# HOLOGRAPHY: THE FUTURE OF AUGMENTED REALITY WEARABLES

An introduction to Computer-Generated Holography and the requirements of AR display

VIVIDQ

# Contents



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# Key Findings

- **Holography engineers light to create realistic virtual images.**
  Holographic images deliver the same three-dimensional information a user's visual system receives when looking at a real object, encoding in all necessary depth cues.
  This eliminates nausea, eye-fatigue and visual discomfort, commonly associated with other well-known '3D' technologies.

- **Currently available AR headsets lack real depth of field.**
  The majority of augmented reality (AR) headsets available or in production rely on stereoscopic displays to produce 3D-like images. Without real depth of field, virtual images in AR appear disconnected from the real world and cause visual discomfort after extended use.

- **Total power consumption and form factors limit AR headset adoption.**
  Current AR headset features are constrained by total power consumption and form factor. It is not possible with the current technology stack to produce an AR headset with advanced features such as 6 DoF tracking, high resolution and high FoV display with daylight brightness within a consumer-appropriate form factor. This limits potential consumer AR headsets to only very basic applications and will limit uptake and market potential.

- **Holography solves the most difficult challenges in AR headsets.**
  Holography produces full three-dimensional objects and scenes, integrating into the real world seamlessly. Holographic display gives intrinsically high brightness at low power and the optical systems can be engineered to be extremely compact.

- **Holographic AR offers the only route to consumer mass adoption.**
  To progress and be a long-term success, the AR industry needs hardware manufacturers to pivot away from conventional headset display solutions that only partially resolve the AR challenges and put holographic display top of their development roadmaps for the next generation of AR devices. This is the only clear route to mass consumer adoption of AR technology.

## Key features of Holography

- Accurate depth information for precise environment matching
- On-screen information updated in real time
- Enables sleek, lightweight AR wearable devices
- Comfortable long-wear use without VAC or eye fatigue
- Exceptional image quality: retina-level resolution
- Natural depth of field for enhanced viewing experience and increased immersiveness
- Superior brightness for all lighting conditions (light/dark)
- Multi-user collaboration on holographic images
- Integration of tracking systems into full-depth scenes for free movement

# Foreword

Holograms are usually thought of as the stuff of science fiction. Take your favourite futuristic world, be it Star Trek, Blade Runner, Altered Carbon and many others. These fictional worlds all feature technology with the ability to create highly realistic, three-dimensional virtual images that users may interact with in a completely natural and intuitive manner. Holography represents the ultimate in display technology and ushers in a revolution in the interaction between human and machine.

Imagine everything from personal holographic wearable devices, casting 3D images straight to your eye, all the way up to entire holographic rooms placing you in the middle of your favourite television show, transporting you to a famous landmark you always wanted to visit or even to some imagined far-flung planet from a video game. The possibilities for entertainment, communication and productivity are endless.

While sci-fi writers may still fantasise of such technology, scientists and engineers have been working to make this a reality. The main takeaway from this paper is that **holographic display technology is now within reach.**

The first steps have already been taken and now holographic display is emerging from academic labs into the commercial world. The technology has already attracted significant funding within major tech companies and startups looking to advance the field and bring holographic display enabled products to market. This is due to the huge impact that holography is expected to have across the display industry and the far-reaching consequences it will have for everyday human experience. Based on current trends the first products are likely to be clustered around two primary applications, Augmented Reality (AR) Wearables and automotive Head-Up Display (HUD).

This paper will summarise why holography will take an influential role in the future, detailing why it forms a core component of future devices. On behalf of the whole team at VividQ, we welcome you to join our exciting journey.

**Darran Milne**
*Co-founder and CEO, VividQ*

# What is holography?

Consider how we perceive the world around us. In a very real sense, we never actually 'see' anything. What we actually 'see' is light that has reflected off the surface of objects around us. The reflected light forms complex patterns that our visual system interprets as physical objects.

Now imagine that instead of having a real object, we were able to precisely control light to recreate a pattern of light reflected off a real object. Then we could just direct the light pattern into an observer's eyes and they would receive the same information as the real object would have given. Since we have recreated the same light pattern as the real object, this encodes all the three-dimensional information about the object, creating a fully 3D virtual image. This image (see figure 1), which is visually indistinguishable from the real object, is known as the **holographic image**.

"Holographic augmented reality displays make it possible to truly integrate digital content into the real world with correct depth and focus cues. This scientific breakthrough uniquely promises technological engagement that is more active, more social, and more aware of the world around us. I am confident that the first generation of displays, possessing the necessary function and form factor, will revolutionize our lives on the same scale as smartphones in the early 2000s.

