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Laser Beam Scanner and Combiner Architectures

Louahab Noui*[a], Jörg Reitterer[a], Michael Schöffmann[a]
[a]TriLite Technologies GmbH, Frankenberggasse 13, 1040 Vienna, Austria, Europe

ABSTRACT

Augmented reality (AR) displays have been a hot topic for many years as they offer potential for a high return on investment. With this high potential come many technical challenges to be addressed before AR displays and smart glasses become more accepted in the marketplace. One of the technical challenges is the optical design of compact and lightweight optics capable of projecting an augmented image onto the user line of sight with comfort. Major advances are being made in waveguide technology to produce large FOV and eye-box. Equally, light engines are also being developed to be less bulky and more efficient. In this paper we present an insight on how a next generation laser beam scanner (LBS) developed by TriLite Technologies can be integrated with different combiners and implemented for different AR displays and smart glasses architectures. The unique design of the LBS lends itself to fit in different configurations as dictated by the different designs and layouts of waveguide and combiners. In addition, the extremely low profile of the next generation LBS make the glasses look smart literally.

Keywords: Laser Beam Scanning, LBS, AR, XR, VR, HMD, Microdisplays

1. INTRODUCTION

The development of AR displays to enable large acceptance base in both consumer and enterprise market is continuing. Although this technology has been evolving since late 80's and arguably well before then, it is still progressing towards a lightweight, comfortable, acceptable, fashionable and mass manufacturable device. For an AR display to be accepted by the users it has to meet various criteria and address many issues as reported in various publications and media literature[1,3-5,8,10-12]. Among these is comfort in its different declinations as described in the SPIE publication[1].

For short term use of an AR display there is an absolute requirement of good image quality; Image resolution has to meet or at least approach the human eye resolution limit. There should be no image artifacts visible to the naked eye in different use cases. The contrast should be high enough to show image details and without stray light effects under different lighting conditions and especially in low lighting environment. Colour registration at every field point is necessary to maintain high-definition image across the FOV. Colour uniformity across the FOV is also critical for a good and pleasing image quality as the human eye is very sensitive to colour non-uniformity.

For longer term use, it is critical that AR display is comfortable to wear without feeling the physical strain of the eyes, the weight or the heat of the display. The AR display has also to be comfortable to wear without the visual strains of bad image quality not just the projected image, but the display should not alter the see-through image of the outside world; Image quality in terms of resolution, brightness and contrast with no artifact is key for a wide acceptance by the marketplace. One of the large barriers to extended usage of AR displays with fixed focus is the vergence-accommodation conflict, which cause headaches and nausea as an AR display is used for extended period of time[1,10]. In addition, the AR display has to actively adapt to different lighting conditions of the environment it is operating in. As the see-through image changes because of head movement for instance, the augmented image projected by the AR display has to be seamlessly refreshed so there is no motion blur introduced. Latency of the whole AR display system is therefore critical.

Other parameters like social acceptability of AR when out looking cameras are being used while the user eyes are barely visible due to lack of transparency of the combiner or the visor are extremely important and require a more specialised study and therefore are not the subject of this publication.

In this publication we present a summary of display and projection technologies relevant to AR applications. We describe in more details the characteristics of the next generation of LBS projector Trixel® 3 developed by TriLite

*noui@trilite-tech.com; phone +43 1 947 5371; www.trilite-tech.com

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Technologies. We also give an extract of the different optical combiner technologies currently used for AR applications. We also illustrate the unique advantages of LBS Trixel® 3 in adapting to different configuration when it is integrated with different combiners. We finally conclude by looking ahead and highlighting the major challenges which need to be addressed before AR becomes a reality.

2. SUMMARY OF DIFFERENT DISPLAY TECHNOLOGIES

2.1 LCoS displays

A liquid-crystal on silicon (LCoS) is a reflective display, based on liquid crystals (LC). A CMOS backplane controls the voltage applied to the LC, on a reflective electrode. Like in transmissive LCD, the LC arrangement in LCoS panel also controls the polarization of light passing through it. The LCoS is also a light modulator, which utilizes polarization and requires a light source in order to project an image[13-14,29].

2.2 OLED displays

An organic light-emitting diode (OLED) microdisplay has many advantages for AR systems compared to LCoS display. It is self-emissive and does not require any backlight. Another advantage of the OLED is that it has an excellent image quality, it is more efficient comparing to LCD or LCoS for example and has an ultra-high contrast ratio (CR) and wide colour space. On the other hand, the OLED has limited luminance and limited lifetime. That makes it marginal for applications that require very high luminance level or when using waveguide combiners, especially for outdoor applications when a colour image is required, with a reasonable lifetime[15,16].

