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Laser Beam Scanning in XR – benefits and challenges

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ABSTRACT

As of today, display performance is a major development criteria in the quest to deliver consumer-ready, high-quality XR glasses. Laser beam scanners in comparison with other display technologies are among the most promising high-dynamic range RGB display engine architectures, e.g., because the size of these devices remains unchanged when increasing the display resolution and field of view. This is in sharp contrast to competing display engines where each pixel constitutes an individual component and these technologies at some point seem to reach their physical limits. On the other hand, manufacturing state-of-the-art laser beam scanners including optics seems especially labor intensive, exhibiting a low yield, therefore driving up the price of XR glasses. This paper addresses the potential benefits and pitfalls of using laser beam scanners in XR and gives an insight into new solutions in next-gen laser beam scanning devices like, e.g., replacing cumbersome hardware beam combination by mere software solutions.

Keywords: display technologies, laser beam scanners, AR, XR, software beam combination, optics, lasers

1. INTRODUCTION

The overlay of information by means of a virtual image onto an impression of the real world is in general referred to as Augmented Reality (AR)[1]. Mixed Reality (MR)[2] even goes beyond that concept by embedding the virtual image into the real environment also using information about the real objects surrounding the user. The level of immersion is increased. An example is a virtual object being displayed behind a real one while omitting the covered areas, whereas AR would just overlay it onto the real world[2]. Virtual Reality (VR)[3] on the other hand describes the displaying of solely virtual images to the user, i.e. visual impressions of the environment are not received. Often, when referring to AR and MR all together, the term Extended Reality (XR)[1] is used. While XR in general induces immersion by incorporating vision, sound and interactive elements[2], in this work we are only addressing the sense of visual impression.

Visual performance is a major development criteria in the quest to deliver consumer-ready, high-quality XR devices[1], such as look-through XR glasses. Some major challenges arise when it comes to selecting and implementing display technologies into XR devices[1], e.g. display form-factor (size and weight)[4], large optics[5], waveguide coupling[6] or retinal projection[7,8], visual artefacts[9], performance issues with respect to field-of-view (FOV) and the eye box[10], resolution[9], color space (gamut) & brightness[11], daylight compatibility[12], power consumption[4] and many more.

According to literature[1,8,13–17], laser beam scanners (LBS) are among the most promising high-dynamic range, full-color (RGB) display engine architectures. In this paper, we refer to a LBS as a device which redirects one or multiple laser beams in one or two dimensions using micro-electro-mechanical-system (MEMS) mirrors[17]. We address the potential benefits and pitfalls of using LBS in look-through XR glasses and give an insight into new solutions in next-gen laser beam scanning devices with respect to the challenges mentioned above. The goal of this work is to present an extended benchmarking for display technologies that can be used in XR and to offer a holistic view on various properties of LBS. Based on a manageable set of features, benchmark scores will be presented that indicate the suitability of LBS relative to two other major XR display technologies, namely Liquid Crystal on Silicon cells (LCoS) and Micro-LED (mLED).

2. BENCHMARKING OF XR GLASS DISPLAY TECHNOLOGIES

A LBS steers one or multiple laser beams in one or two dimensions. Techniques for beam steering are, e.g., piezo-electric bending of optical fibres[18], optical phased-array antennas[19], rotatable wedge prisms[20] or MEMS mirrors[17]. In this paper, we refer to the latter. Kress et al.[1] gives a very good insight into how such systems work. For clarification, Figure 1 shows just one very basic principle of an optical look-through XR glass using LBS: The LBS has to contain the light source (1), which usually incorporates RGB laser diodes. Moving mirror(s) (2) redirect the light incident on its surface, forming a

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pattern or an image. In XR glasses, the light from the LBS is then further guided by some means of reflective or diffractive optics, e.g. it is coupled into a waveguide by an in-coupler (3). The light travels through the waveguide (4) by total internal reflection at its surfaces or diffraction, until it reaches the out-coupler (5). The out-coupler partially couples light out of the waveguide, redirecting it to an observer (7). The ambient light (6) also reaches the observer by travelling through the transparent waveguide.