Rachel Brown, Research Scientist at NVIDIA"

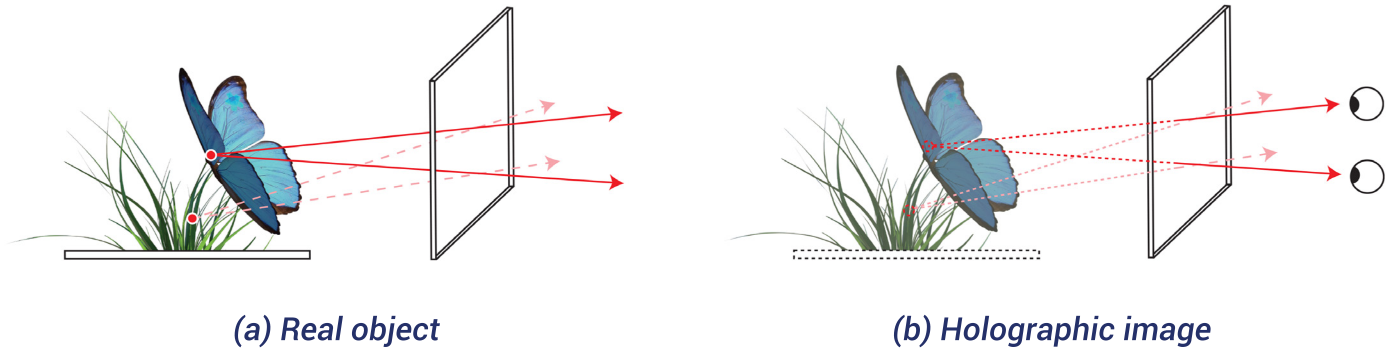



*Figure 1: (a) When we view the world around us, we are actually observing complex patterns of light reflected from objects. Our visual systems interpret these complex light patterns as the objects we see. The complex light patterns contain all the visual information from the objects.*

*(b) If instead of having a real object, we were able to artificially engineer the corresponding complex light pattern and display it to the observer, the image they see would be visually indistinguishable from the real object. Furthermore, because we have engineered the entire light pattern, the image would be naturally three-dimensional as the light pattern encodes all the three-dimensional information about the object.*

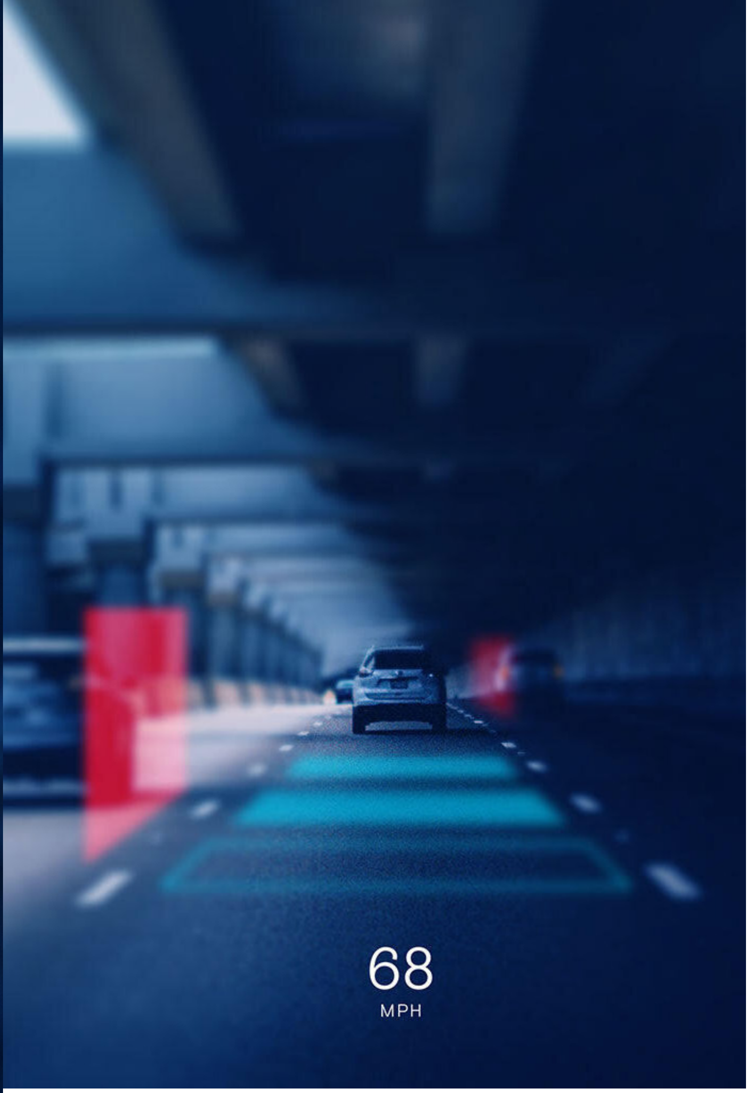
Later in this paper, we will explain a specific type of holography using digital display, known as **computer-generated holography (CGH)**.
This method of holography uses 3D data from sources such as game engines, 3D cameras and CAD software to create the light pattern of an object without having to use a real object at all. This allows the creation of dynamic and interactive holograms required for AR wearable applications.

