The story of the Lightgate dot-matrix hologram mastering system

The Lightgate B system, 2004.

What is a dot-matrix hologram

Dot-matrix holograms are a distinct type of hologram whose origination, appearance, and viewing characteristics differ fundamentally from those of conventional holography. They consist of thousands, and often millions of microscopic "dots," each containing a precisely formed diffraction grating. These dots are usually recorded individually, under computer control, by converging two or more tightly focused laser beams to a common point to create a tiny interference pattern. Because dot-matrix holograms are generated from computer-created imagery and typically recorded onto photoresist to produce surface-relief structures, they are easy to view under almost any lighting conditions. Crucially, the orientation and spatial frequency of the grating within each dot can be independently specified, enabling the creation of complex, fully synthetic imagery and making dot-matrix holograms a mainstay of optical security and anti-counterfeiting applications.

A eureka moment

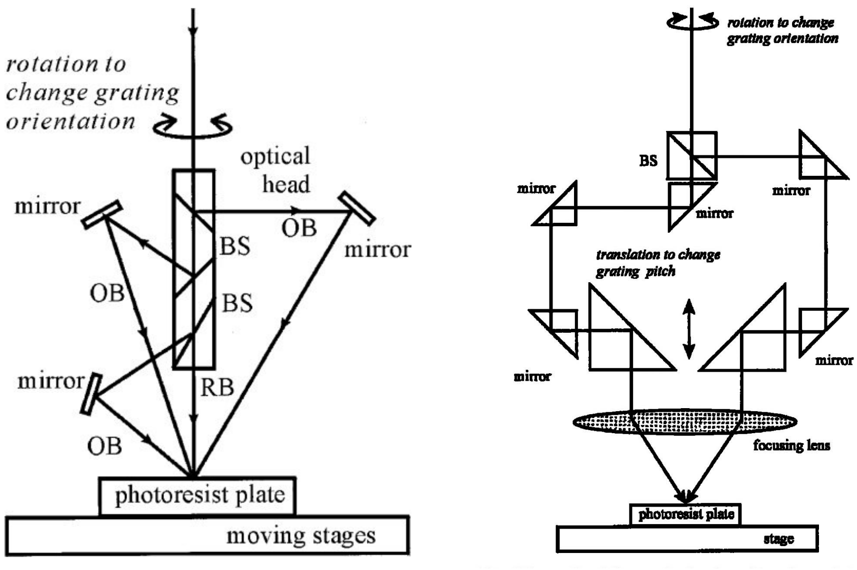
In the late summer of 1996, one evening while relaxing in the bath at home, I experienced a eureka moment that would shape the technical side of my holographic career and drive the business of my company, Spatial Imaging Ltd., for the next thirty years.

I had been tasked by Walter Clarke, a Canadian-Irish investor and owner of the American holography company Global Images Inc., to design and build a dot-matrix hologram-mastering system. Walter had previously purchased two of my DI-HO digital holographic stereogram mastering systems for his security hologram companies in China and India, but he had recognised the potential advantages of dot-matrix technology for security-hologram origination.

In 1996, only four dot-matrix mastering systems were known to exist. The earliest, the Light Machine, was developed by Frank S. Davis in 1986, with later technical input from Kenneth (Ken) Harris of Dimensional Arts Inc. The second and third were proprietary systems developed by Craig Newswanger for Applied Holographics plc in 1990, and Fujio Iwata for Toppan Printing Co., Ltd. in 1994. The fourth was developed by Chih-Kung Lee at the National Taiwan University in 1996 and was released and marketed as the Sparkle system by Ahead Optoelectronics, Inc. in 1998.

Little is known about the Toppan system, however, both the Dimensional Arts and Applied Holographics systems were relatively slow and produced only low-resolution dot-matrix holograms, limiting them to making simple diffractive patterns. C.K. Lee's system offered a somewhat higher speed and resolution, but it did not become commercially available until 1998. Only the Light Machine, however, could be purchased at the time and yet was incapable of making advanced security holograms and digital stereograms. As discussed in more detail below, both the Light Machine and the later Sparkle system relied on an assemblage of cumbersome optical components to split and then recombine the interfering beams, whereas Craig Newswanger's system used a spinning diffraction-grating/lens assembly. All were limited in operation and features.

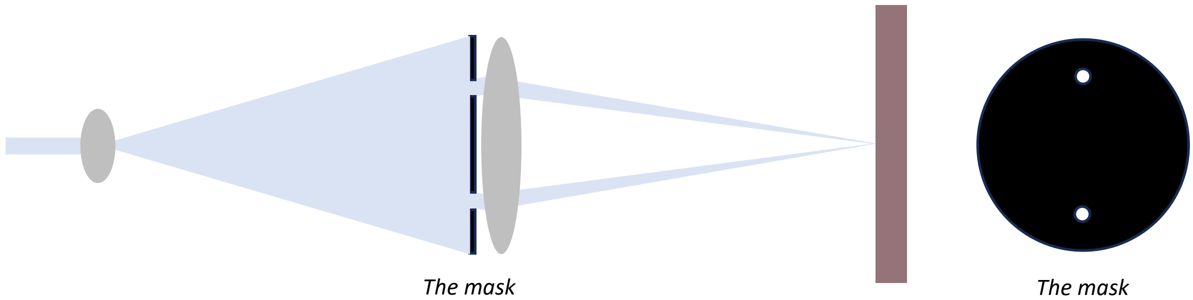
Below are diagrams of the optical configurations for the Light Machine and the later Sparkle system. As can be seen, these systems comprised of a multitude of glass beamsplitters (BS) and mirrors, to split and then recombine pairs of beams. In the case of the Light Machine, only three object beams (OB) were arranged at different angles relative to the reference beam (RB) to allow for the selection of only three grating spatial frequencies (colours). The entire assembly of optics for both systems then needed to move, rotate, stop and settle before recording each diffractive pixel, resulting in ungainly, difficult to align, and slow machines.



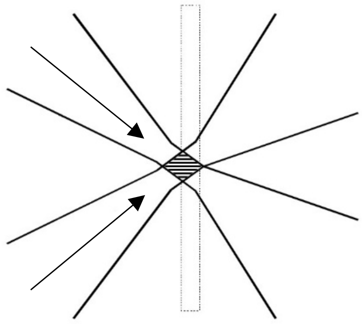
Left: A diagram of the optically complex 1989 Light Machine by Dimensional Arts Inc.
Right: A diagram of the even more complex 1995 C. K. Lee / Sparkle system by Ahead Optoelectronics, Inc.

Keen to avoid replicating any of the existing technologies, I spent several weeks trying to devise an alternative approach. Then, as I relaxed in the bath, an idea struck me - so simple and so much more elegant than any other system that I was convinced there must be a reason it couldn't work. By the next morning, having failed to think of one, I eagerly travelled to my studio at 8 Wheatash Road, Addlestone, Surrey, to test the idea.

The concept couldn't have been simpler: make two holes in a thin piece of cardboard and place it in a diverging laser beam. The mask would block all but the light passing through the two apertures, creating two spatially separated coherent beams of light. A single lens placed in front would then bring those beams to a common, overlapping focal point. At that intersection, the beams would interfere, and the resulting interference pattern could be recorded as a diffractive pixel.



The mask *The mask*



The Lightgate optical principle.

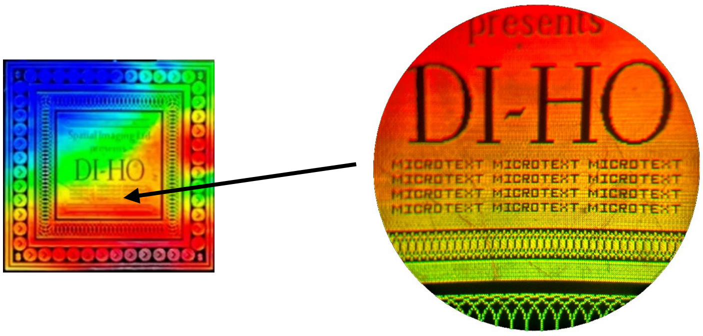
Arriving at the studio, I realised that I could use my DI-HO system's optical recombiner to translate a photoresist plate in X and Y directions to make a test, and so I quickly wrote a simple software routine on my Amiga computer to step it in very small, pixel sized increments between exposures. I then set up the optical components seen in the diagram above, an expanding lens to diverge the beam, a thin piece of cardboard with two holes, and a large lens to reconverge and focus the resulting pair of beams onto the photoresist plate. With excitement I exposed a small area roughly 2 mm square.

At that time, the highest-resolution, and indeed the only commercially available system in the world was the Dimensional Arts Light Machine, with a resolution of only 100-200 diffractive pixels per inch and a speed of only 1-2 exposures per second. After developing my very first test, and seeing bright rainbow colours diffract from its surface, I placed it under the microscope and, to my amazement, discovered a near-perfect dot-matrix hologram with a resolution of 1,270 dpi - some six to twelve times higher resolution than the Light Machine. What's more, and with further testing, a speed of 20 pixels per second was achieved, 10-20 times faster than the competition. In short, I had built the highest-resolution and fastest dot-matrix system in the world.

The rest is history. The idea worked, no one else had conceived it, and that single eureka moment resulted in the bestselling dot-matrix hologram mastering system ever built, and the first dot matrix system to be able to make complex and sophisticated security holograms, spawning a whole new security hologram industry worldwide.

Walter Clark suggested the name Lightgate, and I added 1270 to convey its resolution, thus the *Lightgate 1270* was born.

It is often quoted that the simplest ideas are the best ideas, and this simple idea earned the company millions of pounds Stirling in revenue over subsequent years.



The second hologram test made in the early autumn of 1996.
Thought to be the first dot-matrix hologram to record microtext. The microtext is just 100um high.

Significant advantages of my optical configuration included:

- **The interfering beams are simply two, or four parts of a single converging beam**, which means:
  a) their path lengths are inherently identical, allowing the use of lasers with very short coherence lengths,
  b) their focal spots remain always perfectly aligned with one another,
  c) their focal spots are always perfectly circular,
  d) there is no movement of the convergence point along the optical axis as the angle between the two beams is varied.

- **The system contains no moving optical components**, eliminating sources of mechanical drift or instability in the interfering beams.

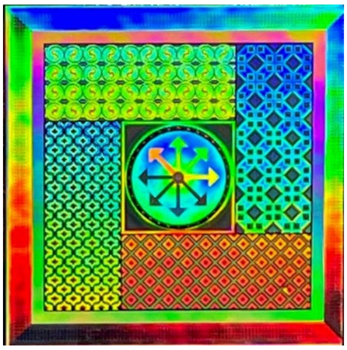
- **The only moving element is a simple, lightweight mask** (later two masks) that can be rotated at high speed, dramatically reducing the exposure time required to record a dot-matrix hologram.

- **The compact optical system fits within an open-frame XY table and beneath the photoresist plate, which lays face down**, thus:
  a) Providing a highly stable platform,
  b) Preventing dust from settling on the photosensitive surface,
  c) Shielding the photosensitive surface from ambient light,
  d) Enabling straightforward visual focus alignment from above using a microscope.
  e) Ensuring that focus remains consistent regardless of variations in photoresist plate thickness.

Having now proven the concept, the next step was to build a simple mechanical system to rotate the mask - and therefore the two interfering beams - to any angle. This was simple enough. I made a more rigid mask, this time from a thin sheet of aluminium, drilled two 1mm diameter holes in it, and mounted it in such a way that it could be rotated using a stepper motor under computer control. It was at this point that my Lightgate Control software program was born. The program needed to rotate the mask, and hence the two interfering beams, in accordance with the grey level of the pixel in the computer bitmap image being recorded - see below for a full explanation of the dot matrix principle.

