differences between the image matrix systems presented in Section 3 are also obvious, and differences also exist between successive image matrix systems of manufacturers. Present-day dot matrix and image matrix systems are capable of writing dots or image details measuring only a few microns with submicron position jitter, and they are thus capable of writing microscopically fine security features. As such they appear well-matched to any other holographic origination system. Quality properties, as listed in Table 1, are paramount for the security value of dot and image matrix devices. However, such quality only becomes apparent under microscope observation, unless it is made apparent by additional security features, based on this quality, that allow inspection without microscopic observation. First-line kinematic effects, 2D/3D, 3D, holographic animations and true color, however attractive and indispensable for holographic designs, do not serve this purpose because these can be realized with relatively low resolution systems as well; the naked eye can hardly or not distinguish between low and high resolution images. Fourier type holograms, also referred to as covert laser read images, and moiré based hidden images, both also being machine readable, require relatively high resolution and can be simply inspected in second-line without the use of a microscope. For instance a 1,000 dpi hidden moiré image requires a dot position precision better than at least 2,000 dpi, and well resolved dots as small as 25 µm.

- Summarizing, important optical issues from a forensic point of view are the following:
- Minimal cross talk between dots (low noise)
- Dot size and dot shape control
- High optical resolution and low dot/image position jitter
- High filling factor
- · Hidden laser read images, moiré hidden images, micro images
- Hidden, unique machine readable codes
- · Computer Generated Holograms, projecting optical effects based on asymmetric grating profiles.

#### 4.2 Detecting and Tracking Counterfeits

It is assessed that about a hundred dot and image matrix systems are currently sold worldwide, but the number of privately designed and built origination systems, sometimes even being illicit copies of existing systems, is harder to assess. Moreover, new developments take place continuously, so that the diversity of origination systems continuously grows.

Dot and image matrix origination systems are extremely versatile. With their use it is possible to compose a virtually unlimited variety of intricate high resolution diffractive images with 2D, 2D/3D, 3D and true color properties. A serious risk exists that such systems are abused to imitate existing security DOVIDs. Such imitations require an analysis of the spatial image content and grating frequency content of the original hologram and dedicated software to convert these data into a dot matrix holographic imitation. Expectedly, even without the analysis being very accurate, such imitations can be extremely deceptive even for the expert first-line inspector. Once such imitations appear, it will be paramount to (1) detect them as fakes and (2) track on which origination system they were composed.

McGrew proposes a hologram analysis system - the Universal Hologram Scanner (UHS) - for accurate analysis of holograms in both the spatial and Fourier domain [9-13]. This system scans the frequency content of a hologram as a function of its spatial composition with a scanning resolution up to 2000 dpi. The current data can be compared with the data of the original (reference) hologram, possibly present in a database, and any counterfeit remake is revealed although it could pass visual examination by even a holographic expert. This is because the remake of a security hologram will not likely contain the exact frequency content of the reference hologram as a function of its spatial content. A passable remake would require the exact geometry of the original holographic set-up, with original object and identical optics. But even most holographic copies would not have identical spatial frequencies to the original, for instance because of optical aberrations in the beams. Obviously, contact copies will be nearly identical to the original, except for noise picked up in the copy process. Holograms made from a stolen shim, of course, are identical to the original. Consequently, the UHS can also prove that a hologram is derived from the original shim. This has been used to prove that some supposed holographic counterfeits in Eastern Europe were actually made from stolen shims [14]. In the case of dot matrix holography, which origination does not involve a holographic set-up, such a remake would require a dot by dot exact replay of dot grating frequency and grating orientation. The data extracted by the UHS in the spatial and frequency domain can also reveal information about the counterfeiter's holographic set-up, and can thereby provide forensic evidence potentially useful in proving the source of a counterfeit.

Apart from recognizing imitations of security holograms made by dot matrix technology, the task of determining on which origination system they were made is of paramount importance for tracing counterfeiters. Manufacturers will often be able to recognize their origination systems by microscopic study of a sample and tell which particular system this is. Revealing features are dot positioning jitter, dot size and shape, hidden codes, etc., together making up a "fingerprint" identifying the origination system.

A more difficult task in the first place is establishing the manufacturer of the origination system of a questioned hologram. The exposition in sections 2 and 3 of the variety of dot compositions is presented as an indication of the enormous variety of dot matrix and image matrix compositions currently in existence. It would involve a major effort to collect and categorize the fingerprinting characteristics of at least the majority of existent systems and their whereabouts. Given sufficient resources, this might be a feasible task, but, expectedly, in a few years time this task may be too disheartening to be even seriously considered. However, it is believed that no one has done the research to make a comprehensive database of all the different dots and images from all the various commercially available origination systems, letting alone the privately built systems. Currently, therefore, recognizing origination systems appears more of a concept than a reality. If authoritative bodies such as the FBI, Europol, Interpol or the ECB now started to undertake such an endeavor, then it might be possible to compile and maintain such a database of samples and quantitative forensic characteristics from a major part of the existing origination machines. The UHS could be a suitable instrument aiding such a forensic task [15].

An even more demanding task for these authoritative bodies might be to compile a list of at least the majority of the companies in the world manufacturing and selling holograms and collecting samples from them. A database should then be compiled with forensic data of the materials that the holograms are made of (mostly polyester with a lacquer coating) and a materials supply tree can then be composed. This materials supply tree would start at the small number of suppliers of polyester and subsequently of manufacturers that provide the lacquer coating and it would expand as different components, such as analyses of label adhesives and embossing machine adhesives, are added to the data tree. Counterfeits can then be forensically analyzed and their location in the materials supply tree can be established, perhaps tracking the counterfeit down to just a few companies. Cross-matching these results against a parallel database of optical characteristics of origination systems might allow narrowing the origin of the counterfeit down to a single source [16].

Apart from the worldwide cooperation required from origination system and hologram manufacturers, undoubtedly, these parallel tasks demand considerable and continuous expenses and a permanent capacity of experts in the field, operating under the flag of an authoritative international body. However, considering the ongoing development of holographic counterfeits, it appears paramount to undertake a feasibility study without unduly delay. Ultimately, curtailing the inevitable damage through timely research may turn out to be significantly less costly than an "après nous le déluge" approach.

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