Displays & optical vision systems for VR, AR & MR
OBJECTIVE OF THE REPORT

Everything you need to know to get a grasp of VR & AR

• This report is a comprehensive survey of Virtual Reality and Augmented Reality as headsets, providing the reader with a deep understanding of the displays and associated optical vision systems.

• Understand the current status of VR and AR display and optical vision systems technologies:
  • What are they? What are the key benefits? How do display considerations differ in this context? Why are optical vision systems mixed in the equation?
  • What are the roadblocks? How challenging are they?
  • Detailed analysis of key technological nodes: field of view, pixel density, persistence, étendue, optical combiner manufacturing, holographic and diffractive elements, microdisplay sources

• This report also reviews the global VR and AR industries and provides insights into the possible evolution and the necessary technological developments for consumer adoption. The technological roadmap provided herein will allow the reader to analyze those.

• For each application, market metrics are detailed for displays and optical vision systems.

• Also, an Intellectual Property (IP) analysis is presented in order for the reader to better understand the patent landscape related to VR and AR.
TABLE OF CONTENTS

Part 1/4

- Executive Summary P3
- Introduction P7
- Virtual Reality – Introduction P26
  - Introduction P31
  - Basic of lenses P32
  - Regular lenses vs. Fresnel lenses P34
  - Trade-off in lenses’ choice P41
  - FOV in commercial VR HMDs P42
  - The dilemma to simply increase FOV P43
  - Alternatives to increase FOV P44
  - The cost of increasing FOV P45
- Virtual Reality – FOV P47
  - Introduction P48
  - Common metrics P49
  - PPI and PPD in VR HMDs P50
  - Consequences of low pixel density P52
  - Mitigating aliasing and screen door effect P54
  - Display technologies P56
  - Manufacturing challenges for increasing pixel density P61
  - OLED-on-Silicon and the display size limit P63
- Virtual Reality – Persistence P67
  - Introduction P68
  - Refresh rate P69
  - Sample-and-hold structures introduction P70
  - Sample-and-hold structures issues P71
  - Low persistence, concept P74
  - Low persistence, challenges P75
  - Low persistence, implementation P77
  - LCD versus OLED P79
- Virtual Reality – The display technology of choice P83
  - LCD versus OLED P84
  - MicroLEDs P86
- Virtual Reality – Sensorial challenges P97
- Virtual Reality – Trends for future development P112
  - Overview P113
  - Understanding eye physiology P114
  - The 60PPD cost on hardware P115
  - Foveated rendering P116
  - Color rendering P125
  - Different generations for different applications P127
- Virtual Reality – Display and optical vision system markets P128
# TABLE OF CONTENTS

## Part 1/4

- **Executive Summary**
  - P3

- **Introduction**
  - P7

- **Virtual Reality – Introduction**
  - P26
    - P31
      - Introduction
      - Basic of lenses
      - Regular lenses vs. Fresnel lenses
      - Trade-off in lenses’ choice
      - FOV in commercial VR HMDs
      - The dilemma to simply increase FOV
      - Alternatives to increase FOV
      - The cost of increasing FOV

- **Virtual Reality – FOV**
  - P48
    - P49
      - Introduction
      - Common metrics
      - PPI and PPD in VR HMDs
      - Consequences of low pixel density
      - Mitigating aliasing and screen door effect
      - Display technologies
      - Manufacturing challenges for increasing pixel density
      - OLED-on-Silicon and the display size limit

- **Virtual Reality – Persistence**
  - P67
    - P68
      - Introduction
    - P69
      - Refresh rate
    - P70
      - Sample-and-hold structures introduction
    - P71
      - Sample-and-hold structures issues
    - P74
      - Low persistence, concept
    - P75
      - Low persistence, challenges
    - P77
      - Low persistence, implementation
    - P79
      - LCD versus OLED

- **Virtual Reality – The display technology of choice**
  - P83
    - P84
      - LCD versus OLED
    - P86
      - MicroLEDs

- **Virtual Reality – Sensorial challenges**
  - P97

- **Virtual Reality – Trends for future development**
  - P112
    - P113
      - Overview
    - P114
      - Understanding eye physiology
    - P115
      - The 60PPD cost on hardware
    - P116
      - Foveated rendering
    - P125
      - Color rendering
    - P127
      - Different generations for different applications

- **Virtual Reality – Display and optical vision system markets**
  - P128
# TABLE OF CONTENTS

## Part 2/4

- **Augmented Reality – Performances, challenges and trends**  
  - AR requirements  
  - Introduction to paradigms for display and optics in AR  
  - Immersion and superposition of virtual data on real world  
  - The projection paradigm  
  - The user’s needs  
  - Display and optics dependence  

