ACADEMY OF PERFORMING ARTS IN PRAGUE

FILM AND TELEVISION FACULTY

Film, Television, Photography, and New Media

Photography

BACHELOR'S THESIS

Holography in the Age of New Media Technologies

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Examiner:

Date of thesis defense:

Academic title granted: BcA.

Prague, 2019

AKADEMIE MÚZICKÝCH UMĚNÍ V PRAZE
FILMOVÁ A TELEVIZNÍ FAKULTA

Filmové, televizní a fotografické umění a nová media
Fotografování

BAKALÁŘSKÁ PRÁCE

Holografie ve věku nových mediálních technologií

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Přidělovaný akademický titul: BcA.

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ABSTRACT

A hologram is a photographic recording of a spatial light field, rather than of directional light formed by a lens. Its defining quality is a three-dimensional appearance that exhibits visual depth cues and can be viewed without the aid of intermediate optics. The holographic method was invented in 1947 and its technology advanced throughout the twentieth century, most notably since the development of the laser in the early 1960s. It has contributed to numerous scientific innovations and applications in the fields of industry, business, and medicine. Culturally, holography has fascinated society by positioning itself early on as the photograph of future and making its way into entertainment such as science-fiction films. This paper will examine the emergence of the hologram, from its scientific origins to its manifestations in commercial and popular culture. The aim of this work is to better understand holography as a photographic medium, its history, and to provide some insight to its future potentiality with the recent development of 3D digital displays.

ABSTRAKT

Hologram je fotografický záznam prostorového světelného pole, spíše než směrového světla tvořeného čočkou. Její definovanou kvalitou je trojrozměrný vzhled, který vykazuje vizuální hloubkové podněty a může být viděn bez pomoci mezilehlé optiky. Holografická metoda byla vynalezena v roce 1947 a její technologie pokročila v průběhu dvacátého století, zejména od vývoje laseru na počátku šedesátých let. Přispěla k četným vědeckým inovacím a aplikacím v oblasti průmyslu, obchodu a medicíny. Kulturně, holografie fascinovala společnost tím, že postaví sebe brzy jako fotografie budoucnosti a dělat jeho cestu do zábavy takový jako vědecko-fantastické filmy. Tato práce se bude zabývat vznikem hologramu, od jeho vědeckého původu až po jeho projevy v komerční a populární kultuře. Cílem této práce je lépe pochopit holografii jako fotografické médium, jeho historii a poskytnout určitý pohled na jeho budoucí potenciál s nedávným vývojem 3D digitálních displejů.

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1. Introduction

In the history of photography, the holographic method has occupied a rather niche position, which still remains mainly relevant to the field of scientific imaging; but has nonetheless succeeded in capturing the interest of cultural imagination with its mesmerizing visual qualities in the form of the optical hologram. Thanks to the development of the laser in 1962, a new way of photographic recording was created, which facilitated the capturing of a whole light field rather than a flattened image formed by a lens. It is this particular encoding of coherent light onto a photographic emulsion which creates the appearance of a three dimensional image of the recorded object.

Many decades have passed since then, and while the holographic method realized many real-world applications in the fields of science, security, and art, it is still mainly considered to be a technology reserved for the narratives of science-fiction and the entertainment industry. However, with the increasing advancements of computational technology, 3D display devices have recently emerged which enable 3D vision in a way that resembles a hologram visually, but operate completely differently from traditional holography. They currently represent a new wave of in the future of technology and communications, as they are just beginning to change how we might view media in the near future.

The following dissertation will begin with the fundamentals of holography, and follow with an overview of its scientific history, commercial adoption, and appearance in popular culture. Finally, it will examine various developments in digital 3D display devices – which attempt to redefine holography in the age of information, technology, and new media.

2. Principles and Applications

2.1. Basics of Holography

Holography is a diffraction-based coherent imaging technique that enables a light field scattered off an object to be recorded and later reconstructed when the original light field is no longer present. This enables a complex physical object to be reproduced from several different angles, and viewed with the naked eye. The resulting image of a hologram retains visual depth cues, such as parallax and perspective, which means the image changes as the position and orientation of the viewer changes in the same way as if the object were still present, thus making the image appear three-dimensional.

The recording medium of a hologram can be comprised of a variety of different materials, however, the most common type is a specialized silver halide type of photographic film that is mounted onto a transparent substrate, such as glass or plastic. Due to the very high resolutions that are required to reproduce a clear and sharp image, a holographic film emulsion is generally made up of a much higher concentration of photosensitive grains than conventional photographic film.