To create a specific light pattern, we use the diffraction and interference properties of light. Put simply, diffraction is the effect that light fronts fan out into a cone when passed through an aperture. Interference is when two light waves sum together to form a wave of higher intensity (constructive interference) or sum to cancel each other out (destructive interference).

In CGH, a digital display device known as a spatial light modulator (SLM) is used to create the light pattern. For each object we wish to display, we must find the set of values for each pixel in the SLM such that the light reflected from the pixels interferes in just the right way to form the desired holographic image.

Each pixel in the SLM acts as a small aperture, that modifies a property of light waves known as 'phase'. This allows light reflected off the surface to diffract, allowing light from nearby pixels to overlap and interfere. By accurately controlling the phase, we can control exactly how the light interferes and hence create whatever pattern of light we wish. The SLM essentially steers the light into specific patterns that allow us to build 3D images from the overlapping reflected light.

So, the SLM itself does not display an image, but a set of instructions for the incoming light on how to behave. The data displayed on the SLM that controls light is what we refer to as the **hologram**. The term 'hologram' is often mistakenly used instead of 'holographic image', the actual term that refers to the 3D virtual object or scene that a viewer wants to see.




The essential components of a holographic display (see figure 2) are the SLM, a compute platform to calculate and upload the holograms to the SLM, and a light source. Lasers are typically used as the light source due to their high 'coherence'. This means laser light gives a single wavelength, providing accurate interference and a good recreation of the desired light pattern.

To summarise, **holography** is the process of engineering light to project three-dimensional virtual scenes that possess a natural depth of field. This means holography can produce highly realistic AR content that integrates seamlessly with the real world. In the past, the process of creating computer-generated holograms has demanded high power computing resources, meaning it has been confined to research and academic labs. Today, however, new algorithms and software have been developed, bringing CGH to next-generation displays using standard computing power.

The inherent properties of CGH make it a viable technology for next-generation AR wearable devices.