- **Display engine technologies**  
  - Overview  
  - LCOS technology  
    - Overview  
    - Applications  
    - Manufacturing and way of utilization  
    - Color management  
    - Comparison between LCOS and regular LCD  
    - The players at hand  
    - Mapping of players  
    - Market size for AR  
  - DLP technology  
    - Overview  
    - Applications  
    - Manufacturing and way of utilization  
    - Mapping of players  
    - The comparison between DLP and LCOS  
    - The market share between DLP and LCOS  

- **OLED-on-Silicon technology**  
  - Overview  
  - Applications  
  - The differences with regular OLED technology  
  - Manufacturing and way of utilization  
  - Mapping of players  
  - OLED-on-Si standing versus LCOS and DLP  
  - The market share against the LCOS and DLP competition  

- **MicroLED technology**  
  - Overview  
  - The MicroLED concept  
  - The display assembly  
  - The MicroLED microdisplay  
  - Applications  
  - Application roadmap  
  - Mapping of players  
  - A credible alternative to LCOS, DLP and OLED-on-Si  
  - What is happening in the short term?  

- **Miscellaneous technologies**  
  - Smartphone technology used in AR HMDs  
  - Fiber scanning display technology  
  - Light field technology  
  - A credible alternative to LCOS, DLP and OLED-on-Si  
  - What is happening in the short term?  
  - Display technologies conclusions and forecasts
# TABLE OF CONTENTS

## Part 3/4

- **Optical Vision Systems for AR**
  - Introduction to optics for AR
  - The question of optics for AR
  - The AR optical vision system
    - Imaging optics
    - Exit pupil expansion and eye physiology
    - The étendue
    - Coming up to optics
  - Regular combiners
    - Flat combiners
    - Curved combiners
    - Prism based combiners
    - Overview
  - Waveguide combiners
    - Light transmission
    - Cascaded mirror combiners
    - Diffractive element combiners
      - Surface Relief Gratings, principle
      - Material requirements
      - Origin and development of the technology
      - Manufacturing
      - Wafer requirements
      - Mapping of players in the supply chain
  - SWOT analysis
  - Holographic element combiners
    - The patenting activity for HOE
    - Disruption to diffractive element combiners
    - Principles
    - Material requirements
    - Transmission or reflection holograms
    - Example of volume holographic material
    - Alternative volume holographic material
    - The stacking of waveguides
    - Performance issues
    - Work on manufacturability
  - Battle between DOE & HOE
    - Overview
    - Volume forecasts
    - Market forecasts
- **Waveguides and displays intercompatibility**
  - Display requirements
  - Consequences of using waveguide combiners
  - OLED-on-Si, the push for improvement
  - MicroLED, the best of both worlds
- **Market of today and its evolutions**
  - AR headsets: markets and volumes forecasts
  - Focus on some companies
- **Technological developments for future of AR**
# TABLE OF CONTENTS

## Part 4/4

- **Conclusion** [P302]

- **Annexes** [P304]
  - Introduction to display technologies [P305]
  - High Dynamic Range [P309]
  - Color gamut [P314]
  - Color volumes [P323]

- **About Yole Développement** [P327]
LIST OF COMPANIES MENTIONED IN THIS REPORT

AKONIA HOLOGRAPHICS, ALEDIA, APPLE, ATHEER, AUO, AVEGANT, BAYER, BOE, CANON, COLOUR HOLOGRAPHIC, CORNING, DAQRI, DEE POON, DELL, DIGILENS, DISPELIX, EMAGIN, ETRI, EVG, EYEFLUENCE, FACEBOOK, FINISAR, FOVE, FRAUNHOFER, GLO, GOOGLE, HAMAMATSU, HIMAX, HOLOEYE, HP, HTC, IDEALENS, INTEL, ITRI, JDI, KONICA MINOLTA, KOPIN, LEAP MOTION, LENOVO, LETINAR, LG, LIMBAK, LINQ, LITEON, LUMINIT, LUMIODE, LUMUS, MAGIC LEAP, META, MICROOLED, MICROSOFT, MIRA, MOLECULAR IMPRINTS, NINTENDO, NVIDIA, OAKLEY, OCULUS, OHARA, OLIGHEK, OPTINVENT, OSTERHOUT DESIGN GROUP, PICO, PIMAX, PLAYNITRIDE, PUPIL LABS, QUALCOMM, RAONTECH, RAZER, ROCKWELL COLLINS, SAMSUNG, SCHOTT, SEGA, SEIKO EPSON, SENSICS, SMI, SONY, STARBREEZE, SUMITA, SYNDIANT, TEXAS INSTRUMENTS, THEEYETRIBE, TOBII, VALVE, VUZIX, WAVEOPTICS, YOUNG OPTICS (…)
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As a Technology & Market Analyst, Displays, Dr. Zine Bouhamri is a member of the Photonics, Sensing & Display division at Yole Développement (Yole). Zine manages the day to day production of technology & market reports, as well as custom consulting projects. He is also deeply involved in the business development of the Displays unit activities at Yole. Previously, Zine was in charge of numerous R&D programs at Aledia. During more than three years, he developed strong technical expertise as well as a detailed understanding of the display industry. Zine is author and co-author of several papers and patents. Dr. Bouhamri holds an Electronics Engineering Degree from the National Polytechnic Institute of Grenoble (France), one from the Politecnico di Torino (Italy), and a Ph.D. in RF & Optoelectronics from Grenoble University (France).
THE DIFFERENT REALITIES DEFINITIONS