2.3 mLED displays

Micro light emitting diode (mLED) , is a new emissive panel technology causing considerable excitement in the AR community as it does not use some bulky refractive illumination optics and beam splitters, but still requires a bulky projection lens. However, it is brighter compared with OLED display panels. A fundamental problem of mLEDs is that, the technology lacks the collection efficiency of the generated light and brightness even with the best projection optics available. Manufacture is not mature and has to overcome all initial challenges[17-23,26]. The mLED development for microdisplays is still going on. There are several companies that are exploring and developing this technology. Several demos have been presented as monochrome displays but, there are still some technical challenges that need to be addressed, namely reduction of pixel size down to 3 microns pitch, development of full-colour mLED based on a single colour LED wafer, and improvement of spatial uniformity due to variations of colour and luminance between mLED chips.

Figure 1 is a graphical summary of comparison of AR display technologies[24]. For AR applications a FOV of around 50° diagonal is a typical value which satisfies most AR needs and can be achieved by LCoS, OLED, mLED and LBS technologies. The combiner technology itself usually determines the maximum FOV which can be achieved. Holographic combiners can reflect much larger FOV than their waveguide counterparts but suffer from the tiny eye-box size. On the other hand, waveguide combiners have a larger eye-box but less light efficient. Since the LBS does not require projection optics after the scanning mirror, the increase of the FOV does not increase the size of the projector, however, matrix displays such as LCoS, OLED and mLED all require larger optics to increase FOV.

The motion to photon latency of the display is an important characteristic of any AR display where a virtual image is superposed on a see-though image and the overlay has to be maintained as the user moves around. Latency depends not only on the refresh rate of the display itself but also on the complete pipeline from the time of motion to the time of photons received at the eye including time responses of sensors, tracking and rendering time[25]. As the AR display, is used to augment see-through images with virtual images in a highly dynamic environment, it is critical that the time lag between the refreshed image in the display and the see-through image is minimized at any time and with every head movement. LCoS display has inherently a long latency because of colour sequential mode of operation and the fact that the LED sources have to be switched off before the LCoS is activated for each colour frame and switched on again.

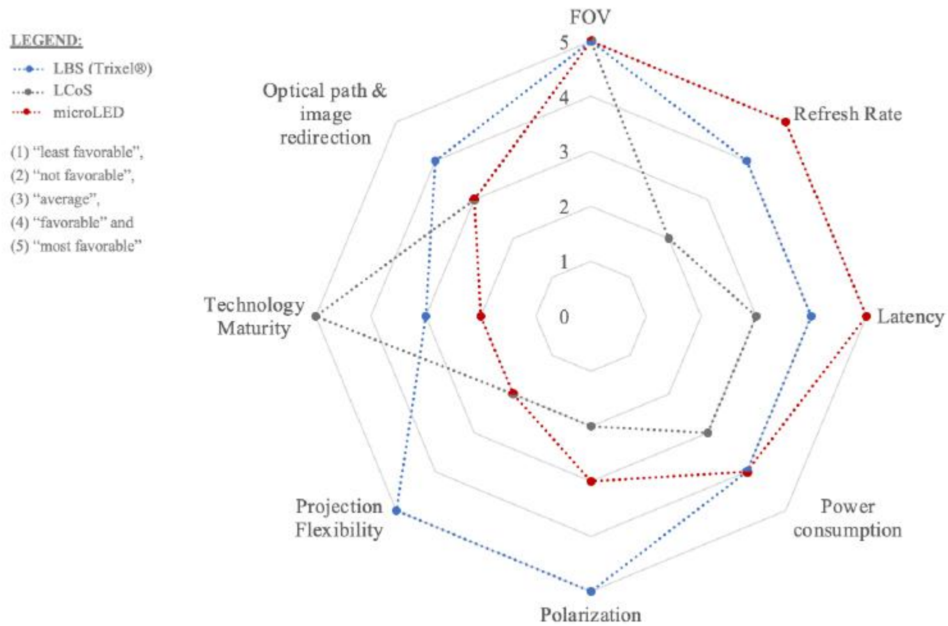


Figure 1: AR display characteristics[24].