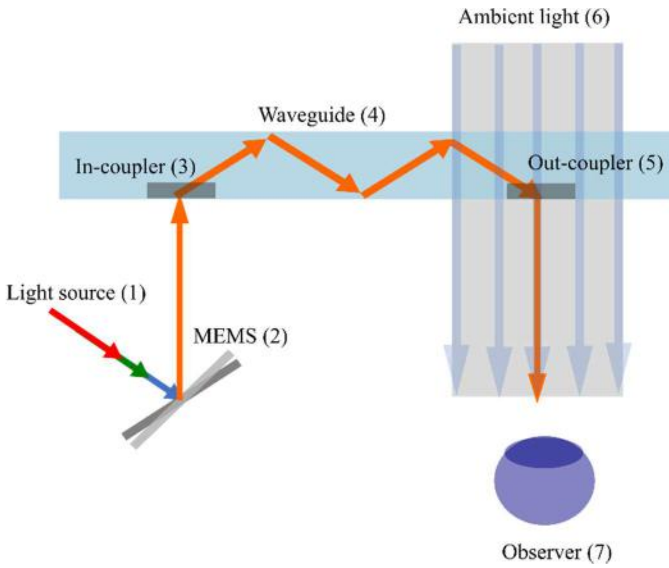

Figure 1: Schematic view of a LBS (1 and 2) coupled into a waveguide (4) in order to redirect the image to the observer (7).

We have developed a compact LBS[17] - the Trixel® - based on an integrated RGB laser light module and MEMS mirror (cf. Figure 2). Our approach allows a compact laser light module architecture, which does not require additional optical elements other than a fast-axis-collimator (FAC) and a slow-axis-collimator (SAC) to combine the RGB beams. The non-coaxial beams are combined at a MEMS mirror and then the so-called TriLite Calibration Module, i.e. a software beam combination approach[21], is applied. The latter is a concept that is capable of correcting for image distortions by placing the pixels correctly in the time domain.

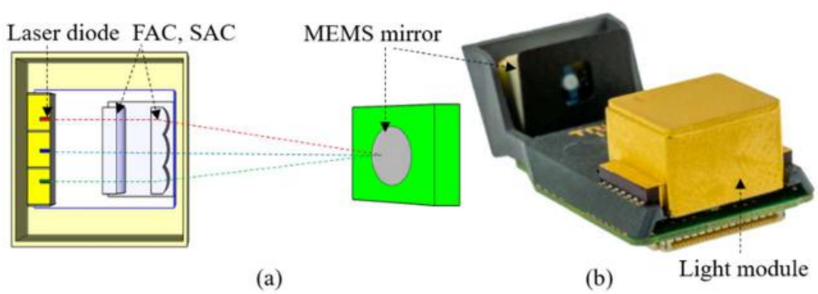

Figure 2: (a) Schematic and (b) image of a TriLite LBS – the Trixel® [17].

In order to indicate the suitability of such a state-of-the-art LBS display for being used in look-through XR glasses, we compare our solution to two other major XR display technologies, namely the already very well established LCoS cells which require a separate illumination engine and the seminal technology of self-emissive mLED which have gained a lot of attention recently.

Active (self-emissive) small-scale mLEDs are made of non-organic semiconductors with pixel sizes as small as 1.3 µm[22,23] in monocolor and 3 µm[24] in full color. The displays aim at providing all the advantages of an OLED microdisplay (simplicity in systems design and integration, good contrast-ratio, low power consumption) with the added values of a smaller form factor, higher brightness and wider color gamut. The reported drawback of mLED technology is that the scalability to such a small form factor requires a more complex system architecture[25]. Also the development of full-color mLED panels based on a single wafer is a still ongoing endeavour[26].