• In 1994, Milgram & Kishino defined a “mixed reality environment as [something] anywhere between the extrema of the virtuality continuum.”

• This can be conceptualized around the concept of mediated reality which refers to the ability to add to, subtract information from, or otherwise manipulate one’s perception of reality through the use of a third-party device.

• Augmented and Mixed Realities (AR & MR) are actually quite similar in terms of displays and optical vision systems and they will all be put together under the name “AR” in this report.
# THE CONTINUUM SEGMENTATION

### Augmented Reality (AR) [1]
- Overlays simple information and computer-generated (CG) images onto the real world.
- There is little to no interaction between the CG content and the user's environment.
- The display must not obstruct the real world. It has to compete with ambient light to generate digital information with similar brightness as those seen in the real world. Resolution and field of view requirements (FOV) vary with the application.

![Augmented Reality Example](Image)

### Mixed Reality (MR) [1]
- Overlays complex, often 3D computer-generated (CG) images onto the real world.
- The CG content can interact with the environment (objects in the room, wall, vehicle, etc.). The system uses multiple sensors to create a real time 3D modeling of the environment and the CG content adapts in real time to any change.
- Display requirement is similar to AR. A larger FOV is usually desirable.

![Mixed Reality Example](Image)

### Virtual Reality (VR)
- A 100% artificial, computer-generated simulation or display of a real life environment that immerses the users by making them feel like they are experiencing the simulated reality firsthand.
- VR requires a fully enclosed head mounted display (HMD) that visually isolates the user from the outside world. For a realistic and immersive experience, the system should offer a field of view and resolution closely matching that of the human eye capabilities.

![Virtual Reality Example](Image)

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[1] this report focuses on Head Mounted Devices (HMD) but and AR and MR can also be experienced on a hand held cell phone or tablet (e.g.: “Pokemon Go”)
THE CONSEQUENCES OF ALTERING REALITY

- If we live our lives while believing we are living them, thus living reality, this is because all our senses make us believe that we live our lives. This can be defined as the idea of immersion. We are immersed in the world we live in.

- If we come to alter reality, then us believing we live in a different life will only be possible if the sense of immersion is believable. That is why immersion will be the common theme for this report. Without a proper sense of immersion, there is no way we can believe we live in reality while it is altered, thus the concepts do not work.
INTELLECTUAL PROPERTY ACTIVITY

- Even though investment deals have been publicly discussed for the past four years or so, the fields have been intensively researched for several decades as illustrated by IP filings. This activity has been on the rise.

Based on the current trend, we expect more than XX patent families for 2018.

- The first patents relevant to the field of AR/VR were filed at the end of the 1980’s.
- The level of activity took off from 2011 and accelerated strongly from 2014.
- Based on both technology trend and current patent filing dynamics, a slowdown in the patenting activity in 2018 is expected while the patent extensions will continue.

Note: The data corresponding to the year 2018 is not complete since patent search was done in March 2018.
INTELLECTUAL PROPERTY STATUS AND REPARTITION

- More than 50% of the patents are currently pending, and the enforceable patents (granted) represent only less than one third of the corpus. This reflects the youth of the technical solutions proposed for solving AR/VR displays and optical vision systems related current technical issues, resulting in recent acceleration of the IP activity in this field.

- Regarding the number of enforceable patents, XX is leading the IP landscape with XX% of the enforceable patents, followed by XX (XX%) and XX (XX%).

- In terms of patent filings, XX and XX are currently the most active patent applicants with XX% and XX% of the patent applications currently pending respectively.

Note: The data corresponding to the year 2018 is not complete since patent search was done in March 2018.
As will come to be illustrated later, for immersion purposes:
- The lenses mainly drive the FOV but they actually make a whole with display (size, etc.)
- The display mainly drives pixel density but it actually makes a whole with the lenses (pixel density over retina, etc.) but also with the driving electronics (low persistence for lack of blur and retinal persistence, etc.)
- The driving electronics mainly drive the persistence level but they are intertwined with the display (pixel density, framerate, etc.)