In addition, the coupling efficiency of these different projector types with different combiners varies from one technology to another. LCoS, OLED and mLED displays can essentially be characterized by Lambertian light source, even after using micro-reflectors for mLED panels, which makes them fundamentally less efficient. This is due the Etendue limitation of these technologies, however, LBS is extremely efficient in producing the right amount of photon energy required at the eye. Combiners based on waveguides are even less efficient as light energy is lost within the waveguide due to multiple diffraction stages and the scattering effects. These add to the requirement for even more brighter displays especially for day light AR applications. For holographic combiners, the combiner can be designed to be wavelength selective and higher efficiencies for LBS projector can be achieved compared to the broadband nature of the mLED and LCoS light source. The increase of efficiency of the LBS compatibility with waveguide combiner comes however at the expense of the interference issue at the waveguide interfaces due to coherence nature of the laser. However, there is currently a lot of activity in reducing this effect including smart driving electronics to break up temporal laser coherence[29].

Laser sources are known to be best at generating very directional and well controlled light beams with high efficiency. The collection efficiency of generated photon energy is a huge advantage for LBS as it has a direct impact on low power consumption compared to LCoS and mLED displays. Additionally, the LBS uses a single beam which can be temporally and spatially controlled which increases power efficiency compared to a whole display matrix like LCoS being illuminated entirely even when the image displayed has 30% pixels on which is a typical use case of an AR display. LCoS displays only work with polarized light and therefore the 50% of light energy is lost at the outset as a polarizing element has to be used in front of the LED sources. Power consumption of mLED displays is higher than LBS display especially as the pixel size is reduced to reduce the display footprint as the efficiency goes down because of crosstalk between pixels and the effect on the collection efficiency of photon energy from these pixels [29].

The advantage of using LBS as a single RGB beam painting an image is as mentioned the ability to effectively control the individual pixels to compensate for image distortion, improve image luminance and colour uniformity which may be caused by the combiners for instance. More importantly FOV can be modified through software for alignment and assembly purposes increasing therefore manufacturability by loosening tolerances, whereas it is completely out of the question for the competing display technologies. So, flexibility of projection in LBS is far better.

All display technologies analysed here have different level of maturity and it is obvious that LCoS has been in the market for a while, and it is more commercially available than the other two. However, LBS display technology is gearing to be mass produced as the technology is maturing and it is not long before LBS become more commercially available. On the other hand, mLED display is a promising technology but still in its infancy as it has to address some technical uses such as brightness, RGB colour, heat management and efficiency.

3. LBS PROJECTOR- TRIXEL® 3

The TriLite Trixel® 3 is LBS projector designed to be modular to allow useability with a wide range of configurations. It was not circumstantial that the Trixel® projector was intended to have a smallest footprint possible while it produces the largest laser beam possible to meet the scan frequencies and the scan angles required to satisfy AR application requirements. Nor was it circumstantial that it can be used for monocular as well as binocular AR displays.

Trixel® 3 consists of a laser module where three laser units (RGB) are combined to produce an RGB collimated beam using customised optics for each colour. The unit is extremely compact, and the parts are aligned and set to within few microns precision. The laser module has all the necessary sensors built-in to monitor and control optical power and temperature for each individual channel. The output RGB beam is then directed to a micro-electro-mechanical systems (MEMS) mirror module which is also custom designed. The MEMS module is equally compact and is based on 1x 2D mirror design. It has built-in sensors to monitor its operation with laser safety in mind. Electronic control system is built in and synchronised with both laser and MEMS drivers to allow seamless control over all the scan and laser parameters expected from a laser display customized for AR applications. The drive electronics is remotely located from the main optical units and connected using flexible printed circuit (FPC) cables. This allows the electronics to be mounted on the glasses temple which can be folded as in normal glasses while the optical module is permanently aligned with the waveguide combiner for example. This is all possible thanks to the compact design of Trixel® 3 design and its characteristics which are summarized below:

- Mechanical Specs for Trixel® 3
  - Volume: 0.92 cm^3 for LBS + 0.32 cm^3 for electronics
  - Weight: 1.5g + 0.85g for electronics
- Power consumption for a typical use case of 30% pixels on:
  - 420 mW for a pixel energy equivalent to 100% pixels on and 15 lm at the output of the LBS.
- Luminous flux: 15 lm for D65 white balanced image
- Colour Gamut: 231% NTSC RGB

In addition to the size, weight, form factor and power consumption advantages of the Trixel® 3, its overall size and weight does not increase with increasing FOV. Unlike any other microdisplay panels used for AR display, the Trixel® LBS is a pixel/point scanner which can generate a pixel and place it on the-fly in the FOV very accurately without the need for projection optics.

Trixel® 3 has been designed to produce a collimated beam for all scan angles with consistent beam quality unlike conventional projection optics required for panel displays with optical performance weighted towards the center of FOV and traded off at the edges of the field. The collimation of the RGB laser beam with a relatively small diameter makes the LBS a focus free projector where the image is in focus over the Rayleigh range. The focus free characteristic is an important advantage as it is a step closer to resolving the vergence accommodation conflict which is a main and common problem for AR displays using micro display panels as an image source[3,4,8,10-12].