This simple technique, whereby the grating orientation, or angle of diffraction, is rotated for each diffractive pixel, creates a moving colour effect as the hologram is tilted, and so I termed this kind of dot-matrix hologram a 'kinetic' hologram.

Having written the software, I then created the first and second embossed kinetic holograms to be made using a high-resolution Lightgate dot-matrix system in autumn of 1996, see below:



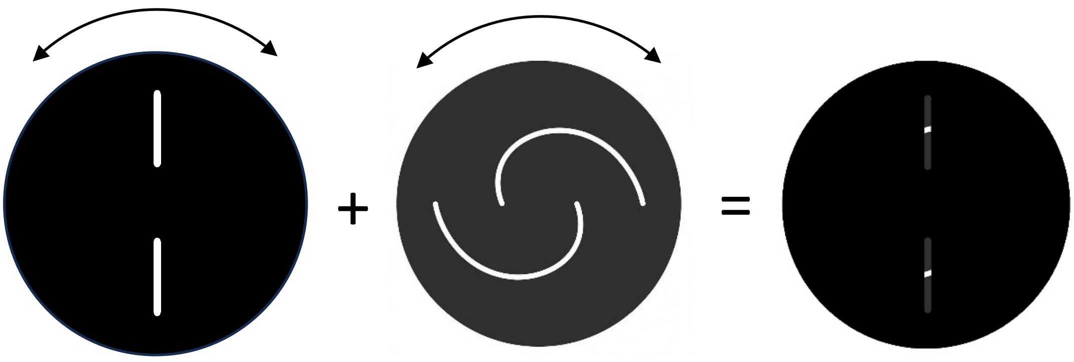
The second 'kinetic' dot-matrix hologram made using a Lightgate in autumn of 1996.

The next significant development followed quickly in January 1997. Whilst it was now possible to create high-resolution, single frequency (single colour) kinetic holograms, the final challenge was to invent a method to additionally move the two beams closer together or further apart, i.e. change the angle between them. By doing so, it would then be possible to also change the spatial frequency (relative colour) of each diffractive pixel on the fly.

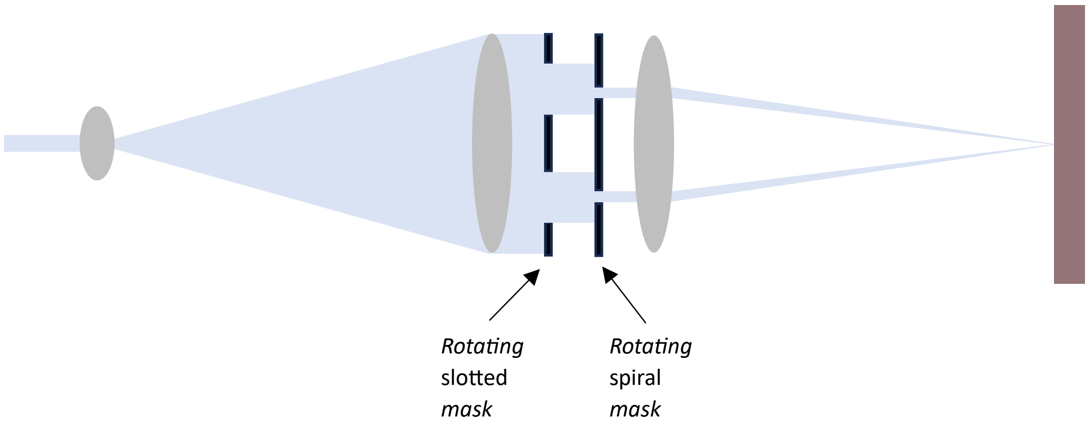
Not only that, but by being able to continuously change both the grating orientation and the grating spatial frequency at the same time, it would be possible to diffract the light from any given pixel in the hologram though any angle and thus to any point in space. This would ultimately lead me to develop several highly sophisticated optical features including the first dot-matrix covert laser projected hidden images and the first dot-matrix full colour, wide-angle holographic stereograms, for which I won a coveted International Hologram Manufacturers 'Award of Excellence' in the year 2000 – see *LPI* and *3Digital* below.

One idea was to use a static electronically addressable mask in the form of an LCD screen, but the limited contrast rendered this approach unviable. To address the contrast problem, I next considered combining a physical mask with an LCD: the physical mask would contain multiple holes or slotted apertures, and these would be selectively masked and modulated by the LCD. This idea was included in my first patent application filed on 4th January 1997. A further difficulty then emerged, however, in the form of scatter and diffraction from the LCD itself, which produced multiple unwanted focal points on the output plane.

Then, later in January of 1997, and to avoid all these issues, it occurred to me that the simplest and most reliable method for generating two beams with any desired orientation and angular separation was to use a pair of physical masks: one containing two slotted apertures and the other containing two spiral apertures. The slotted mask would determine the orientation of the resultant diffraction grating, while the spiral mask would determine its spatial frequency.



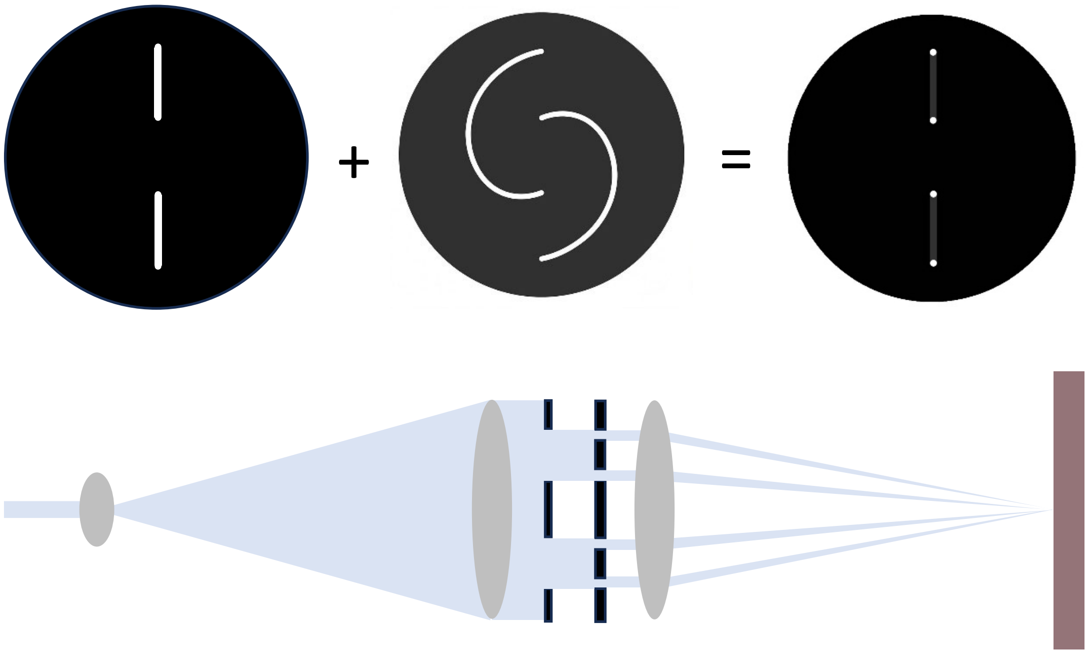
Twin masks for the selection of both grating orientation and grating spatial frequency on the fly.



The final optical configuration for the Lightgate 1270.

Left: A brand authentication hologram for Disney made using the Lightgate 1270 system, comprising of kinetic, guilloche, laser projected covert hidden image, and full colour 3D holographic stereogram optical features. The latter feature, christened 3Digital, won the IHMA 'New Holographic Technique' award in 2000.
Right: A large 100 x 100mm brand authentication hologram for Texas Instruments Inc., USA.

Whilst designing the two masks that controlled both grating orientation and spatial frequency, I realised that there was one final possibility. By arranging the apertures on each mask so that, at a single position, they overlapped to generate four beams of laser light rather than two, all four beams would interfere to form six mixed-frequency gratings. This, in turn, would produce an achromatic, or white, diffractive pixel. The ability to create achromatic pixels was exclusive to the Lightgate system and a unique selling point, enabling the creation of achromatic kinetic patterns, achromatic 3D stereograms, mixed white and coloured elements, and many other exclusive security features.



A mask configuration that produces four beams for the creation of achromatic - white diffractive pixels.

Left: A Lightgate 4-beam achromatic logo on a rainbow kinetic background.
Right: Achromatic kinetic diffractive patterns made using the Lightgate four-beam technique.
One commercially successful use of the four-beam achromatic technique was to simulate the carbon-fibre pattern.

The Lightgate 1270 was the world's first fully computer-automated, light-based, dot-matrix mastering platform capable of producing sophisticated security holograms and wide-angle 3D stereograms, surpassing the conventional 'real model' and '2D-3D' techniques used at the time. Crucially, its exceptionally user-friendly but sophisticated design and exposure software, *Lightgate Control*, allowed operators with little or even no holography experience to create complex security holograms at the click of a button for the very first time.

The Lightgate 1270 used a 442 nm blue helium–cadmium laser, but in the early 2000s this was replaced by a small, far more convenient and longer-lived solid-state 405 nm violet diode laser and the system was rebranded as the Lightgate B.

Between 1997 and 2006, over forty Lightgate 1270 and Lightgate B systems were sold worldwide, an exceptional penetration for what was, at the time, a relatively small security hologram industry.

In 1996, only a handful of large companies dominated the security hologram market, but the cost-effective, simple-to-operate, computer-automated Lightgate system enabled many smaller firms and start-ups, particularly in the Far East and Asia, not only to compete, but to produce superior, next-generation security holograms. The £98,000 Lightgate was, therefore, instrumental in the rapid expansion of the security hologram sector during the late 1990s and early 2000s, a period in which it grew into a billion-dollar industry.

The Lightgate platform then evolved through successive generations of dot-matrix mastering systems - Lightgate S - an ultra-fast system, Lightgate P – the world’s first large format dot-matrix mastering system for packaging applications, Lightgate X, Lightgate P-UV, Lightgate D, and most recently the Lightgate U system, introduced in 2025.

Billions of holograms have been produced from Lightgate 1270 and Lightgate B originated master holograms, including for some of the world’s largest security hologram projects. Even today, three decades after its invention, original Lightgate systems remain in active use for security hologram mastering. Profits from the sale of my Lightgate 1270 systems and its successors sustained Spatial Imaging Ltd., supported the company’s commercial hologram and lenticular work, funded artistic and display projects such as my own holographic portraiture, and paid the wages of its many employees.

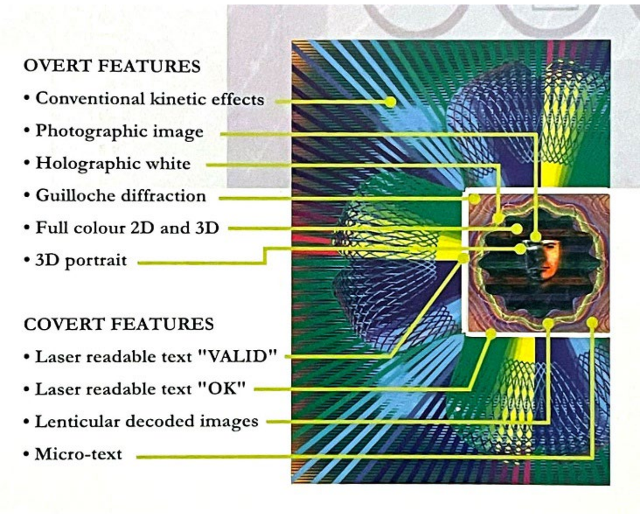
Lightgate dot-matrix holograms for the UEFA EURO 2000 Football Championships, used on all merchandise.