We will come to see how all those form trade-offs that system integrators have to take into account. Some may sacrifice on the FOV to increase their pixel density, over may sacrifice the persistence to increase their pixel density. This pixel density parameter always appears as the most important one (“we want more pixels”) but things are actually not that simple.
In human vision, each eye typically has a horizontal Field of View of 160° (FOV) (and a 175° vertical FOV).

But stereoscopic vision is only achieved over the angle where the FOV of both eyes overlap, which represent about a 110-120° wide (and 135° high binocular FOV).

In VR HMD, FOV is an extremely important parameter as it greatly participates in the feeling of immersion.
  • A wide FOV allows for not seeing the display edges.

The shorter the focal length, the wider the FOV.

However, the whole number of pixels of the display will be extended over the FOV by magnifying the display. That way, pixels may become too visible to the eye, with the risk of decreasing immersion.

It is therefore very important to understand that there is a clear relation between FOV and pixel density parameters.
  • This will be discussed more in details in the next chapter.
VIRTUAL REALITY

Persistence – Issue with sample-and-hold structures in VR HMDs (3)

• Several parameters are in play, causing strobing and smearing and deteriorating the feeling of presence. It is easier to tweak display parameters rather than physiological parameters.

• Trade-offs will need to be accepted anyway, either on the driving electronics (tethering, power consumption, etc.) or on the display performance (lower overall brightness, et.).

It is possible to mitigate the issues met in VR context by going either at higher framerate or at lower persistence.
VIRTUAL REALITY

Persistence – Challenge of low persistence (2)

• The other reported solution when going the zero-persistence route would be to increase the framerate (i.e. the refresh rate).

• By increasing the framerate drastically, even on sample-and-hold full-persistence displays, as long as the refresh rate is of the order of magnitude of eye (and head) movement, then the human’s visual system would be closely matched and it would look like a real-life situation.

• However, with such solution, our estimates of refresh rates would be around 1,000 to 2,000 frames-per-second, which would require an enormous amount of computing power, with a very-high complexity level for driving electronics.

• One needs to trade-off on all this.

• A last possibility not linked to low persistence, if the implementation gets too complicated, is to simply increase resolution, increasing PPD to match the real world. But again, requirements on electronics would be stringent.

Here, the space-time diagram represents an object moving at a constant speed and showed on a very high framerate display, with the eye tracking the moving object.
VIRTUAL REALITY

The display technology of choice – OLED-on-Si – The form factor disruption

• VR is an activity that is done in-house so the importance of being “good-looking” or at least having a headset with a good form factor does not strike as one of the most important parameters that consumers are looking for (exception being, if the headset is too heavy on the nose and/or on the head, comfort is lost and adoption is too).

• However, a smaller headset would still be much appreciated, and it would help with the untethered solutions for which the ideal goal would be to be able to take one’s headset anytime anywhere.

• In order to reduce the size of a headset, the idea is simple: reduce the size of the screens and decrease focal length. This means have a thicker lens and more complicated optics to be able to occupy a decent FOV. And that also means a less manufactural path to mass production. And that is without saying, as will be seen in the AR part of this report, that OLED-on-Si displays, which are basically OLED microdisplays, cost about ten times more than regular OLED displays.

• A European project, combining the efforts of MicroOLED (for the display), Fraunhofer (for the driver) and Limbak (for the optics) led to a prototype of a compact wearable headset called the LOMID. It is to be seen how this will evolve towards a consumer-friendly product (form factor, availability, price).
The physiology behind VR sickness is currently not understood and is still being investigated. It seems to be linked to all senses previously discussed with some being more involved than the others: sight which represents a huge percentage of our sensorial feedback in the CNS loop, thermoception, nociception, proprioception, sense of balance.

This is an active area of research that dates back in the 1950s, starting with the first simulator sickness symptoms from military aircraft simulators. Indeed, VR sickness has similar symptoms to motion sickness from which simulator sickness is a direct subset.
Eye physiology uses different cues for stereoscopic vision. They are all in a feedback loop and when there is a mismatch, it causes fatigue.

- The human brain processes different cues at the same time to assess a situation. For comfortable 3D viewing, the two main cues to stereoscopic rendering used by the brain are vergence and accommodation and when in mismatch, this causes eye fatigue.

- Vergence is the simultaneous movement of both eyes in opposite directions to maintain binocular vision; by changing their viewing angle they try and fit the depth of objects, via retinal disparity.

- Accommodation is the motor response of eyes, according to the distance from an object: this is similar to a camera or a microscope for which one needs to adapt focus to clearly see an object. For accommodation, basing on blurring image feedback, muscles controlling the eye contract and relax the lens according to distance to accommodate properly with the distance of the object (i.e. the angle at which rays enter the eyes).

- Both those cues actually feed off each other in a closed feedback loop. If the loop is broken, this is called the Vergence-Accommodation Conflict (VAC).