4. OPTICAL COMBINERS

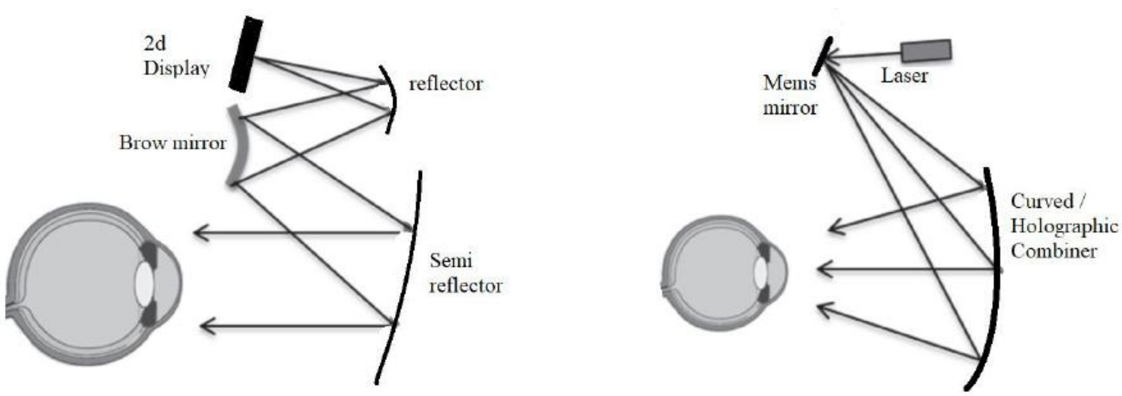
For AR displays combiners types range from simple beam splitters to complex metasurfaces. These can be classified as free space or waveguide based optical elements. There are numerous types under each category; Free space combiners are usually where the image source is relayed onto the eye using a semi reflective surface, while light beams forming the image propagate in air before they interact with the reflective surface. The reflective surface can be on the front or rear side or embedded inside of the combiner. However, for the waveguide type of combiner and TIR prism type, the image is coupled into the glass material of the combiner and waveguide before the image gets extracted using an embedded optical element such as a grating or semi reflective surface and directed onto the user's line of sight.

Different combiner types have different advantages and disadvantages. The main advantage of a waveguide-based combiner is its planar shape which lends itself to fit glasses profiles. As the image is couple inside the waveguide, this allows obscuration-free image projection. The projected image in this case would not be obstructed by eyelashes for instance. The other important advantage of the waveguide combiner is the large eye-box; however, this comes at the expense of poor optical efficiency and relatively large mass[1,10,27-33]. The free space combiner has the advantage of being curved to look like glasses and where holographic or freeform optical element can be built-in[1,5-8,10,27-28]. These combiners are more efficient than their waveguide counterparts. However, the small eye-box is the main disadvantage. TIR prism combiners suffer from both bulkiness and image distortion across the eye-box.

In all cases, the combiner serves a critical role in AR displays and smart glasses as it is what the user looks through all the time during the use of the AR device for whatever application is used for. The combiner therefore has to maintain the image quality produced by the projector while transmitting unaltered and non-aberrated see-through image of the outside world. The most desirable combiners are the ones which do not obstruct peripheral vision. In addition, combiners should provide the functionality and flexibility of being used by a high percentile of users considering all the physiological differences, without the need for a customized combiner for every user. All these factors contribute to the wide acceptability of such combiner technologies.

The main combiners which are currently being adopted are waveguides and holographic. One common property of these two types of combiner is the flat nature for the combiners which lends itself nicely for integration into glasses. The flat combiner is not necessarily the best form factor required to fit in glasses, but it is the best compromise between what is currently manufacturable and what is on the limit of acceptability in terms of shape and form factor. To improve acceptability of these combiners, they should be shaped to look like normal curved glasses and taking into consideration the face wrap and pantoscopic angles. The combiner technology is slowly progressing towards this target as the design and manufacturability challenges come into play.

Figures 2-5 summarizes most types of combiners in a graphical illustration. For more details, please refer to references[1,10].