The Lightgate system was followed by the KineMax system, developed by Pawel Stepien of Polish Holography Systems. The KineMax employed an equally innovative but fundamentally different digital mastering technology called ‘*image matrix’*, and became the leading system from the mid-2000’s until it too was surpassed by the truly groundbreaking PicoMaster platform, a single-beam, direct-write lithography (SB-DWL) system developed in 2013 by the Dutch company 4Pico B.V. (now Raith Laser Systems B.V.), and exclusively distributed worldwide by Spatial Imaging.

Whilst other systems have come and gone, such as the accomplished but commercially unsuccessful Sparkle system from Ahead Optoelectronics, Inc, a more refined and capable version of the Light Machine; the Firefly system from Combustión Ingenieros S.A.S., modelled on the KineMax image-matrix system; and various systems produced in China and India that replicated the original Light Machine, only three digital security hologram mastering platforms have dominated the market over the past thirty years: first, the Lightgate dot-matrix system; second, the KineMax image-matrix system; and third, the PicoMaster SB-DWL system.

My eureka moment, however, and the Lightgate 1270 system that followed, proved pivotal. It set in motion a transformation of the security hologram industry and reshaped its capabilities and competitive landscape.

N.B. At this point I will mention two papers written and published by C.K. Lee: the first, *Dot Matrix Holograms*, for *The Holography Marketplace 7th Edition,* November 1998, and the second, *Optical configuration and color-representation range of a variable-pitch dot-matrix holographic printer*, for *Applied Optics*, Vol. 39, No. 1, 1 January 2000. Both contain a good explanation of dot-matrix holography, but neither mention the Lightgate system in their surveys of available systems, even though the Lightgate - with full spatial-frequency modulation and full colour 3D capability - had been developed 18 months before the first paper and several systems had already been sold. The omission was simply a consequence of my art-school background: to this day I have never written a formal technical paper and have seldom sought to publish patents or gain publicity for my technical achievements, as scientists and engineers are trained to do. As a result, those in Taiwan and elsewhere did not know of the Lightgate system or how it worked. A similar issue surrounded the invention of my DI-HO system, the world-first "digital" holographic stereogram printer in 1989–1991. In many fields, recognition of an achievement depends on publishing papers, patents, and articles; without them, new and innovative developments are easily lost to the historical record.



Right: A sample multiple-resolution Lightgate dot-matrix security hologram, 2002, incorporating the features listed on the left. At its centre is a 3Digital holographic portrait of Rob Munday. This may have been the first digital holographic portrait created using a 3D digital scan of a person's head. The resulting 3D data was then used to construct the computer model from which the stereographic image sequence was rendered.

Following are three examples of prominent Lightgate dot-matrix holograms

The Millennium Dome 2032 dpi hologram

In 1999, Spatial Imaging secured a commission from the London Millennium Dome to create three holograms, two security hologram to authenticate official Dome merchandise and a larger hologram to be applied to gift items. For such a landmark project, I set out to push the boundaries of the Lightgate still further. By adopting a shorter-focal-length focusing lens, I was able to produce an even higher-resolution dot-matrix hologram - achieving a fitting 2,000 dpi (actually 2,032 dpi) for the year 2000. N.B. 3,000 dpi resolution dot matrix holograms were ultimately achieved.

15 mm and 20 mm diameter, 2032 dpi dot-matrix holographic stereograms, of a computer-generated model of the Millennium Dome, surrounded by dot-matrix text was produced using the Lightgate 1270. These holograms were the first commercially produced >2,000 dpi dot-matrix holograms, and they are also believed to be the first commercially produced dot-matrix security holograms to contain a full colour, digital dot-matrix holographic stereogram.

A third larger 25 mm diameter hologram was also produced using a DI-HO digital holographic stereogram with overlaid dot-matrix text.

Holographic security seals for Proctor and Gamble

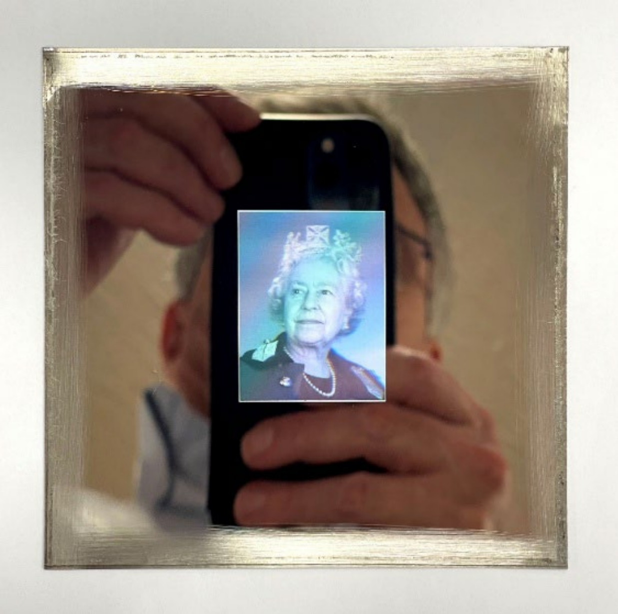
Lightgate dot-matrix holographic security seals were commissioned from Spatial Imaging for Procter & Gamble shampoo bottles distributed across South America. The project was secured after a one-hour meeting in Lima, Peru, for which I had expressly flown from London to Peru via Miami. The purpose was to curb the widespread practice of refilling and reselling discarded bottles. The design specified a single-colour 2D–3D background layer, over which text in a second colour and a four-beam achromatic logo were rendered on the hologram's surface. The project required the manufacture of millions of tamper-evident holograms, produced by Crown Roll Leaf Inc. in New Jersey, USA, which were supplied directly to P&G on a rolling three-month schedule.

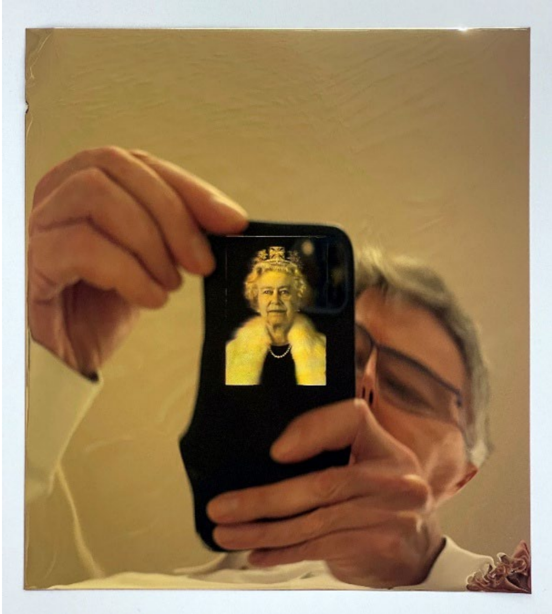
Lightgate hologram portrait miniatures of Queen Elizabeth II

Perhaps the most notable Lightgate dot-matrix holograms, made using my award-winning 3Digital holographic stereogram technique, were created by me using my Lightgate B system in 2004 and 2005. These works were the first and second hologram portrait miniatures of the late Queen Elizabeth II, or of any British monarch, and are believed to be the world's first digital dot-matrix hologram portrait miniatures, and perhaps even the first-ever hologram portrait miniatures.

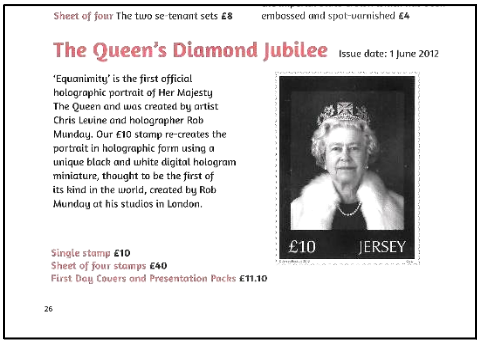
In 2003, I was commissioned to shoot and create the first officially commissioned 3D holographic portrait of Queen Elizabeth II and in doing so became the first, and to date the only royal holographer. The project was a joint creative collaboration with my former agent, designer, and now artist, Chris Levine, undertaken for the Jersey Heritage Trust to commemorate the Island of Jersey's 800-year allegiance to the English Crown. The final commissioned work was a large-format lenticular stereogram; however, between two sittings at Buckingham Palace, in February 2004, I created the first portrait miniature especially to show the Queen at the second sitting in March 2004.

The second portrait miniature - the first achromatic miniature - was created in December 2005. It was later gold-coated and unveiled to great acclaim at the Royal Miniature Society's annual exhibition at the Mall Galleries, London, in 2013. Elizabeth Meek MBE, President of the Royal Miniature Society, and the Rt. Hon. Michael Portillo, Chairman of the Federation of British Artists, described the work as "extraordinary and spellbinding" and "the future of portrait miniatures." A third portrait miniature was produced in 2011, again using my Lightgate B system, for the Island of Jersey's Diamond Jubilee postage stamp, the first stamp in the world to contain a 3D holographic portrait of a Head of State, and the first to feature a black-and-white achromatic hologram.





Left: The first digital dot-matrix hologram portrait miniature of Queen Elizabeth II, 2004.
Right: The second digital dot-matrix hologram portrait miniature, the first achromatic portrait miniature, and the first gold portrait miniature of Queen Elizabeth II, 2005/2013.


Sheet of four The two se-tenant sets £8 embossed and spot-varnished £4

The Queen's Diamond Jubilee Issue date: 1 June 2012

'Equanimity' is the first official holographic portrait of Her Majesty The Queen and was created by artist Chris Levine and holographer Rob Munday. Our £10 stamp re-creates the portrait in holographic form using a unique black and white digital hologram miniature, thought to be the first of its kind in the world, created by Rob Munday at his studios in London.

£10 JERSEY

Single stamp £10
Sheet of four stamps £40
First Day Covers and Presentation Packs £11.10

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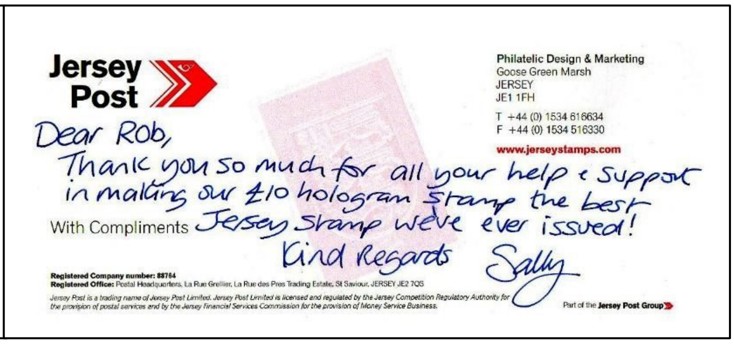
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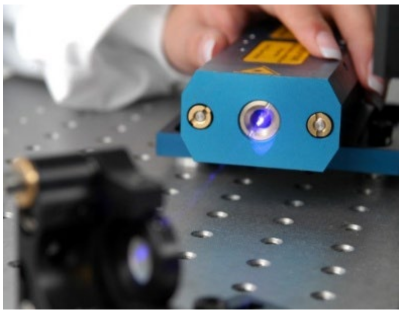
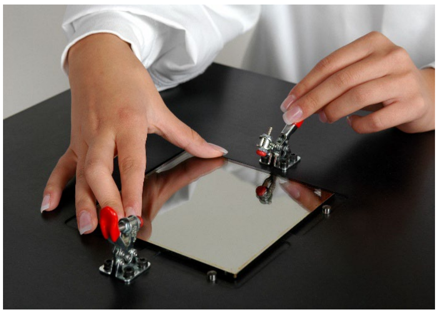
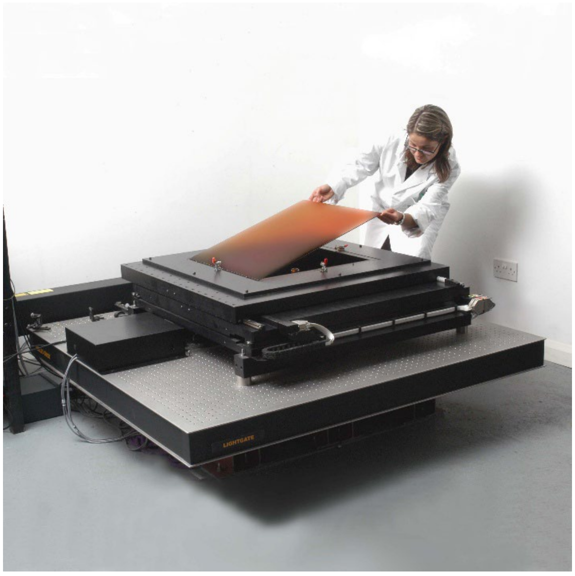
The third digital dot-matrix hologram portrait miniature of Queen Elizabeth II, 2011, for the Island of Jersey's Diamond Jubilee postage stamp, the first stamp in the world to contain a 3D holographic portrait of a Head of State and the first to feature a black and white 'achromatic' hologram.