The diagram indicates a left and right eye. Both eyes converge on a box but due to retinal disparity, the angle of viewing is slightly different for each eye. The brain combines the two images to create the perception of a 3D object. (Source: NMU School of Art & Design)

Accommodation difference for a given eye depending on object distance. (Source: Kramida et Varshney)
**VIRTUAL REALITY**

**Future development trends – The 60PPD cost on hardware**

- Most high-end commercially available VR HMDs only work at 90Hz refresh rate, with some pushing it to 120Hz.
- If we make a simple calculation regarding data transfers and processing requirements for several base hypotheses, it appears that the ideal 60PPD case as previously discussed is far away from today’s technology, just in terms of data management; other display aspects have not been taken into account.
- An interesting solution would be to take advantage of the eye physiology and to focus efforts on the fovea.

<table>
<thead>
<tr>
<th></th>
<th>Pixel density (PPI)</th>
<th>Number of screens</th>
<th>Number of sub-pixels per pixel</th>
<th>Refresh rate (Hz)</th>
<th>Raw data rate (Gbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC Vive</td>
<td>XX</td>
<td>2</td>
<td>2</td>
<td>90</td>
<td>XX</td>
</tr>
<tr>
<td>HTC Vive Pro</td>
<td>XX</td>
<td>2</td>
<td>2</td>
<td>90</td>
<td>XX</td>
</tr>
<tr>
<td>Playstation VR</td>
<td>XX</td>
<td>1</td>
<td>3</td>
<td>120</td>
<td>XX</td>
</tr>
<tr>
<td>Google/LG 2018</td>
<td>XX</td>
<td>1</td>
<td>2*</td>
<td>120</td>
<td>XX</td>
</tr>
<tr>
<td>Ideal case</td>
<td>XX</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>XX</td>
</tr>
<tr>
<td>HDMI 2.1 limit</td>
<td>XX</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>XX</td>
</tr>
</tbody>
</table>

*Required raw data rate for several existing HMDs, compared to most recent HDMI 2.1 cable maximum theoretical data rate.*

(*assumption; **assuming no need to reach 1000Hz if 60PPD is reached)*

Hardware requirements for 60PPD are too stringent (driving, transferring, etc.) so an alternative solution is required.
On March 2018 at the Game Developers Conference, Oculus presented a new rendering technique for their Oculus Go, a standalone headset with limited computational power, going a bit further than the previously discussed blurry edges.

This Fixed Foveated Rendering (FFR) features hard-coded zones in which the rendered fidelity will only be a fraction of the highest achievable fidelity which is focused on the center of each screen. Eye-tracking is not implemented yet for this solution but when eye-tracking solutions make themselves readily available for consumer-centered headsets, FFR can evolve into something associated with it to further enhance immersion.

Oculus' FFR technology
(source: tomshardware.com)
MARKET SHARE FORECASTS OF DISPLAYS FOR VR

• VR headsets are considered to almost all have two displays per headset (with a few exceptions, like today’s Sony Playstation VR). We expect OLED’s dominance to end by 2020 when untethered stand-alone headsets, driven by price, will take a small part in the game if they can work on their cost for the consumer.

• As is the case with TV or smartphone markets, OLED competes with price when LCD competes with performance. As illustrated thus far, lots of efforts are made to push for the use of LCD panels in VR headsets and the ultimate price point will be of utmost importance for mass market adoption.
AR REQUIREMENTS

AR requirements: many of them to get accepted by the consumer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
<th>Trade-off</th>
<th>Consumer’s acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form factor</td>
<td>Glasses-like designer look</td>
<td>Bulky</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Acceptable, Not &quot;real AR&quot; though</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Mildly acceptable, Poor man’s solution</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Acceptable, depending on application</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Unacceptable, Lose half of the population</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Acceptable, depending on application</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Acceptable, depending on application</td>
</tr>
<tr>
<td>Color</td>
<td>RGB and HDR for realism</td>
<td>Monochromatic and SDR</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Acceptable, depending on application</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Acceptable, depending on application</td>
</tr>
<tr>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>Mildly acceptable, Poor man’s solution</td>
</tr>
</tbody>
</table>

Many elements are required to an acceptable consumer headset and the room for trade-offs is all depending on applications.
**MICROLED TECHNOLOGY**

**What is happening in the short term?**

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Finalize technology development</td>
</tr>
<tr>
<td>2019</td>
<td>Set up supply chain. Manufacturing of dedicated equipment</td>
</tr>
<tr>
<td>2020</td>
<td>Test and ramp up</td>
</tr>
<tr>
<td>2021</td>
<td>First high volume consumer products</td>
</tr>
<tr>
<td>2022</td>
<td>More high volume consumer products</td>
</tr>
</tbody>
</table>

There is still a risk that the remaining challenges prove unsurmountable for most applications.

Remaining technical and manufacturing challenges prove too difficult to overcome.