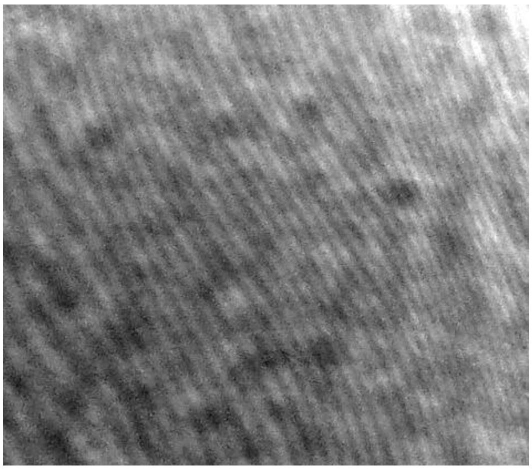

Figure 1: Close-up photograph of a hologram's surface.[1]

1 Image source: https://en.wikipedia.org/wiki/Holography.

Looking closely upon the physical surface structure of a hologram, one can see that it consists of a very fine random pattern. The regular pattern of lines in this image is due to interference arising from multiple reflections in the glass plate on which the photographic emulsion is attached. The grainy structure underneath which appears like television static represents the actual encoding of the holographic image information. Much like one cannot identify what music has been recorded by looking at the surface of a vinyl record or CD, no more is it possible to discern the visual subject of a hologram from this random pattern. The principle of holography also operates analogous to a sound recording, whereby a sound field created by vibrating matter like musical instruments or vocal chords, is encoded in such a way that it can be played back later, in the absence of the original vibrating matter.[2]

What is particularly interesting about the way that a hologram is created, is that when the image is recorded onto the film, the complete image information is encoded onto the entire piece of film. The reason for this is that each and every point of the hologram receives light from various points of the object. Thus, even if the film is cut into multiple pieces, each part is still capable of reproducing the whole object. One can compare this effect to looking through a window. No matter from how small of an area of the window you look out, you are always able to view the entire scene that is outside. This unique characteristic of "all the parts containing the whole", also known as redundancy, is a defining aspect of a hologram which sets it apart from conventional photographic recording media. The term "hologram" from the Greek words '*holos*', meaning "whole", and '*gramma*', meaning "message", directly alludes to this quality as well.

2 Berger, M., Full-color 3D meta-holography with a single nanostructured layer [online] 2016, Sourced from: https://www.nanowerk.com/spotlight/spotid=45011.php.

2.2. Recording a Hologram

Holography is based on the physical principle of interference, a phenomenon in which two waves superpose to form a resultant wave of greater or lower amplitude. Ordinary light, because it is made up of many different wavelengths, none of which have any fixed phase relationship with each other, is incapable of interfering with itself. Therefore, in order to record a holographic image a monochromatic laser is essential. Laser light is a beam of one wavelength that is uniform, in-phase, and thus coherent. When two laser beams of the same source interact with each other an interference pattern is formed, which is recorded onto the photographic plate as a hologram.[3]

Using a single laser, a beam-splitter divides the laser beam into two identical beams, which are then aimed in two different directions. One of those beams, the reference beam, bounces off a mirror and directly strikes the photographic plate. The second beam, the object beam, is directed at the object to be recorded and is reflected by the surface of the object onto the photographic plate. Hereafter, the two laser beams interfere with each other and expose the light field of the object onto the holographic film.

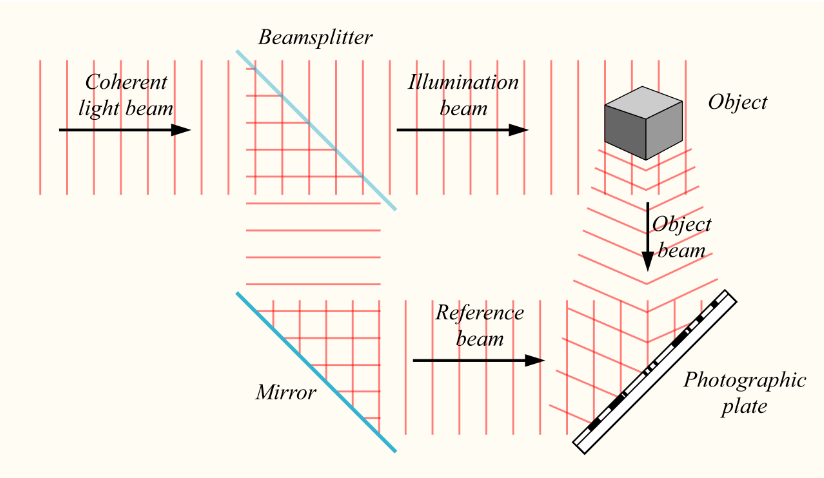

Figure 2: Graphic representation of the recording of a hologram.[4]

3 Hung, T. H., Fundamentals of Photonics, Module 1.10, 2008.
4 Image source: https://en.wikipedia.org/wiki/Holography.

Because the film not only records the amplitude of the light but also the phase of its light rays, the spatial dimension of the object is able to be captured. This means that the hologram actually contains much more information than a conventional focused image, and exhibits itself as a parallax effect which enables the viewer to perceive a three-dimensional image.