The Lightgate 1270, 1997, utilising a 442nm helium cadmium laser.





Left: The Lightgate B System, 2004, utilising a 405nm diode laser. Right: Loading a photoresist plate.



Left: The Lightgate P1 large-format system, 2002, also known as the Lightgate Extreme.
Right: A large-format dot-matrix hologram made using the Lightgate P1 held by Spatial Imaging holographer Olivier Pitavy.

The next generation Lightgate S and Lightgate P2 systems with LightSpeed technology

In 2005, after eight years of highly successful sales of the Lightgate 1270 and Lightgate B systems, I set myself another challenge. Smaller-format dot-matrix had performed very well commercially, but no digital hologram mastering technology of any kind existed that was fast enough to produce large-format, seamless holograms for packaging applications. I had built the medium-format Lightgate P1 existed but was extremely slow.

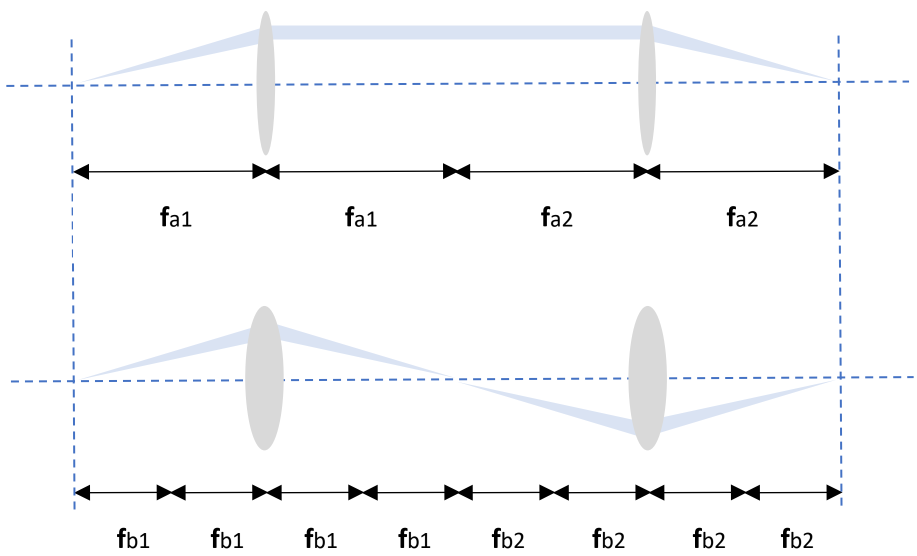
At that time, large area diffractive patterns for packaging, product enhancement, interior design, and architectural use were created by tiling a small hologram edge-to-edge. This approach inevitably introduced visible seams, an unacceptable flaw for packaging manufacturers who wanted uninterrupted, seamless imagery across their products.

The only true solution was to originate a single, large-format hologram, but with existing systems running at only a few hundred pixels per second, producing a master of that scale would have taken weeks - commercially unviable by any measure. I therefore set out to invent a system capable of producing holograms up to, and even exceeding, 1 × 1 metre in just two to three days, transforming what had previously been impossible into a practical, production-ready process.

An idea first took root through a conversation with Jeffrey Wyle of Light Dimensions Inc. in Miami, Kevin Brown's company. Jeffrey had been developing a higher-speed dot-matrix mastering system that utilised rotating dove prisms in the two legs of a Mach-Zehnder interferometer, and he flew to London to explore the concept with me. Although ingenious, that optical approach proved unsuitable for the speed and precision I needed. More importantly, my aim was to devise a completely original method, one that avoided replicating existing technologies and opened a genuinely new pathway for large-format digital hologram mastering.

The interferometer concept was compelling, however, and so I began to explore it more deeply. Scanning a beam through an interferometer causes the two emerging beams to move together while remaining superimposed. My idea was to find a way to invert one of those beams so that it became the mirror image of the other, opposite and perfectly symmetrical about the optical axis. Achieving that symmetry would unlock a fundamentally new method of generating dot-matrix holograms at high speed.

The turning point came in a brief but pivotal meeting. I arranged to see Prof. Paul French from the optics department at Imperial College, London and put the above challenge to him. His response was immediate: *"a 4F–8F system."*

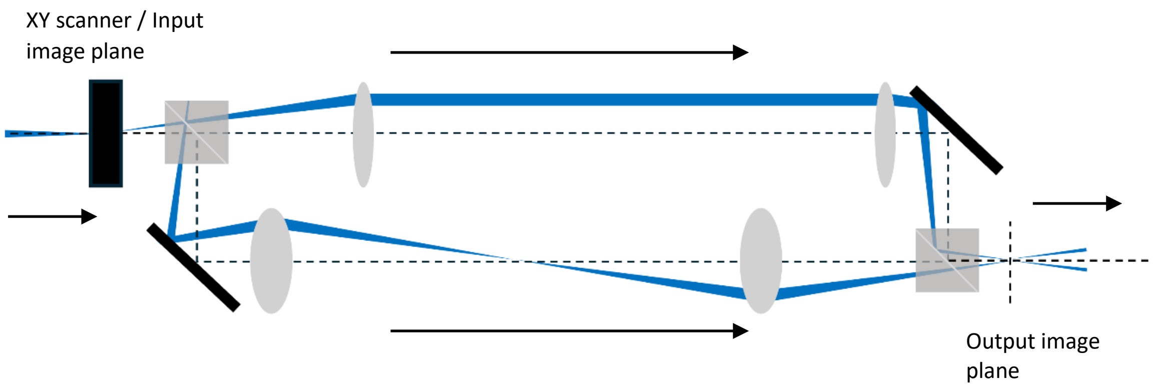


The standard 4F – 8F optical system.

A 4F–8F imaging system is essentially an asymmetric arrangement of lenses placed on either side of the interferometer, whereby the input and output images for each arm, in this case a point of light, are equal but opposite to each other.

On the first arm, two lenses of equal focal length are arranged so that the input image lies exactly one focal length in front of the first lens, and the output image is formed exactly one focal length beyond the second lens. The lenses themselves are separated by two focal lengths, giving a total optical path of four focal lengths. This configuration produces a collimated beam between the lenses, parallel to the optical axis, and yields an inverted image at the output. On the opposite arm, two lenses are again used, but with half the focal length of those in the first arm. In this case, the input image lies exactly two focal lengths before the first lens, and the output image is formed exactly two focal lengths after the second lens. The lenses are separated by four focal lengths, giving a total path length of eight focal lengths. This arrangement causes the beam to cross the optical axis between the lenses and produces an upright output image. This creates the symmetry required for the idea to work. I called it the 'scanning interferometer' dot-matrix method.

As shown in the diagram below, the first incarnation of my scanning interferometer used a narrow but expanding beam from a point source directed through a Mach-Zehnder interferometer optical system. This single input beam arrives at the far end as two output beams on opposite sides of the optical axis which refocus and recombine at the output image plane to create interference.

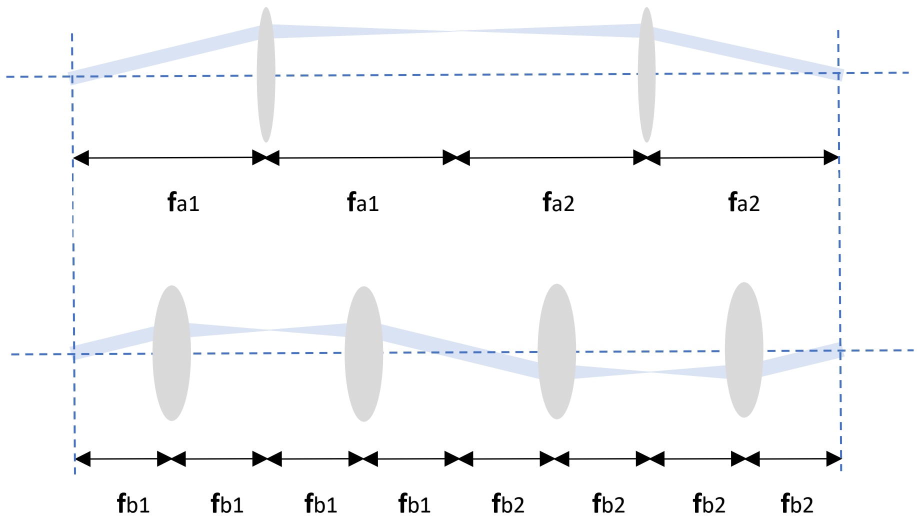


A scanning Mach-Zehnder interferometer based on a standard 4F-8F optical system.