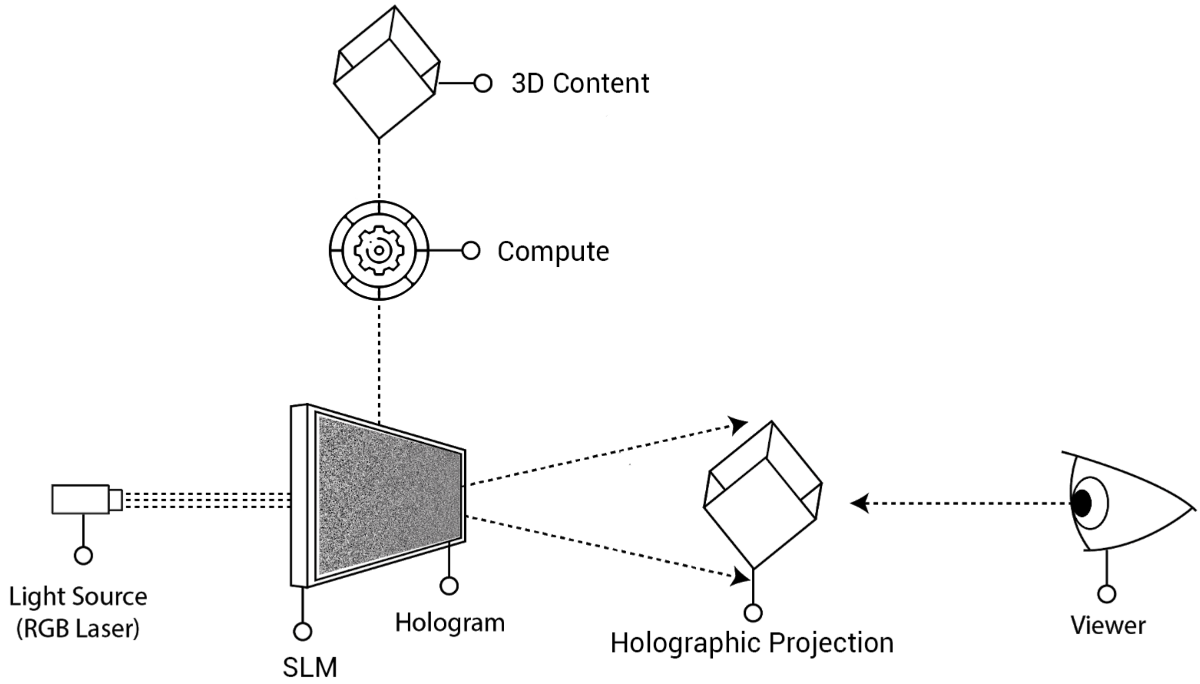



***Figure 2:*** *A holographic display is composed of three major elements. A Spatial Light Modulator (SLM) display element, a light source, such as a laser and a compute engine to calculate the hologram pattern. The compute engine consumes three-dimensional data from a 3D content source and calculated the hologram pattern. This pattern is displayed on the SLM and illuminated by the laser light. The hologram pattern displayed on the SLM causes the laser light to interfere and form a three-dimensional image to the viewer.*

# How does this relate to AR?

As readers will know, **augmented reality (AR)** is an exciting area of investment and research for all major technology companies, with industry professionals following what Facebook and Apple, among many others, will do next. Given the huge application space, AR has the potential to span both the consumer and enterprise industries, from wearables and Internet of Things to cloud computing infrastructure.

We will explore how holography relates to AR by outlining how we define 'AR wearables'.

Under our definition, we cover most major devices currently available, including: Google Glass, Nreal Light, Magic Leap 1, Vuzix Blade and Microsoft HoloLens.

Our definition of AR wearables covers:

- Virtual objects or scenes overlaid with a real-world environment by a near-to-eye device such as a headset, or smartglasses.
- The ability to recognise and update its display information based on feedback from the environment using spatial location and mapping. This could be anything from a simple gyroscope all the way up to depth-sensing cameras and full inside-out tracking.
- Virtual images displayed can be anything from simple text and icons overlaid in context with the environment all the way up to highly immersive experiences where 3D virtual assets are integrated into the real world.

> "As a developer of miniature optical engines for AR wearables, I expect that holography will become the ultimate solution for overlaying virtual worlds on top of the physical one. To the human eye, holographic virtual objects are really "there". Although this will still require further advancements in several key technologies, AR wearables are the holy grail and have the potential to one day replace our mobile phones."
>
> Steve Yeung, CEO at iView

# Challenges for AR wearables adoption

The limitations of AR wearables have been widely documented, with the underlying technology struggling to meet the demands required for everyday applications. Owing to this, AR has mostly been restricted to use within industrial settings.

| What we care about in AR Wearables | | What we require for AR Display |
|---|---|---|
| **Field of View (FoV)** | The observable cone within which virtual objects are visible through an AR wearable device. | Immersive gaming requires >80°. Current devices display 40 - 50°. |
| **Eyebox Area** | The amount the eye can move around and still see the virtual images on the headset optics. | 1cm$^2$ or greater to ensure the eye never loses sight of the images. |
| **Depth of Field** | The apparent defocus between virtual objects. | Virtual objects should appear at any depth and defocus naturally. |
| **Resolution** | The effective resolution of the images to the user, measured in pixels per degree (ppd), giving an estimate of the smallest detail that can be resolved by the eye. | Smooth realistic images require >60ppd. Typical values in current headsets range around 20 - 30ppd. |
| **Brightness** | Apparent brightness of the virtual images to the eye. | For outdoor display in bright daylight, the display should provide images in excess of around 6000 nits. |
| **Contrast** | The observed ratio of the brightest colour (white) to the dimmest colour (black) in the display. | Contrast should be in the range of 400-600:1. Display should be transparent where no content is being shown. |
| **Colour Accuracy** | A measure of how accurately colours are depicted in the image and how uniform they are across the FoV. | AR displays should have high dynamic range colour with no noticeable colour variation across the image. |
| **Power Consumption** | The power draw to drive the display panel and illumination. | For consumer-ready form factor, this should be <500mW on average. |
| **Size and Weight** | The bulk and weight of the display. | To optimise form factor, the optical system should be small with a weight less than 30g. |


To meet the wider consumer requirements and enter mass adoption, the industry needs to look towards next-generation display devices, capable of giving users a visual experience that can be realistic, immersive and practical.