For the reconstruction of the holographic image from the photographic plate, diffraction becomes the governing physical principle in a process referred to as holographic diffraction grating. By illuminating a laser beam through the back of the plate, one of an identical wavelength of the reference beam that was used in the recording of the object, the light is diffracted by the fringes of the interference pattern and an exact reconstruction of the original object wavefront is obtained. This beam is referred to as the reconstruction beam. It is possible to obtain a holographic image using a different laser beam configuration to the original recording beam, but the reconstructed image will not match the original exactly.[5]

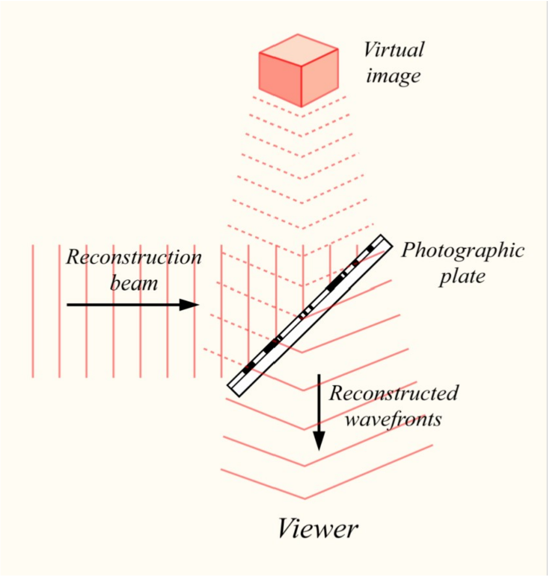

Figure 3: Graphic representation of the reconstruction of a hologram.[6]

5 Hariharan, P., Basics of Holography, Section 2.3., Cambridge University Press, 2002, p. 17.
6 Image source: https://en.wikipedia.org/wiki/Holography.

2.3. Types of Holograms

The two basic geometries for holograms are *transmission,* where coherent monochromatic laser light is shone through the hologram, and *reflection,* in which the hologram reflects white light to reveal the holographic image. They each have different methods of procurement and distinct optical characteristics.

Transmission Hologram

Laser viewable transmission holograms allow for near perfect reconstruction of the recorded optical light field. The virtual image can appear very sharp and with great depth depending on whether the same type of laser wavelength is used as in the recording of the hologram. Artist Paula Dawson (1954–) who has worked extensively with transmission holograms describes them as 'concrete' holographic images because of the way they appear to have a distinct physical presence.[7] An example of this kind of holographic image is her triptych installation of large-format holograms, *'To Absent Friends'* (1989), in which she captures a bar at three different times during a New Year's Eve party, crystallized memories of three frozen moments.[8] They are known as the largest holograms ever produced.

Figure 4: 'To Absent Friends' holograms by Paula Dawson, 95 x 150 cm.[9]

7 Dawson, P., The Concrete Holographic Image: an Examination of Spatial and Temporal Properties and their Application in a Religious Art Work. PhD, College of Fine Arts, University of New South Wales, p335

8 Mrongovius, M., 2013, J. Phys.: Conf. Ser.415 01202

9 Image souce: https://www.researchgate.net/figure/To-Absent-Friends-hologram-by-Paula-Dawson-Reprinted-with-permission_fig1_318316108

A refined variant of the transmission hologram is the *white-light transmission hologram,* or "rainbow hologram", which gets its name from its shiny multi-colored aluminum coating which is able to reflect light through the back of the hologram to reconstruct its image. These versions are most commonly seen today on credit cards as a security feature as well as on commercial products and their packaging.

Reflection Hologram

In a reflection hologram, the reference beam and object are incident on the plate from opposite sides, as opposed to the transmission hologram where the laser beams both meet on the same side of the photographic plate. The main characteristic of reflection holograms is that they are able to be viewed naturally with a white light source that is held at a certain angle and distance from the viewer. The holographic image here is seen near its surface and consists of light reflected by the hologram's thicker emulsion. They have less depth and projection than images of transmission holograms, but can be layered with more than one image.[10] It is possible to record a full color reflection hologram by using multiple color lasers. This type of hologram closely resembles the photographic practice of Lippmann photography, in which light rays that strike the film are reflected in themselves and create interference phenomena of stationary waves.[11]

10 Vacca, J. R., Holograms & Holography: Design, Techniques, & Commercial Applications, First edition, Chapter 1, Charles River Media ,2001, Chapter 1, p. 7.