MicroLEDs remain too expensive & difficult to manufacture for high volume consumer applications, and/or today’s technologies keep improving too fast.

Niche product only (where MicroLED performances are highly differentiating)

Crash and burn: no MicroLEDs
- Large screen AR headsets should disappear on the long run because their form factor just will not be acceptable anymore when all the potential waveguide based products will be on the market.
- As for XX, it will lose shares due to technical limitations after a few years.
- This is all without taking into account possible technologies that could have a breakthrough (fiber scanning, laser retinal projection, light field displays, etc.)
Curved combiners need to block visible light

- Considering a X:X contrast to outside light is acceptable for proper visibility of the augmented, we can plot an abacus showing how stringent requirements are on display luminance for use with curved combiners, assuming XX/XX combiners used.
- As can be seen, if no shading of the outside world is done, there is no way a proper augmented vision can be done with certain displays.
DIFFRACTIVE ELEMENT COMBINERS

SRGs – the physics behind (2)

• It has been shown that not to lose half of the light, it was required to slant the gratings to force diffraction in one direction only. This has been one of the fundamental works developed within Nokia.

• It is possible to play on the grating structure and several parameters enter into play:
  • **Period**: it will have an effect on the diffraction angle
  • **Spacing**: it will have an effect on the spectral range covered
  • **Shaping**: it will have an effect on diffracted wavelength and efficiency

• There are many other elements that have to be taken into account to well understand the physics of SRGs: orders of diffraction, spectral efficiency, spectral selectivity, polarization selectivity (TE vs. TM), materials, etc.

If gratings become slanted, then first order diffraction operates in one direction only. Dimensions will impact the diffracted wavelength.

- The asymmetric in-coupling grating has twice the grating area without back-diffraction than the symmetric one.
  (source: Novel Diffractive Optical Components for Near to Eye Displays, Levala, 2006)

- Different dimensions to wavelength-tune slanted SRGs.
  (source: Patent application, Microsoft, US20160231568)
DIFFRACTIVE ELEMENT COMBINERS

SRGs – manufacturing process challenges

- Many challenges rise from SRG manufacturing, be it cost requirements, XX or XX.

NIL processing is complex, notably in terms of etching, development, but also in terms of required equipment.

**Cost**
- NIL automated equipment XX€
- NIL 8” master XX€

**High capex requirements**
- XX

Displays & optical vision systems for VR, AR & MR | Sample |
HOLOGRAPHIC ELEMENT COMBINERS

HOE – the physics behind

• At its core, the idea is to record the light field of an object by shining some light on it: the resulting reflected and scattered light will be interfering with a reference light (using coherent sources), and this light interaction will create interference fringes that will be written on the holographic material.

• By shining a reference light on the holographic material, its interaction with the interference fringes will create a diffracted light that will be the same as the one that would have appeared if the initial object had been lit up.

Holographic optical elements are obtained by coherent light beams interferences on photosensitive materials.
HOLOGRAPHIC ELEMENT COMBINERS

HOE – alternative volume holographic material (Digilens example)

- Digilens has been working for several years trying to develop a material with more desirable properties.
- The material is called a Reactive Monomer Liquid Crystal Mix (RMLCM) and is the combination of liquid crystals (somehow similar to those used in the traditional LCD panel industry) and monomers. During laser holographic writing, liquid crystals and monomer arrange themselves so that gratings are formed with intertwined layers of each.
- Three properties can rise from that:
  - Better efficiency: compared to a standard photopolymer, the refractive modulation index can be XX times more efficient;
  - Thinner layer: it has been said previously that thick gratings were required for proper angular and wavelength selectivity; the material allows to go with thinner layers, typically XX times thinner;
  - Electrically active: depending on the application, it is possible, similarly to an LCD panel, to apply a voltage on the HOE so that liquid crystals are displaced; this allows for a modulation of the efficiency properties and can be of interest in automotive HUD applications.

An example of a commonly used photopolymer for diffraction in AR applications is the Bayfol®HX for its desirable properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Bayfol®HX</th>
<th>Digilens RMLCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive modulation index</td>
<td>0.03</td>
<td>XX</td>
</tr>
<tr>
<td>Required material thickness</td>
<td>16µm typical</td>
<td>XXµm typical</td>
</tr>
<tr>
<td>Dynamic grating modification</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Switchable Bragg Gratings technology principle. Applying a voltage changes the orientation of the LC molecules, modulating the refractive modulation index. (source: Digilens)
WAVEGUIDES AND DISPLAYS INTERCOMPATIBILITY

OLED on Si – the push for improvement to reach waveguide compatibility

- Pixel density today is somehow close to Full HD LCOS/DLP panels for AR applications; but since those projection based technologies use an external color illumination, for virtually the same pixel size, the three colors can be displayed whereas on OLED-on-Si, one pixel can only do one color. One path of improvement would be to increase pixel density, which can be helped while working on the next points.