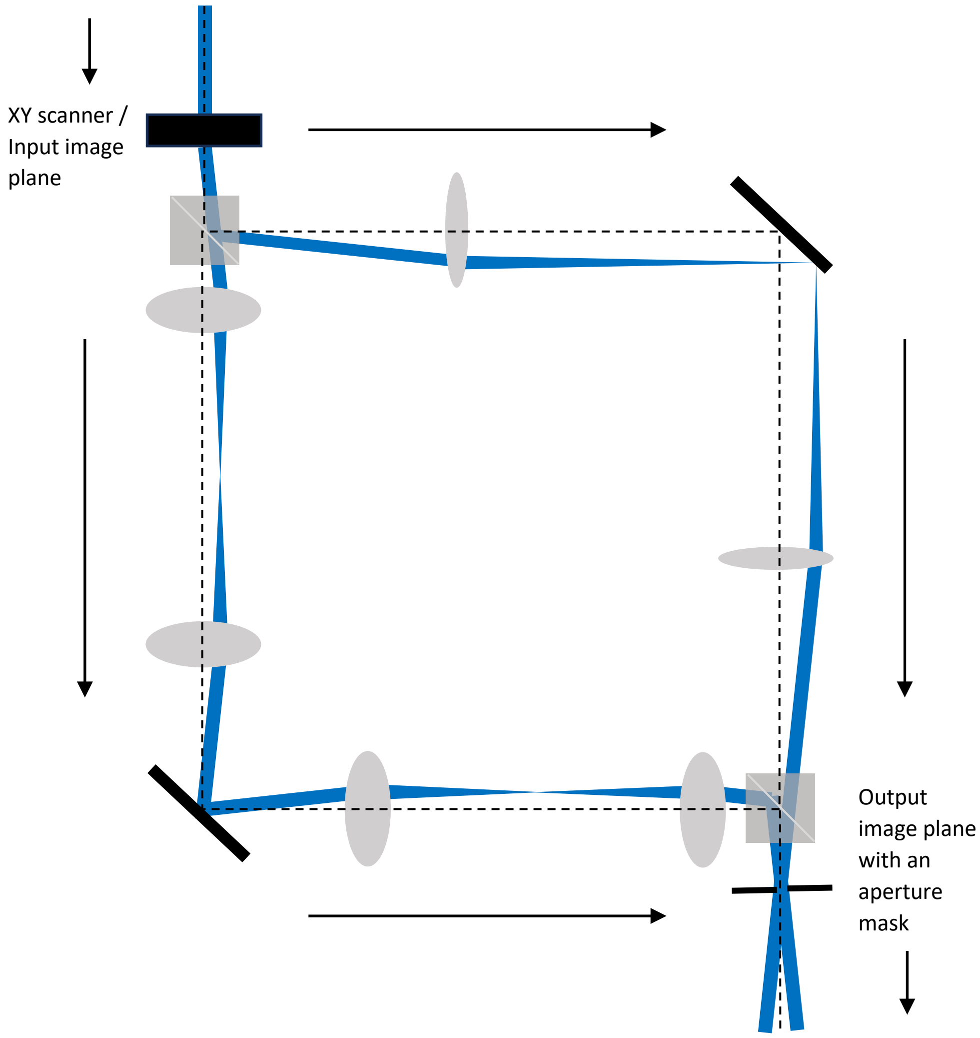
A prototype was built and tested, but it quickly revealed a fundamental limitation. The optical configuration produced two extremely small focal points on the output image plane, and achieving perfect overlap between them, especially when rotating the beams, was extraordinarily difficult. This constraint ultimately rendered the standard 4F-8F configuration unsuitable for a high-speed, scanning interferometer mastering system.

It therefore fell to me to devise another solution. The approach I developed was to scan a collimated beam through a revised lens arrangement. Instead of beginning with a narrow, diverging point-source beam, the input would now be a uniform circular collimated beam - typically 2 - 4 mm in diameter. This arrangement generated two corresponding collimated output beams at the far end of the system. Crucially, these two beams would once again converge and interfere, but without the impossible alignment demands of the earlier point-focus design. A further advantage was that the relatively large overlap region could be easily masked to provide a square, or any desired diffractive pixel shape.

The 4F arm of the interferometer remained unchanged, but the 8F arm required a different strategy. Instead, I used four sequential 2F imaging sections, each employing lenses with half the focal length of those in the 4F arm. This configuration delivered the output beam inversion required.

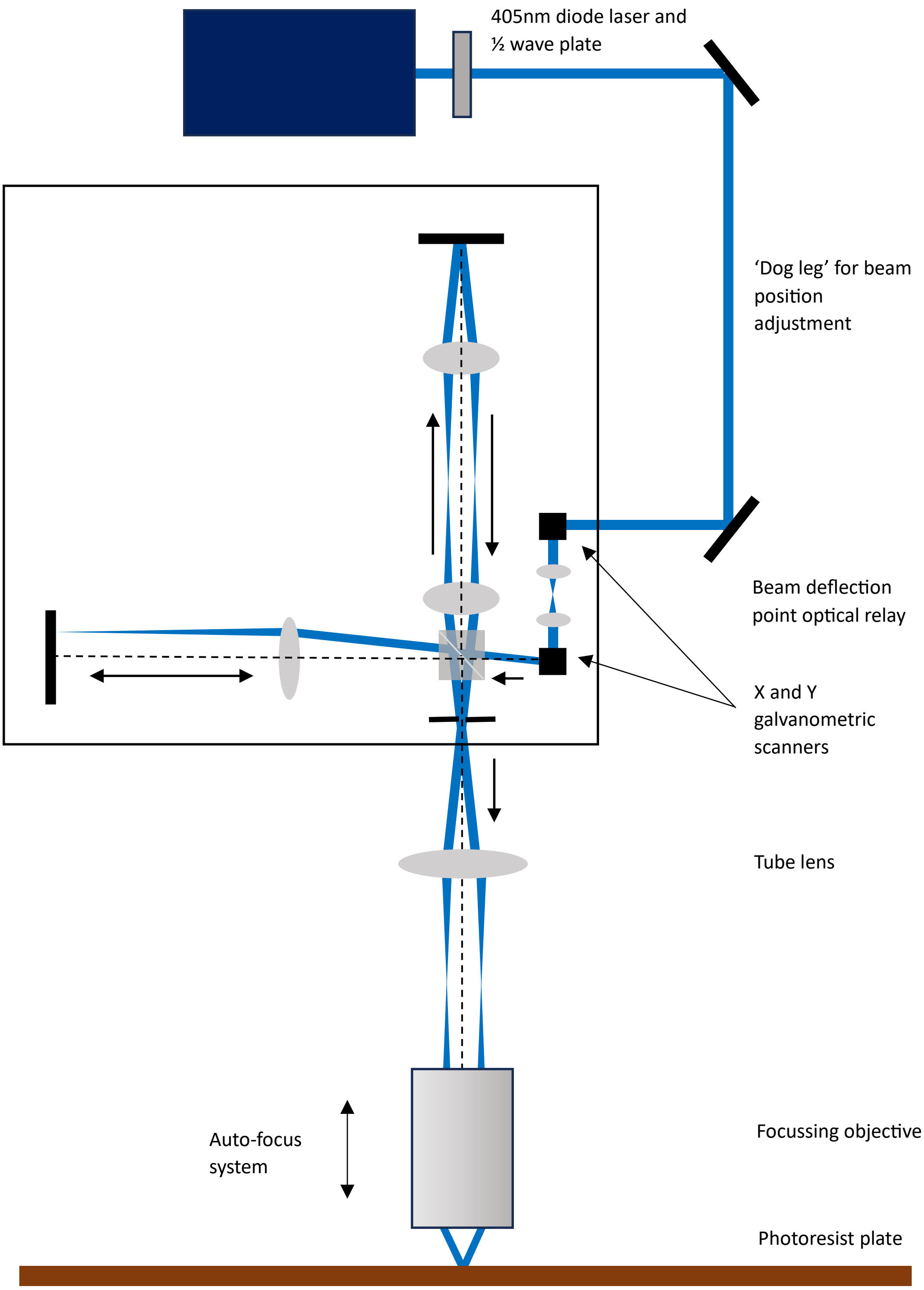


An alternative 4F-8F optical system.



A scanning Mach-Zehnder interferometer based on an alternative 4F-8F optical system.

Because the previous layout lacked the compactness required to fit neatly underneath the open frame XY table of a Lightgate S system, or within the moving optical head of a Lightgate P system, I subsequently devised a more compact Michelson interferometer-based design. The design shown below became the basis for most of the systems that were ultimately sold.



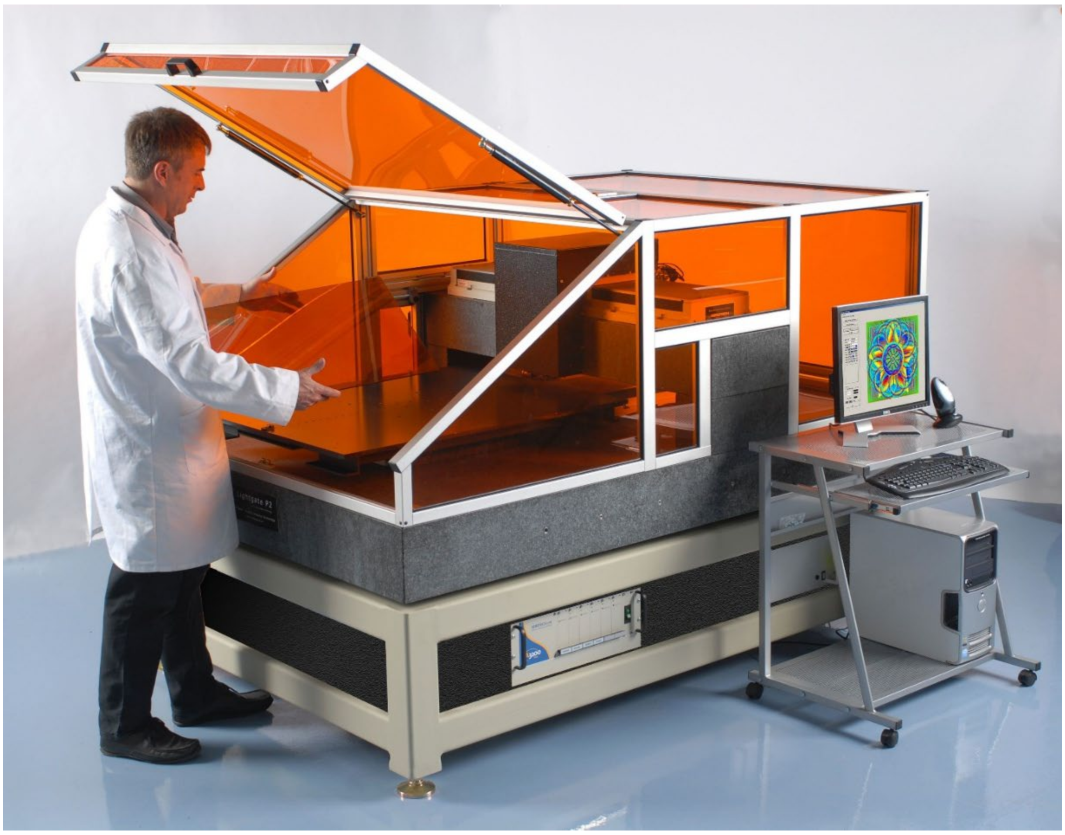
The complete scanning interferometer system used for the ultra-high speed Lightgate S and Lightgate P2 dot-matrix mastering systems. In some configurations, beam-expansion optics were added to increase the input diameter, and a through-the-lens red-laser autofocus system was developed to maintain output image sharpness to within a few microns.

The Lightgate systems that employed the scanning-interferometer technology included the Lightgate S1 and S2, small to medium-format security hologram mastering systems, as well as the large-format Lightgate P2 system for holographic packaging and other large-area holographic applications.