Developers of AR wearable technology face a fundamental tradeoff between the form factor of the device and its functionality. In short, the more features on your device and the better experience, the bulkier and heavier the headset becomes.

On page 10, we list the key display characteristics required for the ideal AR wearable device.

No solution has yet emerged that meets these requirements, despite over a decade of concentrated effort and billions of dollars of investment. The argument remains on whether time and further iteration of existing features and concepts can get us to a consumer-ready solution or whether a revolution is required in digital display technology.

> "Holographic display allows true multi-depth imaging and promises to solve many problems standard stereoscopic displays have, such as VAC, thereby providing obvious benefits in viewing comfort.
> Use cases where arms-length display interaction is required along with medium-near field display gazing (such as engineering, surgical, defence etc) could benefit significantly from the implementation of holographic display technology.
>
> Bernard Kress, Partner Optical Architect at Microsoft HoloLens"

# How holography will revolutionise AR in the 2020s and beyond

Computer-generated holography (CGH) offers huge potential for AR wearables where other technologies have encountered challenges that have blocked their progress in reaching consumer mass adoption. Here we show how holography addresses some of the biggest challenges facing AR wearables today.

## 1 Addressing miniaturised optics

In 1956, Gordon Moore, co-founder of Intel, predicted that the number of transistors on a chip would double every 18 months, therefore doubling computing power. This prediction, known as Moore's Law, has approximately held true for computing since then. The rule has driven much of the greatest technological advancements over the past few decades and is still widely considered to be a leading idea around the latest emerging technology trends. However, while Moore's Law shows us the potential for technological development, the trend does not apply to other key areas of technology - such as optics.

One of the biggest challenges around current AR wearables is the need to balance sleek, ergonomic device form factors with complex functionality. Smaller optical systems are vital for compact and lightweight AR wearables. Yet, the fundamental physical limits on the size of optical elements such as lenses are set by the very properties of light itself. For the best visual experience, AR wearables need to achieve a large field of view (FoV) with a large eyebox, and create a realistic depth of field. While current AR wearables can offer these features, they compromise on form factor with bulky and complicated optics. Miniaturised optics are key to achieving consumer-ready AR smartglasses.

One of the intrinsic benefits of holography is its ability to produce realistic 3D images containing all the necessary three-dimensional data required for AR wearable content. Unlike current AR wearable devices either available or currently in development, holographic AR wearables do not require additional varifocal lenses, multi-waveguides or eye-tracking for focus blur - all used to create a '3D-like' effect. Without these additional hardware components, holographic AR wearables offer reduced bulk and weight in the optical system and remove the additional compute overheads for eye-tracking and blur-rendering.

While current AR wearables are required to compromise core functionality to compensate for good form factor, holography offers the convenience of being able to use miniaturised optical hardware and provide a display experience that is entirely natural to the eye. Even better, in CGH, where holographic images are created digitally from a 3D data source, optimisation and optical aberration correction is performed using specialised software, saving headset manufacturers additional production costs.

Despite Moore's Law indicating that computing power will increase every 12-18 months, important hardware components such as optical systems do not have an equivalent rule that would also make them smaller and more compact over the same time period. Holography offers a solution for AR wearables by reducing the number and complexity of the required hardware components.

## 2 Power constraints & heat dissipation

A key consideration in the design of AR wearables is average power consumption. High power consumption is a consequence of factors such as bright backlit displays and real-time rendering of complex content, as required for a good AR experience. To match consumer demands for a device lasting 'all day' (8+ hours) on a single charge, current AR wearable devices require large batteries. This adds additional weight and bulk to the AR device, compromising on the overall form factor. Advances in battery technology are also relatively slow compared to the lifecycle of consumer electronics, often taking 10-20 years for new technology to advance from the lab to a commercial product. This means we are unlikely to see any groundbreaking solutions soon.

A related issue is heat produced as a by-product by electronics. In the case of a head-mounted AR wearable, the heat must be dissipated efficiently so as not to cause damage to a user's skin during extended periods of use. We have two options: increase the surface area of the device to dissipate the heat away from the user or find ways to reduce the average power consumption. The first brings us right back to the problem of form factor - large batteries and increased surface area for heat dissipation mean bulky and heavy AR wearable devices. The second option, however, is extremely hard to achieve. Consider that a smartphone draws around 1300mW on average and gets hot when displaying video for prolonged periods. Then AR wearables need to be using no more than 500-600mW to allow for acceptable battery life and heat performance. This is an incredibly tight power budget given all the functionality we desire in our ideal consumer AR devices.