(a) (b)

Figure 2: Free space combiners[1,10]

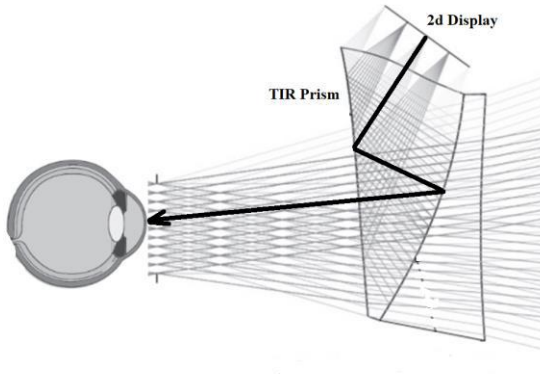
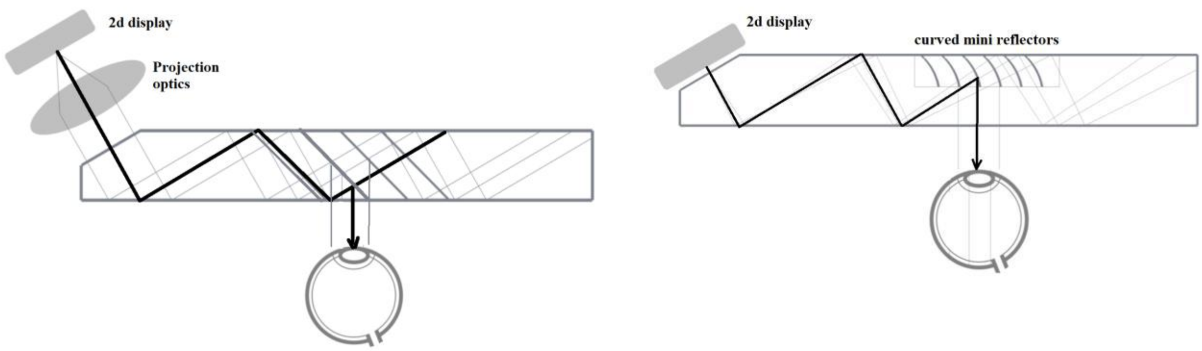
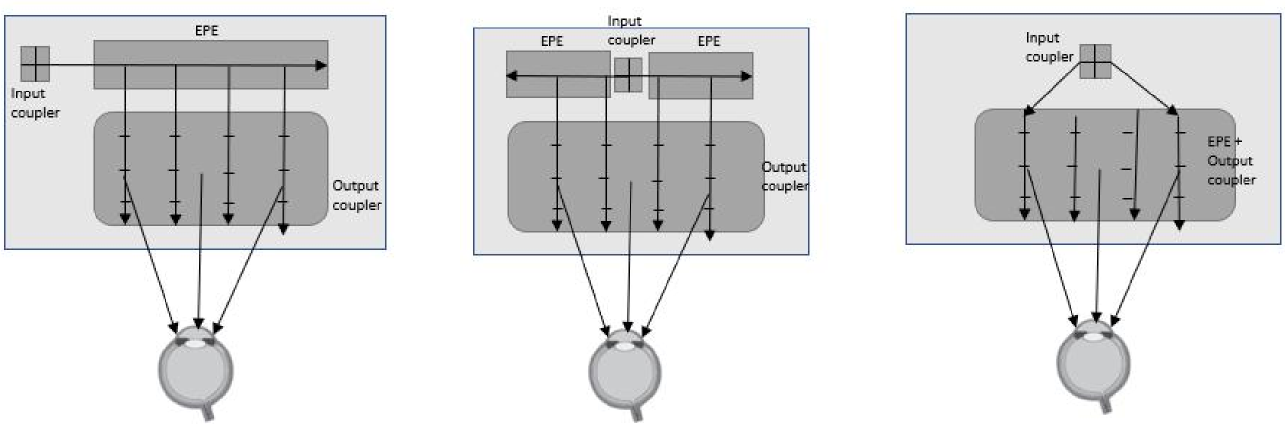


Figure 3: Freeform prism combiner[1,10].



(a) (b)

Figure 4: Reflective/diffractive couplers for waveguide combiners[1].



(a) (b) (c)

Figure 5: Diffractive couplers for waveguide combiners [1,10].

5. LBS TRIXEL® 3 AND COMBINER ARCHITECTURES

One of the main advantages of the LBS technology as designed by TriLite Technologies, is the flexibility of integration with different optical combiners including free space combiners such as holographic and freeform. Trixel® 3 is also ideal for waveguide combiners using 2d pupil expansion schemes. The design of Trixel® 3 was driven by the compatibility requirement to fit the different configurations of combiners developed by partners and other 3rd party developers. It addresses the requirement for a lightweight and compact device which fit seamlessly with the combiner. Because of its small footprint Trixel® 3 can be integrated with the combiner with no obscuration or restriction of the visual FOV. Because of its unique design, Trixel® 3 can be used as a monocular or binocular AR display.