- The other path of improvement would be to change the OLED structure, going from WOLED + CFs to directly patterned RGB. This can help in increasing pixel density and luminance. By going in this direction, it is then possible to improve the main factors to waveguide adoption:
  - Improve color purity (no color spreading effect with waveguides;
  - Improve luminance (no filtering to waste light).

OLED-on-Si is self emitting and uses less power so interest is here, pending technology enhancements technology. Price could remain an issue.
MicroLED – the best of both worlds

- MicroLED is at an advanced R&D stage but no product exists as of yet. MicroLED displays combine the self-emissive advantages of OLED-on-Si while reaching very high luminance which is the point that makes DLP/LCOS used today with waveguides. By progressing and reaching a product phase, MicroLEDs could disrupt the field for AR applications.
RELATED REPORTS
Virtual Reality (VR) and Augmented Reality (AR) have been hot topics for decades. As these concepts aim at changing our reality, it is extremely important to have systems that are properly designed to trick our brain and produce a feeling of immersion. But as the brain is a complex piece of machinery, VR and AR systems require advanced technologies that are not quite ready yet. The key is to understand what must be developed in terms of displays and optics for these headset markets to thrive.

VR has been developed with off-the-shelf components, mainly smartphone-sized displays and magnifying lenses. However, the field of view in today's headsets is small and restricts the user's immersion in the image. Improving it by working on the optics may seem trivial but it implies headset ergonomics and manufacturing challenges regarding size, weight, scalability. And then comes visual fidelity, as improving the field of view without improving the pixel density reduces the number of pixels over each degree of visual acuity, which restricts immersion again. So displays need to improve pixel density, amongst other parameters, in parallel to optics improvement. But associated technical and manufacturing challenges are difficult to attain. Alternative developments are ongoing and should pave the way towards an ideal VR headset: the proper number of pixels per degree on a wide field of view at a very fast framerate, with perfect color reproduction and in a compact form factor.

AR presents a very different visual paradigm compared to VR, as the user needs to clearly see the world through superimposed virtual images. Having a screen in front of the eye is impossible, so the image must be brought to the eye in an efficient and undistorted manner. AR is already big in the military, a field in which there are few restrictions in terms of size, volume and design. But the consumer wants nothing but a sleek headset that must not be cumbersome, and be perfectly see-through. The road to miniaturization and cost reduction from existing technology is extremely complex. Physics cannot be violated, and étendue management, efficient...
diffraction, transparency, field of view, and many other parameters have to be handled. Similarly to VR, developments are ongoing and will define the roadmap for upcoming AR headsets. However due to manufacturing challenges, adoption will start slowly before markets soar.

**MicroLEDs Could Disrupt These Realities and be an Enabler**

VR uses smartphone-like displays and the technology that initially dominated was organic light emitting diodes (OLEDs), despite their price premium, because of their superiority in terms of VR-related specifications such as pixel refresh rate, true black, and form factor. There is however a push for liquid crystal displays (LCDs) that are found in today’s lower-end headsets, pending progress on their bottlenecks in achieving required refresh rates, and perfect dimming. There is potential for OLED-on-silicon microdisplays but optics and price challenges are slowing the technology. The time it takes to mature could be the time required for MicroLEDs to become predominant.

MicroLED technology is far from being mature, but has made advancements in monolithically-assembled microdisplays. If the technological roadblocks associated with MicroLEDs are overcome, this display technology would be an enabler for AR headsets. Today, AR headsets run with either OLED-on-silicon microdisplays or projection display technologies, which are not compact enough, or do not provide enough luminance to the eye. MicroLEDs can link the best of both worlds and provide enough luminance to overcome the poor efficiency of optical waveguiding combiners in a small form factor.

The report presents a detailed analysis of display requirements for VR and AR, the trends and roadmap for the future. This report is also a comprehensive overview of display structures, current challenges and key research directions.

**Displays & Optical Vision Systems for VR, AR & MR**

The report presents a comprehensive technological review of the working principles of VR headsets and AR headsets, with a deep dive into the key elements of displays and associated optics, the main players involved, the potential impacts on manufacturing challenges, and more.

**Display Volumes for AR Headsets – Toward MicroLED Adoption**

[Graph showing display volumes for AR headsets over the years, categorized by type: LCOS, OLED on Si, DLP, MicroLED, Large screen (LCD/OLED).]

**Real AR Headsets with Sleek Design May Be Within Our Grasp**

Current optical waveguiding combiners may be poorly efficient, but they are the only technological approach able to couple an image in and out and transmit it close to the eye without having to put bulky optical parts in the headsets. Initiated by Nokia, Microsoft and Vuzix have all followed this path. Diffractive optical elements exhibit performance limitations linked to the underlying physics that also imply complex manufacturing challenges. Some players with holographic optical elements are trying to circumvent these performance and manufacturing issues by going on a different route, such as Digilens.