11 Eder, J.M., History of Photography, Forth edition, New York: Dover Publications, 1978, p. 668, 670, 671, 672

Figure 5: Multicolor reflection hologram by Iñaki Beguiristain, 40 x 30 cm.[12]

2.4. Applications of Holography

Holography's unique ability to record and reconstruct light waves has made it a valuable tool for science, industry, business, and education. One of the main uses is in security applications in the form of anti-counterfeit measures found on financial and legal documents, as well as on money. These security holograms are extremely difficult to forge, because the master hologram from which they are replicated requires highly sophisticated and expensive electron-beam lithography systems, capable of producing surface holograms with a very high resolution down to just a few nanometers.[13]

Security holograms that are typically used on credit cards, such as the eagle on VISA cards, are specific types of embossed white light transmission holograms, whereby their two-dimensional interference pattern is pressed onto thin reflective plastic foils with a mirror backing, thus enabling them to be viewed in ordinary

12 Image source: https://drie3d.home.xs4all.nl/English/Hologram%20Pages/Art%20Holograms%2001.htm

13 Yang, J. K. W., Cord, B., Duan, H., Berggren, K. K., Klingfus, J., Nam, S. W., Kim, K. B., Rooks, M. J., 2009, Understanding of hydrogen silsesquioxane electron resist for sub- 5-nm-half-pitch lithography. Journal of Vacuum Science and Technology B: Microelectronics and Nanometer Structures, 27(6), 2622-2627.

light. Embossed holograms, due to their ability to be mass-produced, are also widely used in commercial and consumer applications such as publication covers, greeting cards, collectibles, trading cards, packaging, and promotional displays. The visual appeal of holography here creates a value-added aspect for the printed business product market.

Another example of a widespread application is found in supermarket scanners, which utilize a holographic lens system to direct laser light onto the bar codes of product labels. This kind of holography is similarly used in aircraft heads-up displays to allow a pilot to see critical cockpit instruments and flight data just by looking at the windscreen. Numerous biomedical applications of holography are also being used and developed today through holographic interferometry, a technique which enables static and dynamic displacements of objects with optically rough surfaces to be measured to fractions of a wavelength of light. These imaging methods have been successfully applied for the study of different parts of the human body in the fields of dentistry, urology, otology, pathology, ophthalmology, and orthopedics.[14]

These are only a few examples of where holography has already become a ubiquitous part of our lives. The hologram, with its awareness of three-dimensional space and capability to record the phase information of light by utilizing the interference phenomenon, has proven itself to be a valuable technology that has greatly expanded our visualization possibilities.[15]

14 Scammell, R., Holography improves heads-up displays for aircraft pilots, [online] 2018, Sourced from: https://www.airforce-technology.com/news/holography-improves-heads-displays-aircraft-pilots/

15 Mehta, P., Medical Applications of Holography, [online] 2005, Sourced from: https://www.integraf.com/resources/articles/a-medical-applications-of-holography

3. History of Holography

3.1. Scientific Development

In 1947 a Hungarian physicist by the name of Dennis Gabor (1900–1979) discovered the basic technique of holography while trying to improve the resolution in electron microscopes at the British Thomson-Houston Company in Rugby, England. It was an unanticipated result - one for which he eventually was awarded the Nobel Prize in Physics in 1971 for his invention and development of the holographic method.[16] Thanks to his discovery, this method is still used in electron microscopy today, where it is colloquially known as electron holography.

Gabor understood that his imaging process could, in theory, create three dimensional images; but technological limitations at the time prevented some progress in this regard. Any attempts to generate an optical image resulted in a poor reconstruction of the original subject; which, in his own tests, yielded a microscopic black text on a transparent background with distortions and an extraneous twin image.[17] Light sources at the time, such as the mercury arc lamp, were not truly coherent, which is the reason for this difficulty throughout the subsequent decade. This specific quality of light was not able to be technically reproduced until the development of the laser in 1960, by Theodore H. Maiman (1927–2007), at Hughes Research Laboratories in Malibu, California.

Just a couple of years later, in 1962, the invention of the laser had, at long last, made it possible to generate the first optical holograms that recorded a 3D object with clarity and realistic depth. This project was spearheaded by Yuri Denisyuk (1927–2006) in the Soviet Union, and followed by Emmett Leith (1927–2005) as well as his junior colleague Juris Upatnieks (1936–) at the Willow Run Laboratories of the University of Michigan, USA. Dubbed "lensless photography" by the American Institute of Physics (AIP), it suggested a close relationship

16 The Nobel Prize in Physics 1971. NobelPrize.org. Nobel Media AB 2019. Tue. 16 Mar 2019. https://www.nobelprize.org/prizes/physics/1971/summary/

17 Johnston, S. F., 2005, From White Elephant to Nobel Prize: Dennis Gabor's Wavefront Reconstruction, Historical Studies in the Physical and Biological Sciences 36, No. 1, 35–70

between holograms and photographs and helped generate flagrant interest in the general public regarding holography,[18] and all its potential, for the following decade.