Passive LCoS[27] cells are built from a stack of a highly-reflective mirror, a liquid crystal layer and a transparent glass plate. Multiple of those cells form an array of switchable pixels, which then still require an active light source, i.e. LEDs or lasers. Typically, individual RGB LEDs are used. The light from emitters is reflected by a polarizing beam splitter (PBS) towards the LCoS panel. By applying voltage, the liquid crystals manage the amount of light which hits the pixelated, reflective surface and thus generate images[6].

2.1 Benchmarking methodology for display technologies

In order to address potential benefits and pitfalls of our LBS[17] relative to the competing technologies LCoS and mLED we use the following methodology: Systematic literature research is used in order to compare these display technologies with respect to the parameter set shown in Table 1. We obtained over 120 papers published between the years 2017 and 2021. We excluded those studies, which were not consistent with our predefined parameter set. The criteria for including or excluding collected papers is explicitly outlined in Table 2. Our survey is based on 96 published studies that were included into our analysis.

Table 1: Key characteristic parameters for XR display technologies

Parameter	Units	Definition	Reference
Acuity	[arcmin]	The ability to resolve fine detail.	25
Brightness (luminance)	[cd/m²]	Amount of light intensity reflected, passed through or emitted per unit area projected in a given direction.	28
Color depth (bit depth)	[bit]	The number of bits used for each color component of a single pixel. An 8-bit value (bit-depth n = 8) has 2^8 = 256 distinct color components. For 8-bit/channel RGB images, each channel has 256 different gradients from 0% (black) to 100% (full saturated pure primary color).	29
Color gamut	[%] of standard RGB	Specific range of colors which a display can produce. Typically, color gamut is expressed with the xy chromaticity diagram of the XYZ color system defined by the International Commission on Illumination (CIE)	28
Color uniformity	-	Pixels brightness or color inconsistencies at different areas of the displayed image.	30
Contrast (Dynamic range)	ratio	The measure of the relative difference between light and dark areas of a display.	28
Ambient contrast ratio (ACR)	*ratio*	$$ACR = \frac{L_{on} + L_{ambient} * R_L}{L_{off} + L_{ambient} * R_L},$$ *where* $L_{on}(L_{off})$ *is on-state (off-state) luminance of a displayed image,* $L_{ambient}$ *is ambient luminance,* R_L *is the luminous reflectance of the display panel.*	31
Michelson contrast	*ratio*	*Defines image contrast using the peak luminance values* $$C_M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}},$$ *where* $L_{max}(L_{min})$ *is maximum and minimum luminance of a displayed image.*	32
Distortion	-	A deviation in an image from straight lines in object (scene).	33
Durability	[hours]	Lifetime of a display.	
Étendue	[mm²·sr]	a quantity which measures the product of the area and solid angle of emitted light from a surface in an optical system. Étendue describes the maximum light flux passed through an optical system. $$\varepsilon = \pi n^2 A Sin(\theta),$$ with ε – Étendue, n – index of refraction, A – area of source or pupil, θ – the cone angle of light cone emitting from source/pupil.	34
Eye safety	-	Tissue interaction of light sources may be photomechanical, photothermal or photochemical, depending on the irradiance and the duration of exposure.	35
Field-of-view (FOV)	[°]	Angular range over which an image can be projected.	25