Holography aims to solve the issue around power consumption by increasing power efficiency with its use of a laser as the light source. Laser illumination in holographic displays is extremely bright and power-efficient. In traditional backlit displays, light is always on across the entire display, resulting in power inefficiency and relatively dim displays that cannot compete with daylight or brightly lit rooms. In holography, the hologram directs light from the laser into the holographic image, only where the image is formed. This process only requires microwatts of power to create holographic images of superior brightness, making it highly power efficient. As holographic displays require less illumination power, original equipment manufacturers (OEMs) can apply miniaturised optics and smaller device surface area to target more compact, sleek and portable AR wearables designs.

## 3 Vergence-accommodation conflict (VAC) & eye fatigue

All-day useability is essential for consumer adoption, and it does not end with battery life and sleek design. To keep users engaged, the visual effect must be convincing and avoid inducing eye fatigue, headaches, or nausea. To achieve a convincing AR effect, users need to experience true three-dimensional images. In currently available AR wearables, this is achieved using a binocular (two-eye) 'stereoscopic' display system that gives each eye a slightly offset image of the desired scene, so the user can effectively see two perspectives on the virtual object simultaneously. This '3D-like' experience is most seen in virtual reality (VR), 3D cinema and 3D TV with varying hardware. The illusion created by stereoscopy is incomplete however and does not provide the user with any focus cues as it contains no inherent depth of field.

This has two major implications:

1. Stereo virtual objects that lay in the same plane of focus will appear essentially flat. These objects cannot integrate with the real world naturally and will always look detached from their surroundings;

2. As the virtual images are confined to a single focus plane, the observer's focus and convergence reflexes can easily get out of sync. Stereo display forces the user to focus on a single depth plane, leading to vergence-accommodation conflict (VAC). This is responsible for eye fatigue and headaches widely experienced by users of AR/VR devices.

As we have discussed, holographic images inherently contain all the three-dimensional data and necessary depth cues to be able to integrate seamlessly into the real world, in a way that feels natural to viewers. This intrinsic feature makes holography a strong contender for the future of AR wearable technology. Holographic AR wearables allows users to experience focus and convergence cues similar to real world vision. This means users can experience AR content comfortably in all-day settings, without causing eye strain and fatigue.

The ability to see virtual objects naturally across different depth planes means holographic images are essential in settings where extreme precision is important for success. This is important in various industrial settings, such as the manufacturing and medical industries where precise environment matching is crucial.

> "I see holography as having the potential to be the ultimate 3D image generator. It effectively solves VAC issues caused by traditional stereoscopic display systems. By retaining all depth information, holography allows people to see and sense images in a way that is most realistic, comfortable and natural.  A major benefit of holographic display is that optical aberrations can be corrected in software. This means reducing the complexity and cost of optical systems."
>
> Fleming Chuang, CTO at Coretronic

# The path to adoption for holography

As holography provides natural solutions for many of the problems experienced by the AR industry, we must continue to drive the development to the ecosystem. Challenges remain for holography that still must be addressed to become a mainstream technology.

### Display Panels

Near-term holographic display devices will be based on phase LCoS (liquid crystal on silicon) display panels, which currently offer display resolutions of up to 4K (with 8K expected to appear soon). Continuing improvements and development of higher resolution displays with improved grayscale mean AR experiences will continue to become more immersive.

Display panel manufacturers should focus on:

- Optimising pixel size and increasing display resolution to provide an improved FoV, eyebox size and image quality;
- Creating compact phase LCoS kits with driver units suitable for AR wearables;
- Designing display driving schemes and liquid crystal layer choices for CGH software, optimising for image quality, colour quality and framerate.

### Optical Systems

As holography works on different principles from traditional display, new optical designs for illumination and novel methods for steering holographic images to the eye must be developed. Such designs must provide a large eye-box for comfortable viewing with a large enough field of view to satisfy the consumer requirements.

Optical system engineers should focus on:

- Development of miniaturised holographic optical engines;
- Integration of de-speckle methods to improve image quality;
- Development of specialised optical combiners to relay holograms to the eye.