In the public eye, the inner workings of holograms seemed to defy common sense, or any sensical truth known to humankind - it was science fiction born. Holograms were products of sophisticated optical laboratories, and the characteristics of the laser were also considered mysterious to most people. Holography was thus seen as a symbol of scientific progress and the future, as it appeared to pull conventional photography into a whole new dimension.[19]

While the hologram captured the imagination of the masses, the subject matter of this novel medium was, practically speaking, unremarkable. Due to the light-insensitive/high-resolution photographic emulsions being used, the recorded objects were required to be completely still for several minutes per exposure, and be no larger than, in Leith and Upatniek's examples, a toy train or chess figurines.[20]

Gradually over the years the technology was refined by a number of international laboratories, and by 1967 a pulsed laser was developed by the Conductron Corporation based in Ann Arbor, Michigan, USA. Using very powerful bursts of laser light that last only a few nanoseconds, this particular operation of the laser enabled "flash" holography, a method that immediately broadened the useable subject matter from simple, inanimate objects, to living things; further linking holography with the possibilities held by traditional photography.[21] The first hologram of a person was made that year.

18 Johnston, S. F., 2008, A Cultural History of the Hologram, Leonardo, Vol. 41, No. 3, pp. 223-229, 221
19 Johnston, S. F., 2006, Absorbing New Subjects: Holography as an Analog of Photography, Physics in Perspectives p. 164-188
20 Leith, E. N., Upatnieks, J., 1965, Photography by Laser, Scientific American 212, No. 6, 24-36
21 Siebert, L. D., 1968, Large-Scene Front-Lighted Hologram of a Human Subject, Proceedings of the IEEE 56, No. 7, 1242-1243

Figure 6: Dennis Gabor, the inventor of holography, stands beside his 18 x 24 inch laser transmission, pulsed portrait.[22]

3.2. Mass Production and Popular Culture

Significant headway was made just a year later in 1968 when the white-light transmission hologram (rainbow hologram) was invented by Dr. Stephen A. Benton (1941–2003) at Polaroid Research Laboratories in Cambridge, Massachusetts. Benton's invention helped propel holography into the realm of commercial viability and mass production. In 1974 it became possible to "print" holographic images onto plastics by transferring the interference pattern from the hologram onto nickel embossing shims. This provided the opportunity to replicate them countless times for just a few cents each. Naturally, by the early 1980s, inexpensive commercial holograms made their way into the market. They initially proved very useful for the security and banking sector as an anti-counterfeiting measure. In 1983, the first credit card was produced for MasterCard by the American Bank Note Company.

22 Image source: https://www.pinterest.com/pin/367606388308163399/

Embossed holograms also became widespread in advertising and publishing industries as graphics featured on magazine covers throughout the decade, one of the most notable being the March 1984 *National Geographic Magazine* hologram of an eagle, produced by Ken Haines, for which 11 million copies were printed.[23]

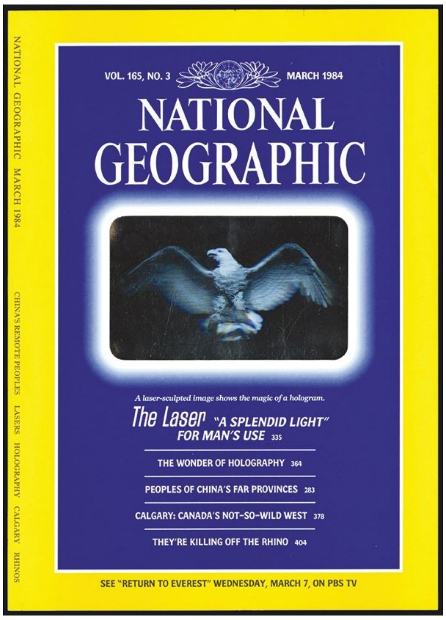

Figure 7: Volume 165, Number 3, March 1984 had the first hot stamped hologram embossed directly onto a magazine cover, with an accompanying story, "The Wonder of Holography."[24]

Rainbow holograms became especially popular through their use in toys and collectible "foil" cards, which increases the value and interest of these products for consumers. Everything from Pogs, to Magic: The Gathering, to Pokemon and even collectible sports cards used holograms; their respective companies recognized the increased interest of their products when this technique was utilized. What was once a gimmick is now an enormous draw for their user base. Presently, many rare foil cards of certain games can garner a value upwards of a few thousand dollars from collectors.[25]

23 Johnston, S. F., 2006, Holographic Visions: A History of New Science, Chapter 12.4, p. 375
24 Image source: https://americanhistory.si.edu/collections/search/object/nmah_713865
25 Good, O. S., One of Magic: The Gathering's rarest cards was bought for $87,000, 2018 Sourced from: https://www.polygon.com/2018/7/28/17625830/magic-the-gathering-black-lotus-auction-sold

Furthermore, as commercialization of holograms progressed and public engagement with the medium was on the rise, popular ideas about a holographic future were beginning to emerge, primarily sourced from science fiction stories and entertainment. In 1977, the release of the film *Star Wars* compellingly represented the idea of the hologram as a futuristic technology for visual communication and broadcasting in scenes where main protagonists in holographic form are depicted communicating with their allies.