Latency	[ms]	The time required for a display to respond to the movement of a head-mounted display. During this time all display components complete their processing tasks and update the displayed image. Sometimes also denoted as motion-to-photon latency.	28
Polarization	-	Direction of the electric field oscillation of a light beam.	36
Power Consumpt.	[W]	The amount of energy used by a display. Power consumption is mainly defined by the driving circuitry designs, quantum efficiency of a light source and optical system efficiency.	37
Projection Flexibility	-	Ability of a display technology in adjusting projection parameters (scan speed, etc).	
Refresh Rate (frame rate)	[Hz, fps]	Is the measure of how fast images are updated on the display, the number of times a display's image reproduced per second.	25,28
Resolution	[1]	Number of discrete pixel elements of a display displayed in horizontal and vertical axis on a screen.	28
Angular resolution/ Pixel density	*[PPD]or [arcmin]*	*Is a measure which describes how much two objects can be differentiated in angular space. Pixels per degree: target 0.3 arcmin = 195 PPD to 1.3 arcmin = 45 PPD Pixel density is a ratio between pixel resolution in horizontal or vertical direction to the respective filed of view in degrees.*	25,38
Size (form factor)	[m]	Describes physical size and shape of a device measured by outside dimensions.	
Visual artefacts	-	Examples: Screen door effect, aliasing, motion blur, Mura effect, color breakup, speckling	
Visual Comfort (Way of Focus)	-	Visual comfort of display systems can be seriously reduced by many factors including jitter, flickering, image motion, and poor resolution.	39
Weight	[g]	Weight of a display unit. System should be lightweight in order to be successfully integrated into a XR device.	25

Table 2: Literature research – exclusion and inclusion criteria

	Criteria	Explanation
Exclusion	without full-text	Paper or source without full text to be assessed or missing important information.
	non-related	The definitions used in the paper are not related to the definitions (key words) shown in Table *1*.
	loosely-related	Paper or source which doesn't focus on the review, survey, discussion or technological aspects of XR glasses display technologies.
Inclusion	partially related	Paper or source about XR/MR/AR/VR including information on used display technologies.
		XR display technologies are one of several objects to be reviewed, surveyed or discussed.
	closely related	(Research) efforts of paper or source are explicitly dedicated to XR display technologies.

In general, system design involves a number of decisions taken by the developing parties, in order to achieve optimum performance. The first step in our benchmarking process based on a methodology given in Braun[40] et al. is thus to select a set of indicators that can be used as a metric (cf. Table 1). The feature set is based on the following rules: (i) The ability to qualitatively determine or quantitatively measure physical characteristics is important. (ii) Dynamic aspects, including price are very important when designing actual products and have to be considered early on. However, they often change with yield and economies of scale. We address the issue with respect to our LBS in section 3.2 but do not include it in the technology comparison. (iii) Categories if not equally represented concerning feature count can be differentiated by individual feature weights. Because each application will have a distinct detailed vector of associated weights that can be applied to a set of display technologies, we keep the weights to 1 and use a normalized benchmarking score in this work.

We leave it to the interested reader to apply weighting vectors deviating from 1 (based on the specific application) and use our results. Our categories are (a) image quality, (b) XR display characteristics and (c) user aspects. Also this selection is based on the authors' analysis of related work (cf. references).

From the selected metrics we create a feature matrix that allows us to associate selected key parameters to a specific rating that is used later in the scoring process of the benchmark model. As suggested in Braun[40] et. al., each feature is mapped to five different ratings on an ordinal rating scale comprised of the items "least favorable" (1), "not favorable" (2), "average" (3), "favorable" (4) and "most favorable" (5). All collected information is then reviewed by at least three examiners, i.e. collaborators of the research that have a working knowledge on XR display technologies. If a majority of examiners cannot reach consensus based on the information given in literature, an additional expert will make the final decision based on calculation, simulation or experiment. The results are given in Section 3.

3. RESULTS & INTERPRETATION

3.1 Image quality

With respect to luminance[1] the laser light sources used in LBS have the advantage of potential high brightness values[4] (even more than e.g.[41] $6 \cdot 10^6$ cd/m² in full-color, compared to approximately $50 \cdot 10^3$ cd/m² for LCoS[42] or from $350 \cdot 10^3$ cd/m² for RGB-mLED[43] to $4 \cdot 10^6$ cd/m² for single-color mLED[23,44]). It renders LBS to be the most suitable technology up-to-date for outdoor XR applications in bright sunlight. This – and the fact that the laser light can be switched totally off in a very fast manner – also leads to a high rating with respect to ACR and Michelson contrast. In general, the contrast ratio[4] for RGB-LBS of typically 50,000:1 is still a clear advantage over competing technologies like LCoS (using fast switching LCs) with values of 1,000:1 or even state-of-the-art mLED with 10,000:1.