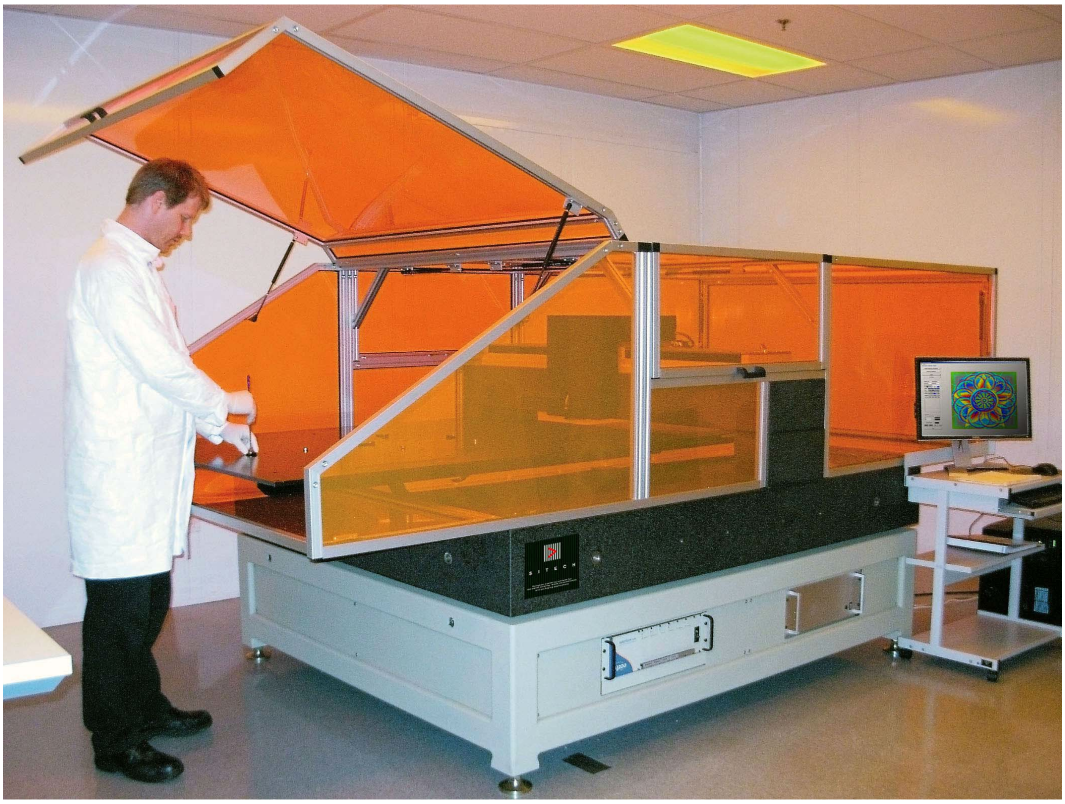
Additional variations of the scanning-interferometer approach were also developed, including a configuration that used Dove prisms in each leg of a Mach–Zehnder interferometer to flip the two beams to opposite sides of the optical axis, and another that used Porro prisms at the end of each leg of a Michelson interferometer to achieve the same effect.

Rob Munday with his Lightgate S2 dot-matrix mastering system.

Left: The Lightgate S2 control units, top, the galvanometric scanner and laser controller, and bottom, the Aerotech motion control system. Right: The Lightgate S system in operation.



Rob Munday with his Lightgate P2 system, circa 2008.



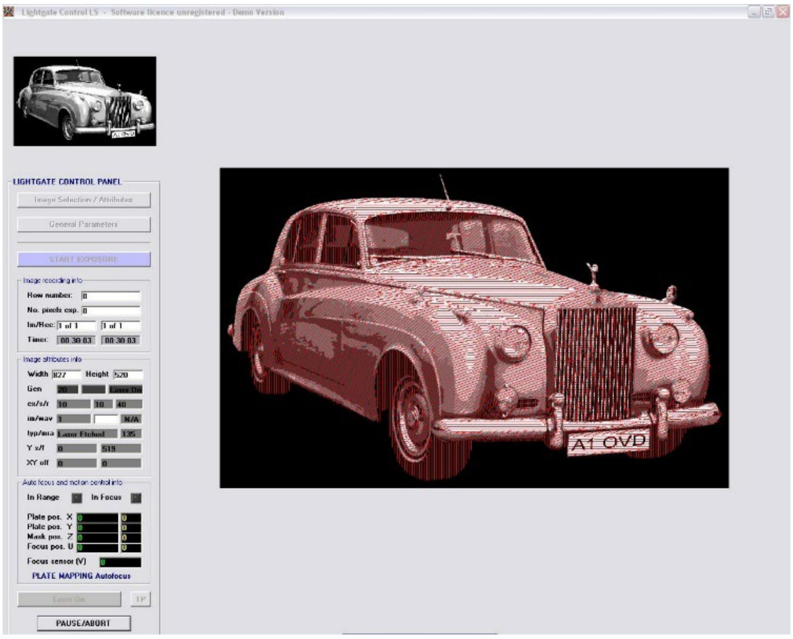
Holographer Brian Mentz operates a large-format Lightgate P2 system at the premises of Vacumet Corp, Franklin, Massachusetts, USA.

Direct Laser Etching

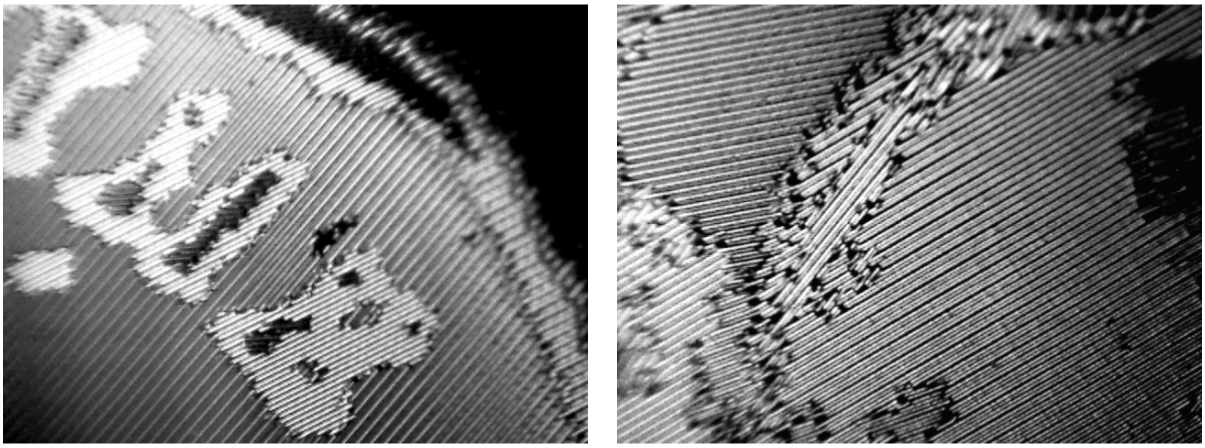
In 2010, I conceived the idea of bypassing the interferometer entirely and directing a single beam of laser light straight through the focusing objective to create a single, tightly focused spot of light. This focused beam was then used to generate a new type of D*irect Laser Etched* optical feature - a low-spatial frequency diffractive image that appeared achromatic or silver - white when viewed.

Lightgate Control first calculated and saved the positional data for arrays of linear vectors for any 8-bit greyscale bitmap image, varying the vector spacing and/or vector orientation according to the grey level. These vectors were then directly written onto the photoresist using the stationary focused laser beam in combination with the fast linear-motor XY stages of the Lightgate system. After development these periodic grating structures were in the order of 2 - 4 microns wide and 1 - 2um deep.

The Lightgate platform was the first light-based hologram mastering system to offer this technique, later followed by the KineMax system. It proved particularly effective for producing silver-metallic diffractive images and patterns. This technique also forms the basis of Spatial Imaging's large-format Lightgate D system.



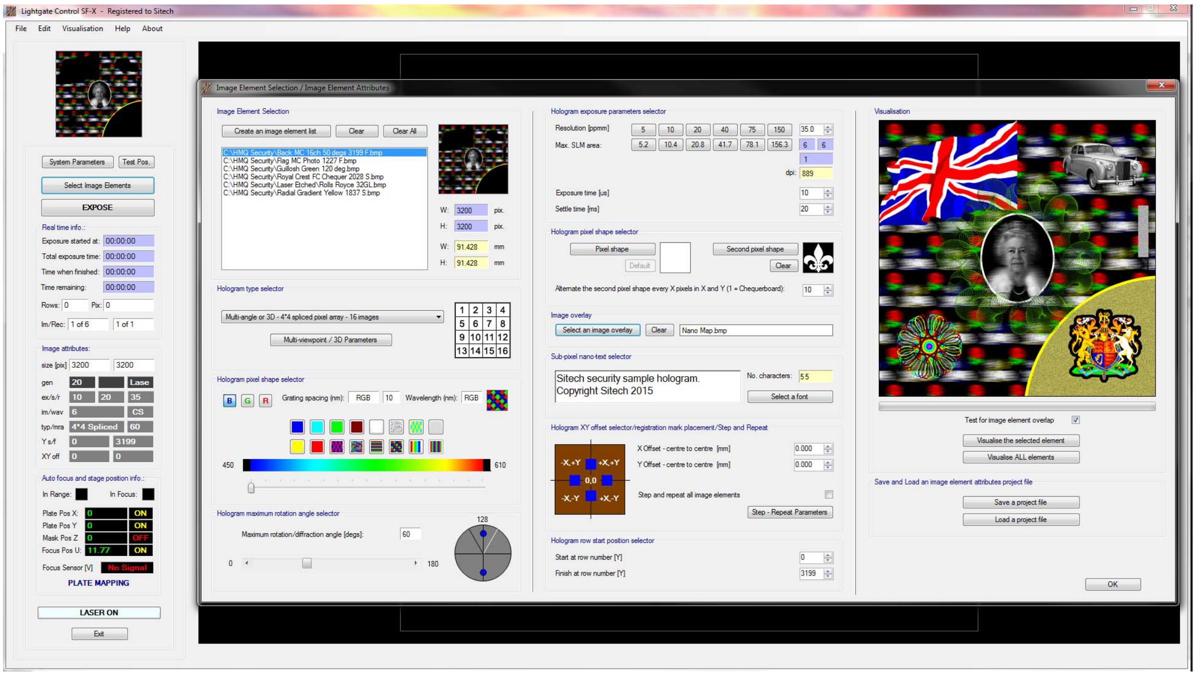
The Lightgate Direct Laser Etch feature selected in Lightgate Control.



Close up photographs of Lightgate Direct Laser Etched images, in this case a 50 pence coin..

Lightgate software and new holographic techniques

Lightgate Control, the software I began developing in 1996, provides a complete environment for the design, composition, visualisation, and automatic exposure of complex multi-element dot-matrix holograms, including full optical recombination. Holograms can be composed of an almost unlimited number of optical elements, each with its own set of unique holographic variables. Written using Microsoft's VB.net, the program has been continuously enhanced for three decades and was the most capable hologram-mastering software available on any platform until the arrival of *PicoHLD* for the 4Pico B.V. PicoMaster system in 2022.

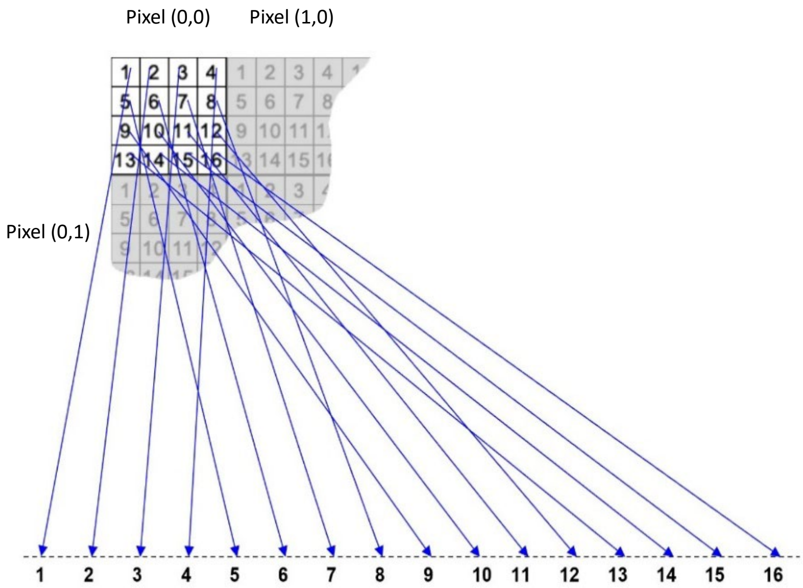


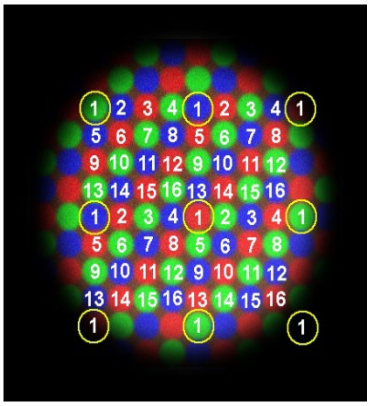
Lightgate Control, circa. 2018.