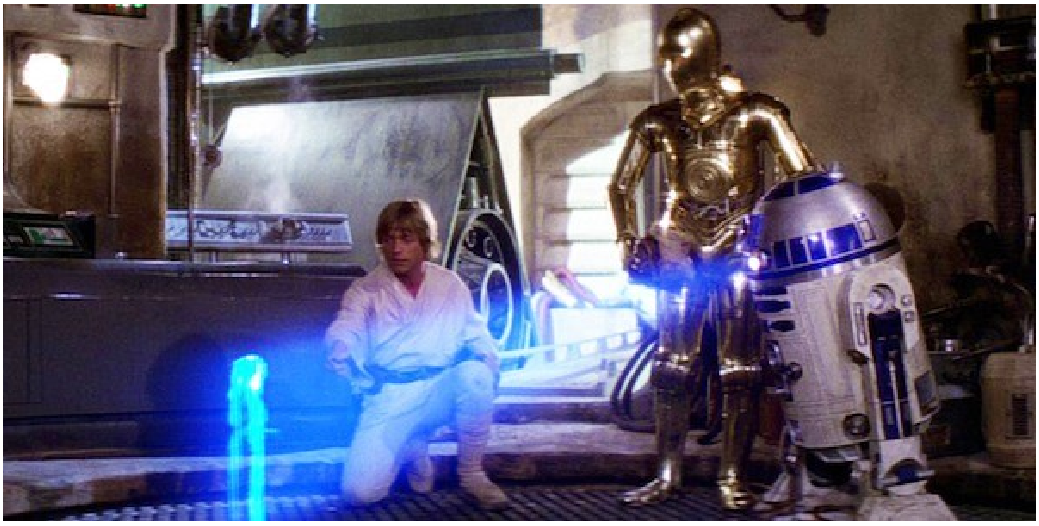

Figure 8: R2-D2 plays Princess Leia's hologram in Star Wars: A New Hope.[26]

Other notable appearances of holograms in motion picture entertainment include the British television series "Red Dwarf" (broadcast 1988-1994), "Star Trek: The Next Generation" (broadcast 1987-1994), and the recent 2017 neo-noir science fiction film "Blade Runner 2049" which features building-sized holographic advertising displays and artificial-intelligence holograms used for companionship.[27]

26 Image source: https://www.starwars.com/news/star-wars-film-concert-series
27 Ong, T., In Blade Runner 2049, can a relationship with a a hologram be meaningful?, [online] 2017, Sourced from https://www.theverge.com/2017/10/29/16468448/blade-runner-2049-relationship-hologram-meaningful

By the end of the 20th century, coinciding with the historic shift from traditional media to digital information technology, it appeared that the hologram, which astonished so many viewers since the mid-1960s, was no longer seen as the display medium of the immediate future. It had receded into the distant and faraway worlds of space ships and interplanetary travel.[28]

Fictional depictions of holograms have, however, inspired technological advances in other fields, such as augmented reality and 3D display technologies that promise to fulfill the fictional depictions of holograms by other means.[29] This is trend is increasingly manifesting itself as global innovations drive the improvements of digital display technology and computational processing power.

28 Johnston, S. F., 2008, A Cultural History of the Hologram, Leonardo, Vol. 41, No. 3, pp. 223-229, 221

29 Richardson, M., The Hologram: Principles and Techniques. Wiltshire, John D. Hoboken, NJ., 2017

4. Holography and Digital Imaging

4.1. 3D Display Technology

As we begin to talk about holography in the context of digital imaging, it is important to clarify that holograms are distinct from 3D display technologies, which can produce superficially similar results, but are actually based on conventional lens imaging. I feel though they are worth mentioning because the perceptual experience they provide does have similarities to the optical qualities of holography, especially when the display does not require the viewer to wear special headgear or glasses to perceive an image as three-dimensional. This technology is known as an autostereoscopic display, and the first flat panel video display of this type was developed in the late 1980s by Reinhard Boerner at the Heinrich Hertz Institute in Berlin. It creates a sense of depth by utilizing a parallax barrier device in front of the liquid crystal display, which consists of an opaque layer with a series of finely spaced slits, allowing each eye to see a different set of pixels.

Sharp Corporation introduced digital autostereoscopic flat panel displays to the commercial market in 2004 with their "Actius RD3D" laptop computer. It wasn't very well received however, due to a very narrow viewing angle and poor computer performance which resulted when its 3D mode was activated. Sharp's display technology would eventually prove successful in 2011 when it was incorporated by Nintendo in their "Nintendo 3DS" handheld console. This helped significantly in bringing autostereoscopic digital displays in front of a mass audience.