The integration of LBS Trixel® 3 as a major part of an AR display is dictated by the system design of the overall application. Figure 6 is a schematic showing the different possible architectures that Trixel® 3 can fit into. This is by no means exhaustive, but it simply is an illustration of popular use cases.

Depending on the specific design of the combiner, the location of the input coupler can be in:

- Use case A – The LBS Trixel® 3 is mounted on the glasses temple and this configuration is compatible for both waveguide and holographic combiners. It is a popular fit as the projector is out of sight of the user´s view and can fit nicely within the glasses frame. For waveguide combiners, the projector butts against the waveguide input coupler with a small airgap in-between making the complete AR look very neat. For holographic combiner integration, the projector will have to sit along the temple and slightly back as defined by the properties of the combiner itself to project an image onto the surface of the combiner.

- Use case B – The LBS Trixel® 3 is fitted on the frame near the hinges. For waveguide combiner, the fitting is not dissimilar to Use case A and will mainly depend on the input coupler position of the waveguide. By fitting the projector on the glasses frame, the temple and its hinges become independent of the position of the projector. However, this use case may not be suitable for holographic combiner as the projection angle is too shallow.

- Use case C – The LBS Trixel® 3 is mounted on the frame and centred along the horizontal direction. This configuration is most suited for top-down arrangement for waveguide and freeform/holographic implementations. This configuration is better suited for enterprise applications where other sensors such as hi-res camera, ALS and Depth sensors are also mounted.

- Use case D – The LBS Trixel® 3 is mounted on the side of the glasses frame and centred along the vertical direction. This architecture suits the waveguide and glasses where the temple is not necessary at the top corner of the frame. Similarly, to Use case A, for holographic combiner the LBS Trixel® 3 is located along the temple slightly away from the combiner to meet the angle of incidence requirement of the combiner.

The illustrated configurations are the major fitting positions which Trixel® 3 can occupy without interference with the user´s head or obscuration of visual FOV. It also demonstrates the tremendous flexibility of the Trixel® 3 to match the fitting requirements for smart glasses.

It is also particularly important that in all the above use cases Trixel® 3 can be adapted to different tilt requirements of a normal looking glass, i.e., it can be fitted to meet the face wrap and pantoscopic angles without obstruction with the user´s view or protrusion into the user´s head or temple. Trixel® 3 can also be used in monocular or binocular configuration. Trixel® 3 is a high brightness projector which can be used for bright light conditions even when combined with waveguide combiners. In addition, it has a high dynamic range of brightness control for individual pixels. So, it can compensate for colour and brightness non-uniformity of the combiner if required. It is also worth noting that the choice of which implementation to use depends very much on whether it destined for enterprise or smart glasses applications and the appropriate combiner selected.