Between 1996 and 2004, and using the unique capabilities of the Lightgate system, I also developed many new and innovative holographic techniques and optical features. These included *3Digital*, a method to create full colour and achromatic, directly written, 3D dot-matrix holographic stereograms with wide-angle parallax, and *LPI*, a technique to produce dot-matrix laser projected covert hidden images (LPI).

3Digital - The process of creating a 3Digital hologram began by first choosing a stereographic image sequence. The image sequence is then post-processed to remove the various image distortions inherent in such sequences, such as keystone distortion and scale distortion. Each image in the sequence is registered to a common point, and all the usual creative variables of composition, contrast, sharpness, etc., are adjusted.

From the post-processed stereographic image sequence only sixteen equally spaced images are required. These sixteen images are then combined using custom-written software to form a single image utilising a process known as interlacing. For example, the first pixel in each of the 16 images is combined to form a 4 x 4 pixel array. This is repeated for the second pixel and so on. The final interlaced image, therefore, contains every pixel from all sixteen source images/viewpoints, arranged as shown below on the left.





Left: A sixteen-image - 4 x 4 diffractive pixel array, producing sixteen stereographic viewing zones in space.
Right: The RGB grating frequency pattern used for full colour and achromatic holograms.

A holographic stereogram is then made by automatically recording each pixel of this interlaced image, one by one, on a light-sensitive photoresist plate. The angle and spatial frequency of each diffractive pixel's diffraction grating is optimized to redirect incoming light to a specific location in space and with a particular intensity. This controlled redirection of light results in the formation of a three-dimensional holographic stereogram image.

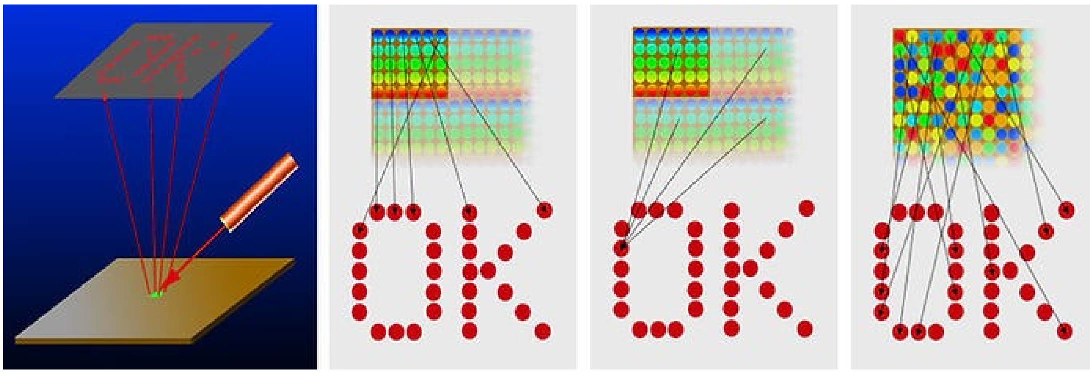
For a single-colour rainbow hologram, such as the first holographic portrait miniature shown above, every diffractive pixel in the hologram is made to contain a diffraction grating with the same spatial frequency. For an achromatic hologram, such as the second holographic portrait miniature shown above, the diffractive pixels recorded contain diffraction gratings with three different spatial frequencies, corresponding to red, green, and blue colours, arranged in a suitable pattern. The pattern, shown above on the right, of red, green, and blue pixels, when combined with a 16-viewpoint / 4 x 4-pixel array, ensures that each viewing zone contains all three colours and hence will merge to produce a full colour or achromatic-black and white holographic image.

Achromatic and full colour 3Digital dot matrix holographic stereograms made for Topps Spiderman trading cards and promotional use using the Lightgate 1270 / Lightgate B system.

In the year 2000, I was awarded the coveted *International Hologram Manufacturers Association 'Excellence in Holography - Best New Technique'* award for my 3Digital technique.

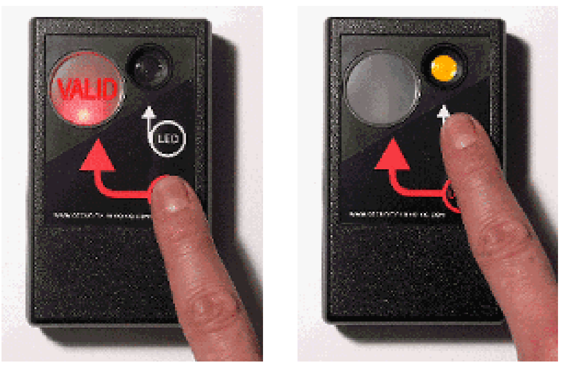
LPI - A new form of laser-projected covert hidden image and optical security feature, that I developed in 1998, thought to be the first of its kind to be produced using a digital dot-matrix mastering system. The feature was created by forming an array of diffractive pixels, each calculated and recorded to direct light to a single point in 3D space at a defined distance from the hologram. When the full pixel array is illuminated with a laser, these points combine to form a complete image or word suspended in space, which can also be projected onto a viewing screen. A further variation involved randomising the position of each diffractive pixel within the array, disguising the LPI as a much more common graphics 'sparkle' effect. The area in which an LPI can be stored can be very small, less than 200 microns square, or cover the entire hologram.

Since 1998, laser-projected hidden images of this type have been widely adopted and now appear on almost all document-security and brand-authentication holograms mastered using digital dot-matrix, image-matrix, and the latest direct-write-lithography systems.



The Lightgate Control LPI feature.

Alongside the development of the LPI feature, Spatial Imaging also introduced an LPI-reading device known as the *Authenticator*. This handheld unit incorporated a small red diode laser and enabled quick, reliable visual identification of LPI features embedded within security holograms. When an LPI image was present, the corresponding text or graphic appeared on the display. The Authenticator also included an illuminated magnifying lens, allowing users to inspect microtext and micro-image elements within the hologram. Many hundreds of Authenticators were sold.

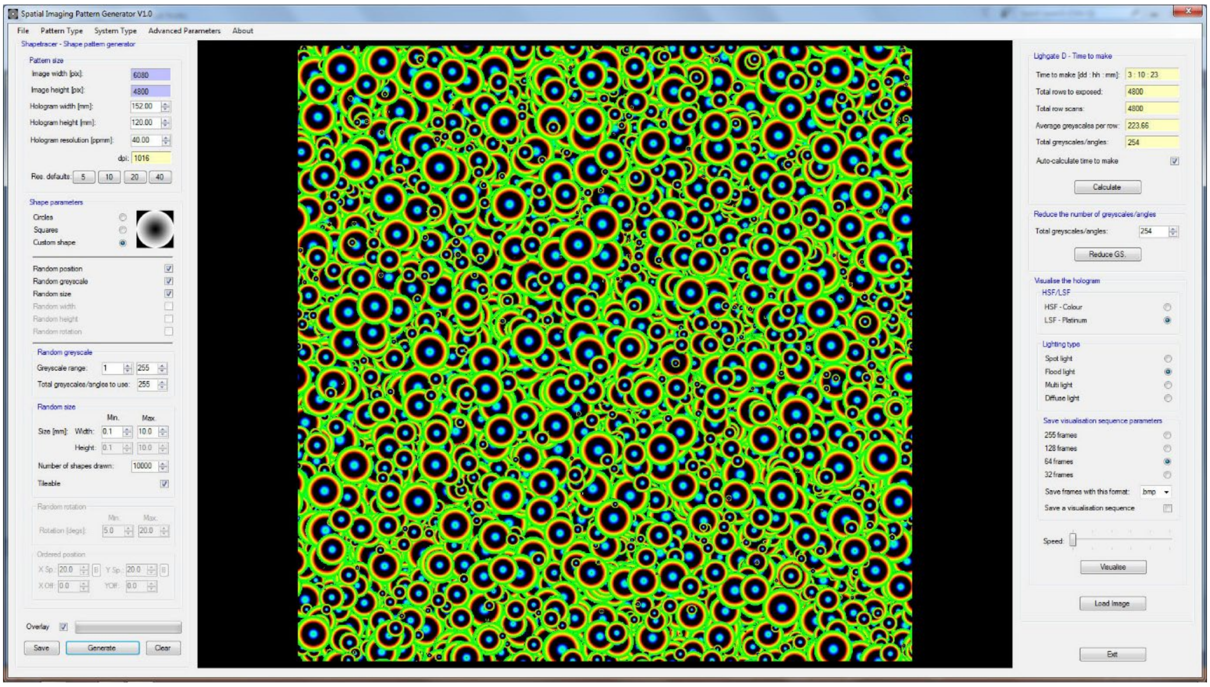


Left: The Authenticator's LPI reader. Right: The Authenticator's micro-text / micro-image illuminated viewing lens.

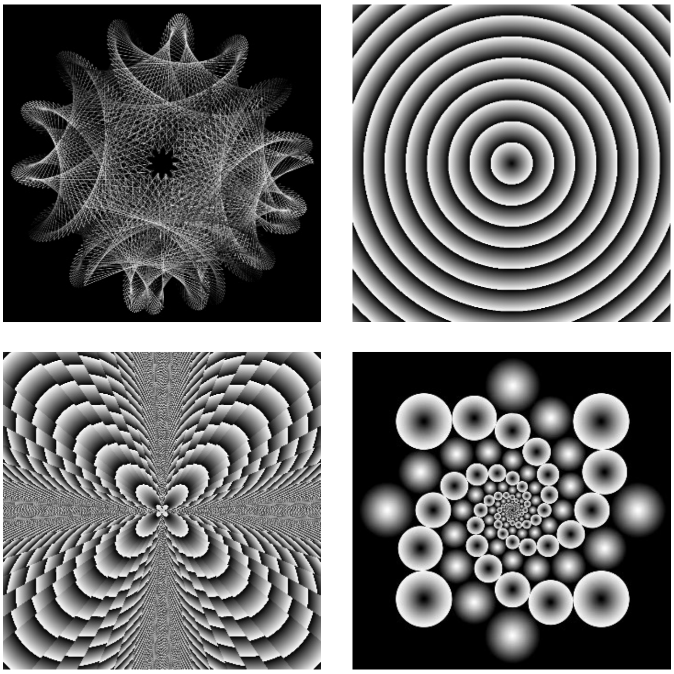
N.B. Ahead Optoelectronics, Inc. filed a patent for this technique in 1999, which was published in 2002 - US 6,392,768 B1.

The Lightgate Pattern Maker

The Lightgate Pattern Maker, as the name suggests, was designed and written by me to computer-generate unique diffractive patterns, up to 1 x 1 metre in size, for security imaging and holographic packaging applications Pattern families include shape/image patterns, line patterns, gradient patterns, and lens patterns. The software enables the mixing of all pattern types with masking, and animated visualisation under different lighting conditions. Once a pattern is finalised, it is output as a greyscale bitmap ready for recording.



The Lightgate Pattern Maker showing a kinetic visualisation of a seamless random pattern created using a custom image.