Flat panel 3D displays are generally quite problematic in accommodating multiple viewers due to their small field of view. Additionally, they do not allow the viewer to move around the image object to see it from different angles and can also occasionally cause eye fatigue.

4.2. Volumetric Displays

Another type of autostereoscopic display is the volumetric display. In contrast to the planar simulation of visual depth used in autostereoscopic LCD displays, a volumetric display forms a 3D visual representation of an object via the emission, scattering, or relaying of illumination from well-defined regions in physical space. This enables spatially accurate representations of images with a 360° view. Volumetric imaging is still very much under development and accessible only to academia, corporations, and the military through various research labs. Commercial adoption is however slowly emerging. Volumetric displays fall into three categories: swept volume display, static volume displays, and free-space displays.

Swept volume displays, also referred to as mechanical 3D displays, create volumetric images from rapidly rotating panels that are embedded with high-speed emitters such as LEDs. By controlling the timing of the light emitter array and the movement speed of the panels, a continuous volume of light is maintained. Because human vision cannot discern images at very high rates, this translates into a 3D image which inhabits the physical space.[30]

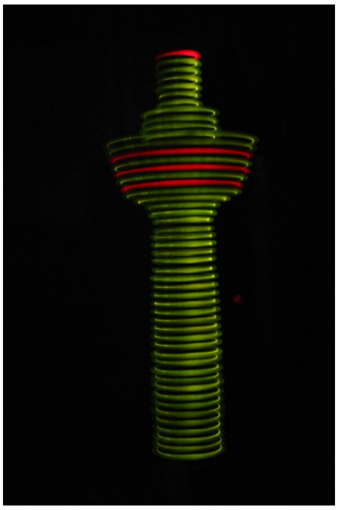

Figure 9: Fast-moving LEDs create a 360° object in air in this prototype by University College Sedaya International.[31]

30 Lueder, E., 3D Displays, First edition, Wiley, 2012, Chapter 7.3, p. 245
31 Image source: https://en.wikipedia.org/wiki/Volumetric_display

The second type, the static volume display, renders 3D imagery without any moving parts in the image volume. They make use of laser light to illuminate an image in nonlinear gases or solids or by projecting onto a number of diffusing planes. One such approach, developed by 3DIcon Corporation, consists of a rare earth-doped transparent image chamber and two infrared scanning lasers used to excite the rare earth ions and creative visible light emission in a process called photon upconversion.[32] A computer controls the two lasers using 3D volumetric data that is provided. The result is a 3D image composed of millions of volumetric pixels, or voxels, able to viewed through the chamber barrier.

Lastly, the free-space display composes an image in air with no barrier between user and image. A fog display system, for example, developed by a team at Osaka University utilizes three projectors all focused on a single column of steam that acts as a parallax barrier, so when the observer moves around the fog, they get a three dimensional view of the projection suspended in mid-air.[33]

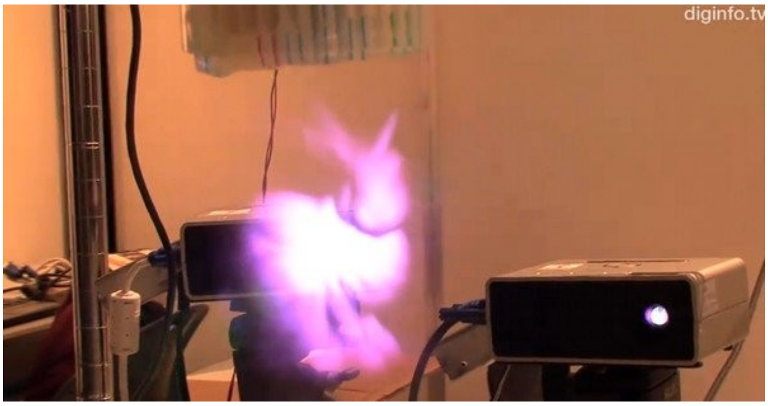

Figure 10: Static volume displaying a volumetric image of a violet rabbit suspended in a column of fog.

The most recent breakthrough in volumetric imaging that comes closest to a *Star Wars*-style 3D projection came in 2018 with development of a optical-trap display led by electrical and computer engineering professor Daniel Smalley and his team of students at the Brigham Young University, USA. This free-space display operates by confining a single particle, a plant fiber called cellulose, using near-

32 Keen, V., 3D Volumetric Display Technology, [online] 2015, Sourced from: https://www.techbriefs.com/component/content/article/tb/features/application-briefs/21710

33 Stevens, T., 3D fog projection display brings purple bunnies to life.., [online] 2011, Sourced from: https://www.engadget.com/2011/03/17/3d-fog-projection-display-brings-purple-bunnies-to-life-just-in/

invisible laser beams. This allows the researchers to push and pull the cellulose around, thus trapping it in the air. The suspended particle is then illuminated with a second set of visible laser beams to draw a 3D image as it is being moved around. Due to the persistence of human vision, the particle's trajectory appears as a solid line. The volume resolution of these images has demonstrated a minimum point dimension of less than a 10 micrometers at all depths, or around 1600 dots per inch, thus allowing for detailed renderings.[34] This optical trap display can only create very tiny images, however, at about the size of a finger tip. As this technology is further developed we are likely to see it become capable of producing larger images in the future.