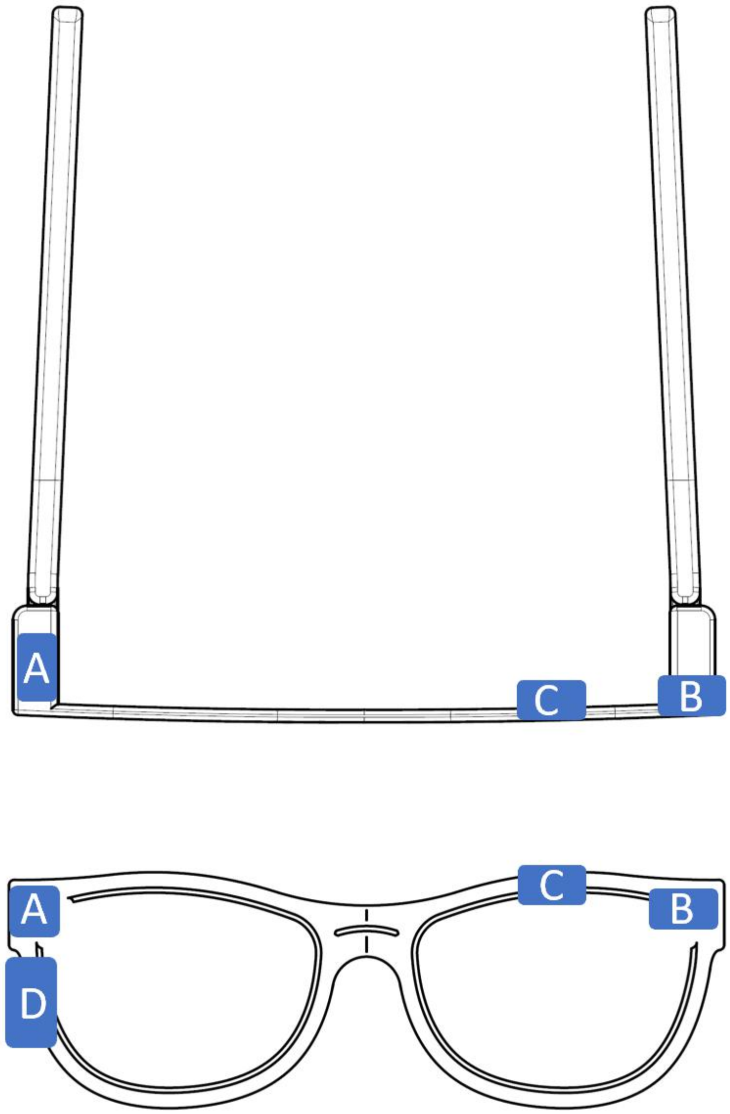


Figure 6: Trixel® 3 and combiner configurations.

6. CHALLENGES AHEAD

AR systems are extremely complicated and complex, combined with the challenge of being lightweight, portable, and inconspicuous, and of course affordable, there are many challenges to be resolved despite all the excellent progress being made towards making smart glasses a widely accepted reality [2,5-6,9-10].

The best representation of an ideal 'sporty' AR display with a wish list of sensory devices is illustrated by Jon Peddie[10]. It includes sensors for localisation, tracking, navigation, depth, ambient light, and eye tracking and front facing cameras. The schematic in figure 8 illustrates the need for other sensory devices for sound such as microphones and bone conduction headphones in addition to all the support, communication, and interface equipment. Figure 7 also shows the challenges of miniaturization of all these different sensors and modules. These in turn will be instrumental in addressing the requirements of human factors in terms of image perception, comfort, and immersion experience. Some of these sensors and devices are being used in mainly headsets where the overall form factor can be compromised to some degree especially for enterprise applications where the display is not continuously used. However, only a limited number of these devices like cameras and Bluetooth and headphones are implemented in smart glasses.

Size and footprint

It is evident that full immersion in the AR environment requires a combination of different and complex technologies with some of them still in their infancy. As a large number of devices and modules are required while there is only limited area and volume for the frame, it becomes a real challenge to fit everything in the frame unless further miniaturisation is achieved for all the components and devices. Trixel® 3 has the smallest size possible and a footprint which allows it to fit in very confined areas and in different location on the glasses frame as dictated by the respective combiner technology.

Mass

Similarly, the number of modules required for a fully immersive experience has a direct impact on the weight of the overall AR display. More importantly the centre of gravity of the overall system will be defined by the location of all these sensors and associated electronics and will affect comfort. Miniaturisation of Trixel® 3 is key to reducing the impact on the mass of the overall AR display. As a result, the location of the center of gravity of the overall AR system becomes less critical.

Power consumption and battery life

Power consumption is extremely important for any portable AR display. Less power-hungry devices and modules are therefore required for AR displays especially when more sensors and modules are needed. The drive for more electrically efficient devices also reduces the complexity of thermal management system for AR displays. Battery life, rating, efficiency, size, and weight are important parameters which need to be carefully considered. Extensive research and development of battery technology is being undertaken not just for AR applications but for numerous applications like electrical cars and space applications. So, it is likely that battery technology will continue to develop and miniaturise while the sensor and computing technology becomes more power efficient to produce a long-awaited solution for AR displays. Trixel® 3 was designed to be as power efficient as possible, the laser beams are controlled on a pixel basis through timing and are only switched where they are need on the image. Trixel® 3 makes use of ASIC technology to reduce computation complexity and power consumption.

Computing power

Any smart technology will need some computing power. As the AR technology evolves into smarter devices it requires mores sensory devices and computing power to monitor, capture and analyse data and control the complete ecosystem in real time. There are a lot of discussions about the different architectures available today to address computing power requirements; these include embedded computer in the headset, tethering the display to a computing unit and Cloud computing where high speed connectivity and coverage are critical. Tethering is not the optimum solution for an AR display even if the computing unit is portable. Standalone AR display with embedded computing units are only attractive if this does not compromise functionality, comfort, and immersion experience of the AR application. The trend is therefore towards using the best of high speed, more reliable connectivity and remote computing power which is also already making great advances in other hardware and software applications.