> “Introducing real time computer-generated holography into consumer display applications will bring a major shift in the way personal electronics are designed and used. This can only be achieved at mass-scale through close collaboration between key innovators in the industry - from software and compute platforms to display hardware.
>
> Aleksandra Pedraszewska, Co-founder and COO at VividQ”

## Algorithms & Compute Platforms

Computer-generated holography (CGH) is a vastly computationally intensive task, requiring large compute resources to generate even a single hologram frame. Where the advantages in power efficiency, compactness and real three-dimensional imagery are substantial for holography, the downside is the computing requirement for hologram generation. For holography to succeed, the compute issue must be resolved. However, while there may not be a Moore's Law for optics, there definitely is one for compute resources.

For holography to be successful in AR wearables, we require new, high-performance CGH algorithms that run in real time (>60fps) and create high-quality holographic images on portable compute hardware, such as NVIDIA GPUs or Arm mobile GPUs.This solution is the first step to allow for portable AR wearable devices, but they would still be tethered to another device, such as a smartphone or portable compute unit. This was adopted by Magic Leap and Nreal, proving its acceptance for certain industry applications.

However, in order to achieve the desired compact, untethered form factor required for consumer-ready AR wearables, the compute task will need to be moved from generic GPUs, and instead be handled by CGH-specific chips such as ASICs (Application Specific Integrated Circuit).

The advantages of ASIC development for holographic AR are:

- **Very high power efficiency** - ASICs designed around a specific CGH algorithm ensure very low power operation;
- **High bandwidth to the display** - ASICs are connected directly on the display panel to eliminate data bandwidth issues, lowering power consumption and latency;
- **Compact form factor** - Dedicated ASICs are much smaller in size than mobile GPUs.

A CGH-specific ASIC requires investment from the big chip manufacturers. With dedicated hardware available, ODMs and OEMs will be freed up to invest in the optical and industrial design of products without the issue of how to drive the display. This will be a hugely important step in the evolution of the ecosystem and will be the catalyst for wide-spread adoption of holographic display.

> “I expect AR smartglasses to be the first holographic devices we see. These devices will look like normal glasses but can provide AI information that I can use in my work and day-to-day life, without needing to connect to a smartphone for data. Depth is a key benefit that holography can provide to AR devices. Use cases like mixed reality training will benefit significantly from the ability the display objects at accurate depth, allowing them to merge easily with the real world.
>
> Dennis Deng, Principal Engineer at HTC Vive”

# Summary

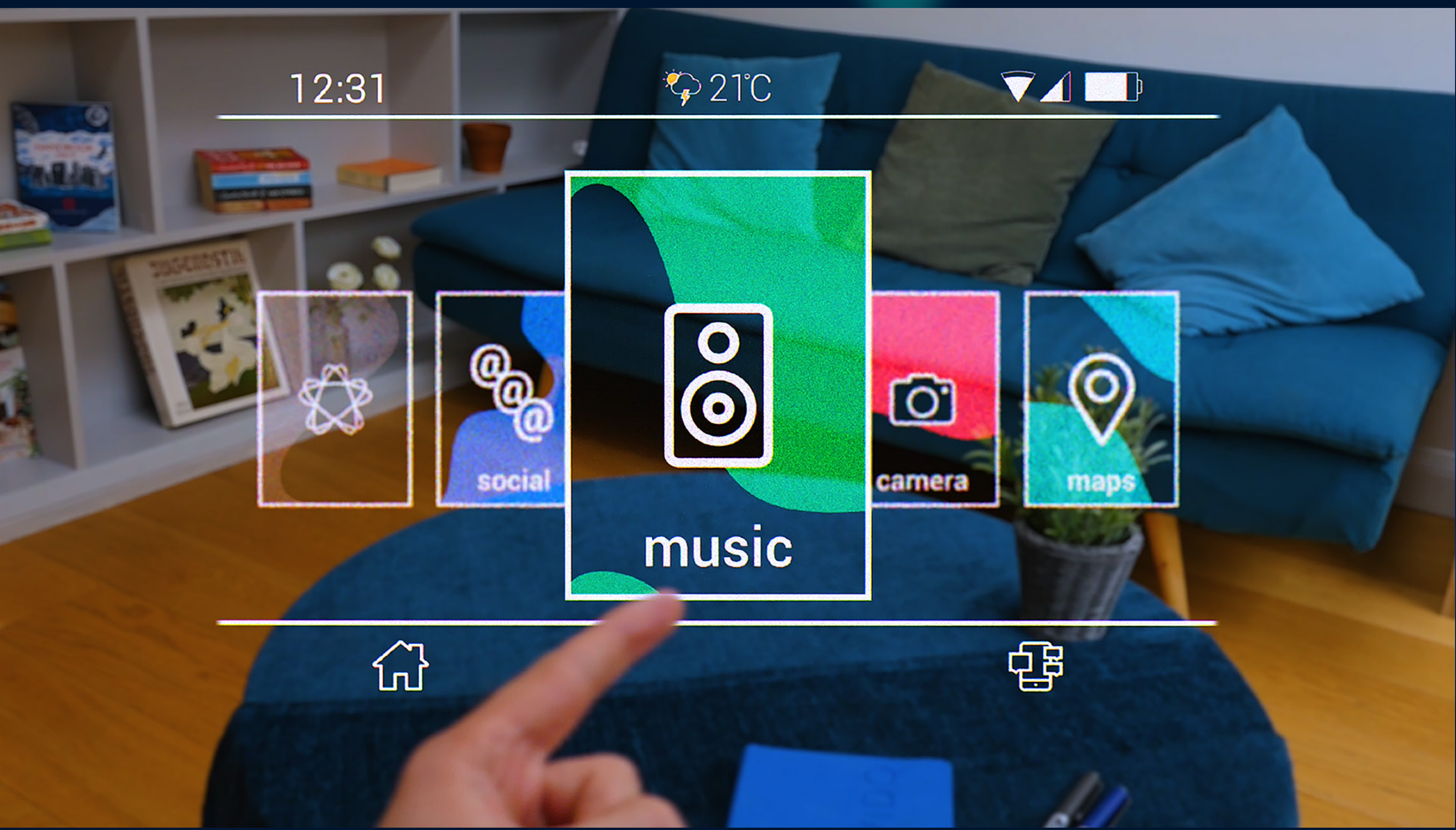
Thank you for reading our whitepaper in which we introduce computer-generated holography (CGH), and its applications for the next generation of AR wearables. Whilst this paper focuses on exploring the road to achieving a consumer-ready pair of AR smartglasses, CGH has the potential to disrupt the whole display industry, from automotive head-up displays (HUD), to personal device screens.