This directly impacts the cost and explains why AR headsets are not the “smartphone killer” that had been advertised yet. The first real sleek products with more acceptable prices are being released in a few months and should spur AR adoption. By working on improving the technology and the manufacturing of those combiners, and taking into account the ramp up time, the AR market will eventually take off, first in business, followed by consumer adoption.

The report presents a detailed analysis of display requirements for VR and AR, the trends and roadmap for the future. This report is also a comprehensive overview of optical structures, current challenges and key research directions.
TABLE OF CONTENTS (complete content on i-Micronews.com)

Virtual Reality – introduction.......................... 26
Virtual Reality – FOV........................................... 31
Virtual Reality – pixel density............................. 48
Virtual Reality – persistence............................... 67
Virtual Reality – the display technology of choice ...83
Virtual Reality – sensorial challenges................... 97
Virtual Reality – trends for future development......112
Virtual Reality – display and optical vision system markets...128
Augmented Reality – performances, challenges and trends 135
Introduction to paradigms for display and optics in AR 137
Display engine technologies............................... 145
  > Overview..................................................145
  > LCOS technology.........................................145
  > DLP technology............................................145
  > OLED-on-Silicon technology.........................145
  > MicroLED technology....................................145
  > Miscellaneous technologies...........................145
  > Display technologies conclusions and forecasts..145
Optical vision systems for AR........................... 196
  > Introduction to optics for AR
    - The question of optics for AR
    - The AR optical vision system
    - Coming up to optics
  > Regular combiners...................................... 196
  > Waveguide combiners
    - Light transmission
    - Cascaded mirror combiners
    - Diffractive element combiners
      - Surface relief gratings, principle
    - Material requirements
    - Origin and development of the technology
    - Manufacturing
    - Wafer requirements
    - Mapping of players in the supply chain
    - Tentative supply chain analysis
    - Structure of lenses
    - Performance issues
    - Improving yield to reduce costs
    - SWOT analysis
    - Holographic element combiners
      - The patenting activity for HOE
      - Disruption to diffractive element combiners
      - Principles
      - Material requirements
      - Transmission or reflection holograms
      - Example of volume holographic material
      - Alternative volume holographic material
      - The stacking of waveguides
      - Performance issues
      - Work on manufacturability
      - Battle between DOE & HOE
        - Overview
        - Volume forecasts
        - Market forecasts
    > Waveguides and displays intercompatibility......277
    Market of today and its evolutions....................283
    Technological developments for future of AR.....297
      Conclusion...............................................302
      Annexes..................................................304
      Introduction to display technology..................305

COMPANIES CITED IN THE REPORT (non exhaustive list)
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  - Applications 2018 – Update
  - Point-of-Need Testing Application of Microfluidic Technologies 2018 – Update
  - Neurotechnologies and Brain Computer Interface 2018
  - CRISPR-Cas9 Technology: From Lab to Industries 2018
  - Ultrasound technologies for Medical, Industrial and Consumer 2018
  - Inkjet Functional and Additive Manufacturing for Electronics 2018
  - Liquid Biopsy: from Isolation to Downstream Applications 2018
  - Chinese Microfluidics Industry 2018
  - Scientific Cameras for the Life Sciences & Analytical Instrumentation Laboratory Markets 2018*
  - Artificial Organ Technology and Market 2017
  - Connected Medical Devices Market and Business Models 2017
  - Status of the Microfluidics Industry 2017
  - Organs-On-Chips 2017
  - Solid-State Medical Imaging 2017
  - Medical Robotics Market & Technology Analysis 2017
- **LINKED REPORTS** – by Yole Développement, System Plus Consulting and KnowMade
  - Organs-on-a-Chip – Patent Landscape Analysis

*Update: 2017 version still available / **To be confirmed
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PATENT ANALYSES – by KnowMade
- Wireless Charging Patent Landscape Analysis
- RF Acoustic Wave Filters Patent Landscape Analysis
- NMC Lithium-Ion Batteries Patent Landscape Analysis
- Pumps for Microfluidic Devices Patent Landscape
- III-N Patent Watch
- FLUIDIGM Patent Portfolio Analysis
- Knowles MEMS Microphones in Apple iPhone 7 Plus Patent-to-Product Mapping 2017
- Consumer Physics SCiO Molecular Sensor Patent-to-Product Mapping
- Patent Licensing Companies in the Semiconductor Market - Patent Litigation Risk and Potential Targets
- Microfluidic Technologies for Diagnostic Applications Patent Landscape

TEARDOWN & REVERSE COSTING – by System Plus Consulting
More than 60 teardowns and reverse costing analysis and cost simulation tools published in 2017

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