Restriction of the normal visual FOV and peripheral vision

Unobstructed view including peripheral vision of the user’s sight is especially important. The AR combiner and its projector module have to be designed to avoid any FOV obscuration of the see-through image. Any tunnel-vision effects or field of view obscuration impact human factors and increase dis-comfort when using AR displays. As result of the many sensors and cameras needed for full immersion experience, there is a high risk that these sensors may protrude in the user’s FOV or produce unwanted visual artifact which will distract the user from the main augmented image.

Interconnectivity of all these devices

As described above, connectivity to computing power unit is very important, and it is equally important to interconnect the devices themselves to provide all the synchronisation and data exchange between the different subsystems of the AR display. Routing and wiring are often considered at the last stage of the design almost as an after-thought. To meet the stringent requirement of an absolute compact AR unit, the design of an efficient interconnect between the different AR module has to be considered right from the beginning of the design and development process. It is even more critical when there are so many subsystems to be considered. It is often underestimated how much an impact of wiring and cabling has on the weight and the volume of the overall AR system. Special design and selection of the cable types has to be carefully considered in terms of robustness and lifetime when they are being used across hinges like folding the glass temples in the AR display case.

The normal look and fashion

For consumer market, the demands are even more stringent when it comes to the look of the 'smart' glasses as AR glasses need to look normal while loaded with the functionality described above. In addition, to be widely acceptable, AR glasses cannot be limited to only one style but have to offered in more frame styles and keep up with the ever-evolving fashion. This further exacerbates the challenges for AR technology.

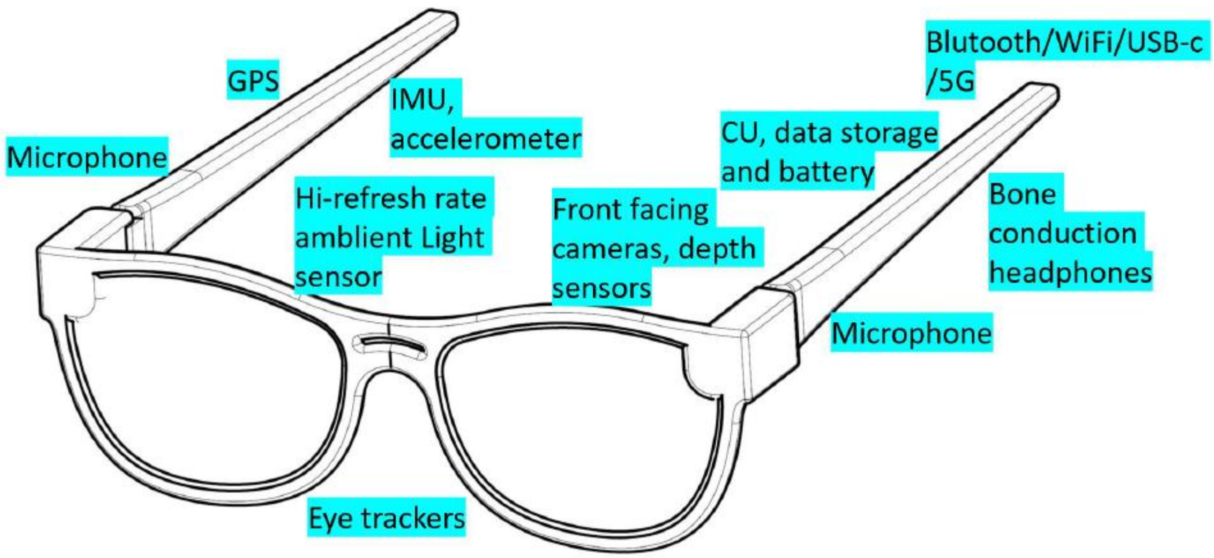


Figure 7: Challenges of AR displays[10].

7. CONCLUSION

AR displays are a complex mix of vibrant technologies and shows so much potential in enhancing our world through visual displays. The full immersion experience requires all these technologies to work seamlessly and in harmony, however, to make AR displays acceptable and attractive in the marketplace, there are a lot of challenges and obstacles to overcome as illustrated above. The challenges are multidisciplinary and are only resolvable if the whole ecosystem is considered together. There are a lot of efforts and costs being spent in advancing respective technology areas to meet these challenges. We, at TriLite Technologies, are playing our part in designing and manufacturing the smallest LBS projector fit for AR display applications with minimum size, footprint, and mass. We also produce a laser display technology with minimum power consumption and making use of ASIC technology to reduce computation complexity while keeping a firm control on size and weight. The design is compact enough not to obstruct the user FOV while adaptable to different glasses frame styles. This is however by no means the destination but is a major step towards a common goal of 'The Augmented Reality of tomorrow, as light as the eyewear of today'.

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