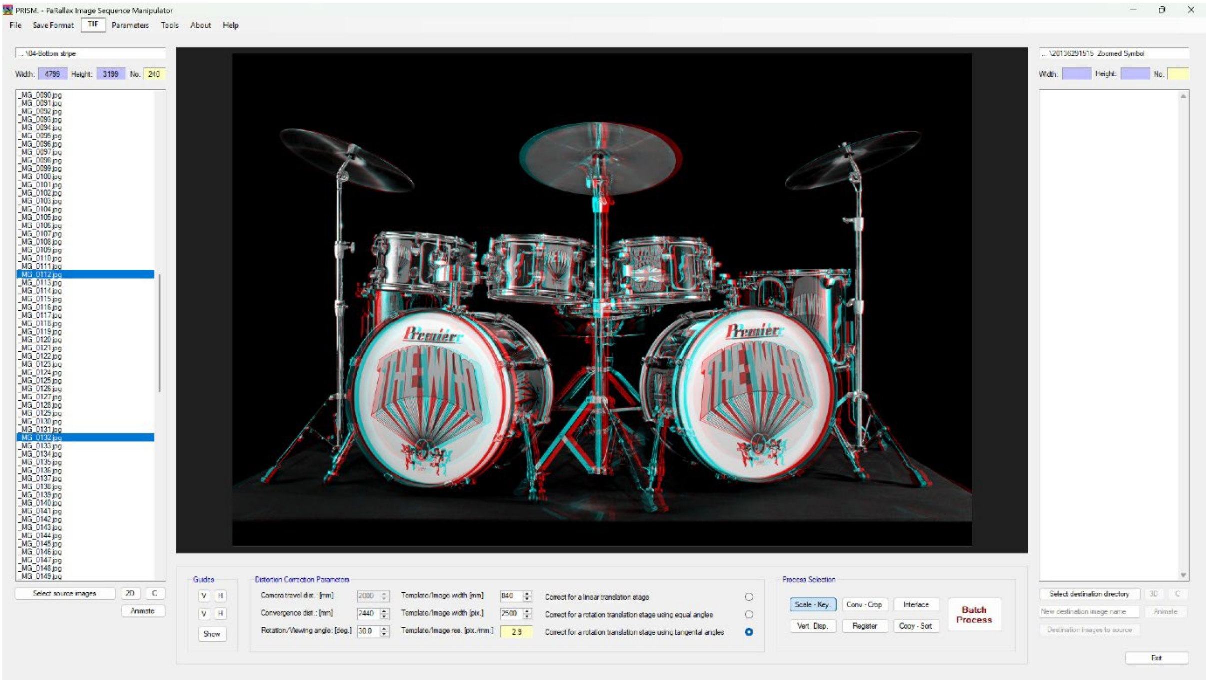


Left: An early promotional poster. Right: Example line, gradient, and lens patterns.

PRISM

PRISM – PaRallax Image Sequence Manipulator – is a software program that I designed and wrote to handle the demanding image-processing tasks required for manipulating the stereographic and animated image sequences used in recording holographic stereograms and animated holograms. It provides an integrated suite of functions: automatic correction of keystone and other geometric distortions; sequential cropping to adjust perceived image-plane depth; frame-to-frame registration; frame interlacing; and batch copying and renaming of files and image sequences. It also incorporates on-screen stereographic visualisation, supporting multiple 3D display methods including anaglyphic rendering and output to 3D monitors and television systems.

PRISM is thought to be the first software specifically written to remove keystone distortion from digital stereographic image sequences. I wrote the first version in 2004 to correct the keystone distortion present in my digital stereographic image sequences of the late Queen Elizabeth II, a step that significantly improved the dimensional fidelity and final visual appearance of the final 3D holographic portrait.



PRISM showing a 3D anaglphic image for on-screen 3D visualisation.

PRISM’s automatic keystone distortion removal.
The upper set of images shows an uncorrected sequence, and the lower set of images shows a corrected sequence.

Patent Applications

I filed five dot-matrix related patent applications over a ten-year period.

1. **METHOD AND APPARATUS FOR CREATING HOLOGRAPHIC PATTERNS** - WO1998029767 - PCTGB9703563 – Priority date 4th January 1997.

2. **FASTER METHOD AND APPARATUS FOR CREATING HOLOGRAPHIC PATTERNS** - WO1998092141 - PCTGB9703563 – Priority date 4th January 1997.

3. **AN OPTICAL DEVICE, AN OPTICAL SYSTEM AND A METHOD OF MANUFACTURING A HOLOGRAPHC OPTICAL ELEMENT** - WO2006003457 - PCTGB200502662 - Priority date: July 7th 2004.

4. **A HOLOGRAM AND ITS METHOD OF MANUFACTURE** - PCT/GB2OO6/OO1039 – Priority 23rd March 2005.

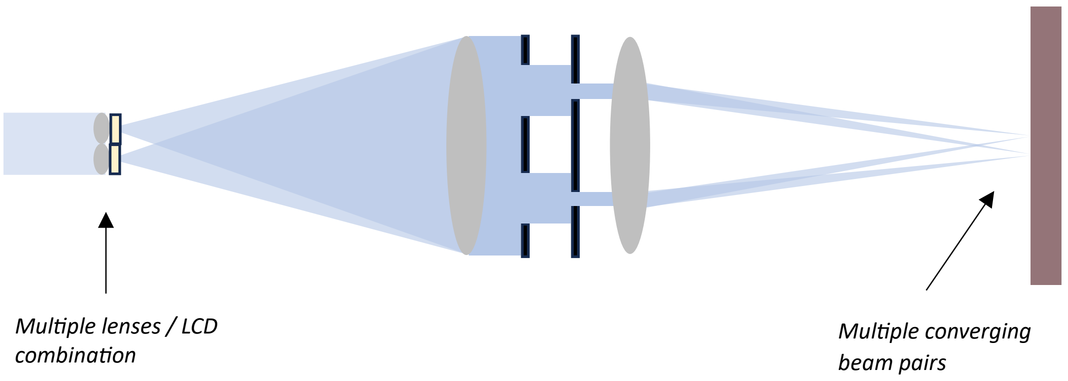
5. **IMPROVEMENTS IN OR RELATING TO OPTICAL SYSTEMS AND DEVICES** - WO2008025999 - PCTGB2007003314 - priority date: 1st September 2006.

All the above applications were permitted to lapse prior to grant due to lack of funds.

METHOD AND APPARATUS FOR CREATING HOLOGRAPHIC PATTERNS

My first patent application was written in the early autumn of 1996 and filed on 4th January 1997. By December 1996, I had already begun to devise ways of changing the angle between the beams and thus the grating spatial frequency on the fly. One such idea was to use a static electronically addressable mask in the form of an LCD screen however the lack of contrast of TFT LCD screens at the time made this idea unusable. Instead, I updated the initial application to include a physical mask / LCD screen combination. The physical mask would have slots instead of holes and these slots would be masked and modulated by the LCD screen. This idea also proved unviable due to the diffraction and scattering of the laser light thought the LCD screen leading to multiple focal points on the output plane.

METHOD AND APPARATUS FOR CREATING HOLOGRAPHIC PATTERNS 2



A multi-lens / LCD Lightgate system – shown here with only two lenses for simplicity.

Another improvement made was a method for recording multiple diffractive pixels with a single exposure by pairing a microlens array or fibre-optic bundle with an LCD modulator at the input image plane. The microlens array or fibre bundle would generate multiple overlapping focal spots at the output plane, while the LCD modulator would selectively transmit only those pixels sharing the same diffraction grating orientation and spatial frequency, blocking all others. The LCD could also be used to modulate the brightness of each pixel individually. This multi-lens adaption was never implemented, however, and although technically promising, this patent application ultimately lapsed for financial reasons.

Awards

Spatial Imaging's inventions have won five technology related ***International Hologram Manufacturers Awards of Excellence***:

2000 Category: New Holographic Technique

3Digital – was the method I devised for creating three-dimensional, wide-angle, digital 'dot-matrix' holographic stereograms using the Lightgate dot-matrix hologram mastering system.

2005 Category: New Holographic Technique and BEST OF THE YEAR

The Lightgate P2 with Lightspeed technology – was the world's first commercially available, largest format and fastest digital hologram design and mastering system enabling the creation of large-format, single-image, seamless digital 'dot-matrix' holograms and diffractive patterns.

2006 Category: New Holographic Technique

The Hydra image capture system – was a unique multiple-camera system for the capture of parallax image sequences. The Hydra system was able to instantaneously capture a sequence of images, automatically register those images for smooth 3D / animation and generate any number of intermediate frames using 'parallax rendering'. The image sequence was then be used to make three-dimensional dot-matrix holographic stereograms or lenticular images, particularly portraits. The system was technically conceived and designed by my co-director and business partner, Jeffrey Robb, for a subsidiary company named FaceStation Ltd.

2008 Category: Industrial

Fast Track – was an optional component of Spatial Imaging's ultra-high-speed digital hologram mastering platform, enabling the extremely rapid recording of digital holograms. It allowed the recording medium to move continuously while maintaining precise 'plate tracking', so that diffractive pixels could be written accurately onto the moving substrate.

Credits

My thanks go to the following individuals who have been instrumental in Spatial Imaging's success from the sale of its very first hologram mastering system in 1994. Whilst both Jeffrey Robb and Olivier Pitavy has since left the company, their input in all aspects of Spatial Imaging's technology business during their employment was invaluable.

Jeffrey Robb worked alongside me for 15-years, from 1994 until 2009, supporting the DI-HO and Lightgate technology business by installing systems, designing and creating promotional and security 'dot-matrix' holograms, designing and writing educational materials, technical manuals, conference papers, and magazine articles for technical publications, and attending technical conferences.

Olivier Pitavy, who, as my primary technical right-hand man for 7-years, from 2002 to 2009 and beyond, built, tested, installed, and supported Spatial Imaging's range of Lightgate mastering systems, travelling the world with me. When the chips were down, a system component had failed, or the owner of a hologram company in the depths of China misunderstood the capabilities of the system, it was Olivier's patience, confidence, and quiet stoicism that always saved the day.

Dr Paul Apte of Rideo Systems Ltd. in the UK, has been an integral part of the success of my technology initiatives for more than twenty years, and continues to work on Lightgate projects. Paul has devised numerous motion-control solutions, contributed major software enhancements, and in recent years has designed, built, and installed new generations of Lightgate systems for leading hologram companies around the world.

Neil Anderson of C&L Developments Ltd. in the UK has, from the late 1990s to the present day, skilfully designed and crafted, with the utmost of patience, every custom component required for my plethora of hologram mastering systems and related technologies. Neil's other claim to fame is that he designed and built the legs for the Star Wars robot R2-D2!

Conclusion

Between 1996 and 2008, the technology business of Spatial Imaging, from designing new systems to writing the software to control them, and from building the machines to installing and supporting them around the world, was sustained and driven by myself with the exceptionally small core team listed above. Since 2008, the operation has been carried forward by me alone, working in continued collaboration with Paul Apte and Neil Anderson.

Despite this exceptionally small operational base, Spatial Imaging has, over the past three decades, delivered more than one hundred digital hologram mastering systems and associated technologies, to companies both large and small throughout the world. Working within what remains a very small and highly specialised global industry, the company has maintained a uniquely long, consistent, and productive presence. Its portfolio of world-leading and best-selling systems includes its DI-HO system, its Lightgate range, and, in more recent years, the paradigm shifting direct-write lithography systems developed by 4Pico B.V., and now produced by Raith Laser Systems B.V., in The Netherlands, for which it is the worldwide exclusive distributor.

Taken together, this represents the largest number of professional digital hologram mastering systems supplied by any company in the world to date, a testament to both the longevity of Spatial Imaging and the technical distinctiveness of its inventions and solutions.

A sample Lightgate dot-matrix hologram made by a customer of Spatial Imaging, Formas Inteligentes, Monterrey, Mexico.

Rob Munday, 2026.