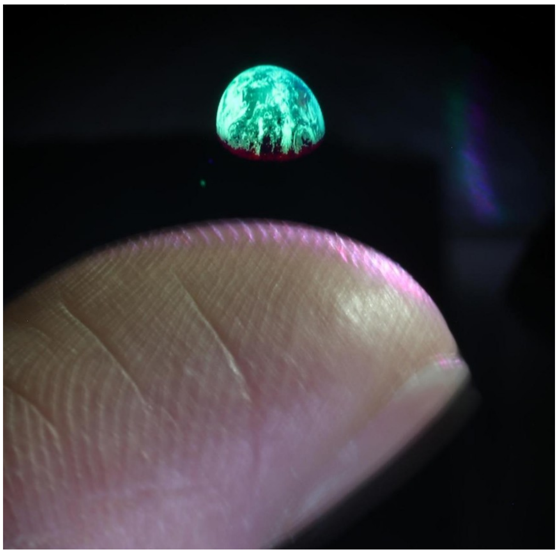

Figure 11: An image of planet Earth projected using an optical trap display.[35]

According to a recent volumetric display market analysis report, the constant innovation and technological advancements in 3D displays are anticipated to drive the market growth past 1 billion US dollars by 2025.[36] Industries such as healthcare, military and defense, aerospace, media and entertainment will be

34 Smalley, D. E., Nygaard, E., Squire, K., Van Wagoner, J., Rasmussen, J., Gneiting, S., Qaderi, K., Goodsell, J., Rogers, W., Lindsey, M., Costner, K., Monk, A., Pearson, M., Haymore, B., Peatross, J., 2018, A photophoretic-trap volumetric display, Nature volume 553, p. 486–490

35 Image source: https://www.slashgear.com/optical-trap-display-makes-r2-d2s-holographic-leia-a-reality-25517047/

36 Volumetric Display Market Analysis By Display Type (Swept Volume, Static Volume), By Technology (Digital Light Processing, Liquid Crystal on Silicon), By End Use, By Region, And Segment Forecasts, 2019 To 2025, [online], Sourced from: https://www.grandviewresearch.com/industry-analysis/volumetric-display-market

adopting volumetric display technology to enhance their user experience and operational efficiency. While complex fabrication and high costs are still associated with these devices, currently hindering its reach to commercial applications, we are likely to manufacturing costs drop as the technology matures and investment is.

Considering this, we may not be that far away from actually realizing the three-dimensional holographic displays of popular fiction, which so greatly captured our imaginations in the past.

5. Conclusion

Since its emergence, holography has contributed greatly to imaging technology, with many of its applications in science and medicine, capable of providing us with data that visible light alone wouldn't allow us to observe. It provided something novel to the medium of photography in the way that it was able to marvel us with its multi-colored dimensionality and mesmerizing depth. It revealed to us the possibilities of a new and optimistic future, a vision that seemed so close; until it was appropriated by the culture which helped create it. The inevitable commercialization of holography, with its appearance in shimmering magazine advertisements, embossed toothpaste packaging, and credit card authentication foils, ultimately caused optimism in the hologram to wane.

Outcomes such as this are not uncommon in the fields of science and technology, but they are quickly forgotten. The declining interest in the hologram parallels that of other 3D media. Stereoscopes, once a Victorian spectacle at the time, also turned into a consumer fad, as it was repackaged by economic interests into plastic children's toys, much like the hologram found its way into "Pogs" and collectible playing cards.

Perhaps the same will be said one day about today's digital 3D "holographic" displays; that they were just used for conjuring up immersive visual gimmicks on social media platforms and other immediate virtual appeals. Regardless, we should recognize that holographic research and development continues, albeit quietly, to this day. Over the past decade, the merging of holograms and computers has been increasingly successful, with innovations synthesizing with the increasing speed of computer processors and real-time electro-optical devices. Although now less visible, they are still widely used in areas that affect our daily lives. Developments reach as far out as to the fields of astronomical imaging through the correction of optical wave-fronts passing through telescopes, including the microscopic field of electron holography Gabor conceived 72 years ago. Holographic technology will continue to progress behind the scenes, rather than in the limelight, to develop new applications and innovations in the not so distant future. Whether or not it emerges as an invaluable tool remains to be seen; but it is certain that the hologram, if for nothing else, illuminated the imaginations of the masses, which is a fire that should always be stoked.

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