Thanks to this innovative display technology, the future of AR will feature the most realistic and immersive experiences to date.

At VividQ, we are making it happen with our world-leading research and development teams and through collaboration with our Partner Ecosystem, bringing together the essential components required to make holographic display a mass-market technology.

Are you interested in learning more about holography, and how it will benefit your products?

Please visit our website at **www.vivid-q.com** or contact us at **info@vivid-q.com**.



# About VividQ

VividQ is a deep tech company with world-leading expertise in computer-generated holography.

Holography has long been considered the pinnacle of display technology, providing a high level of realism and accuracy. Using computer-generated holography, we compute light patterns to display three-dimensional projections.

VividQ software and IP for CGH are used by international technology companies, creating the most realistic and immersive visual experiences. VividQ was founded by a team of engineers, mathematicians and computer-scientists from the Universities of Cambridge, Oxford and St Andrews. Our expert team has brought holography from the realms of science-fiction to everyday applications.

# Bringing VividQ technology to AR product development

VividQ enables the deployment of holographic displays in next-generation AR devices and consumer electronics. Our technology is used by original device and equipment manufactures (ODMs/OEMs), from early-stage R&D projects through to development of consumer-ready products.

VividQ's technology stack for CGH allows the projection of three-dimensional objects and scenes, with a natural depth of field, that integrate seamlessly with the real world. Holographic displays can be integrated in augmented reality (AR) devices from wearables to head-up displays (HUDs) and personal device screens.

VividQ delivers this capability with proprietary Software Development Kits (SDKs) and licensable hardware designs, using mass-produced optical and display components. VividQ products provide engineers with all the tools needed to run and optimise holographic display systems. The VividQ SDK connects to multiple 3D data sources, performs real-time calculation of holograms on commercially available GPU and mobile compute platforms, and interfaces with a variety of display panels. VividQ products include reference designs for optical setups, electronics assemblies, full system specifications for AR wearables and HUDs, and solutions to enhance the image quality in holographic display.

VividQ gives its customers, developing next-generation AR devices, the opportunity to gain a huge competitive edge in product functionality and time to release.

With VividQ's cutting-edge products and support from world-class engineering and software teams, our customers reduce development costs, shrink time to market to less than 18 months and gain a huge technological edge. Beyond the development phase, VividQ software is deployable for mass production and distribution, allowing fast scaling of devices with holographic displays, powered by VividQ.