Look-through XR glasses traditionally suffer from the tradeoff between FOV and the size of the viewing eyebox, i.e. the area in which the eye must be located to see the image. Together, these two quantities describe the étendue of the display, a quantity which measures the product of the area and solid angle of emitted light from a surface in an optical system. Due to their panel-based nature, LED size and Lambertian emitter characteristics, mLED or even LCoS show relatively large étendue values. To compensate for the large étendue, mLED has to use microlens arrays directly on top to collimate the light directly down at the pixel level. LBS on the other hand uses lasers with a very small emitting size and spatially coherent beams, i.e. LBS show a smaller étendue. Since there is no object plane, the LBS system is not as limited as other display technologies by the law of étendue[45], resulting in substantial advantages in terms of display engine size and weight (cf. section user aspects).

High luminance and small étendue of LBS are also advantageous because of the traditional high coupling-loss into waveguides with pupil expansion, minimizing the input collimation issue. To date it is still an open question if mLED will work well with pupil expanding waveguides, especially because full-color RGB mLED panels[24,46] have a significantly lower luminance than monocolor mLEDs[23,47].

Color-depth is not exactly a parameter inherent to the display technology itself but rather how many bits per color channel are used. It is still interesting to note that state-of-the-art LBS, LCoS and mLED displays all provide up to 10bit/color at the moment[37,41]. The color gamut on the other hand is also a well-known advantage of using laser light sources. The color gamut coverage of the display is mainly defined by the central wavelength and full width at half maximum (FWHM) of the RGB emission spectrum. Figure 3 shows our calculation for the gamut comparison, i.e. the CIE 1931 chromaticity diagram and the CIE 1976 u'v' diagram, of these 3 technologies, using state-of-the-art parameters[23,41,42]. The calculation shows values of up to 214% over standard RGB (sRGB) for LBS, 150% for LCoS and 185% for mLED or below[48].

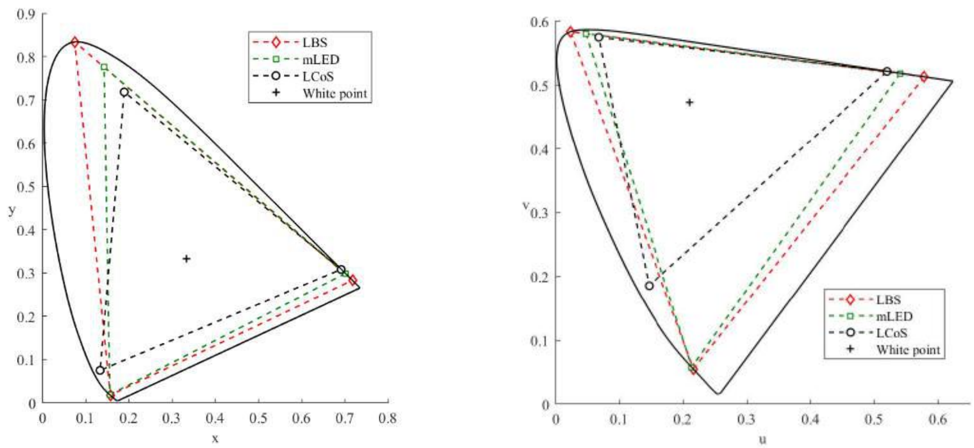

Figure 3: CIE 1931 and CIE 1976 gamut comparison between state-of-the-art LBS, LCoS and mLED.

Panel-based technologies like LCoS or mLED show uniformity issues[49,50] like the Mura effect (especially for lager panel size) or pixel-to-pixel variations. Poor pixel-to-pixel brightness uniformity leads to grainy images and causes issues for moving pictures. Also LBS projectors can show grainy intensity patterns superimposed on the image[10]. These are caused by speckling due to the coherent nature of laser-light. However, in XR glasses it is somehow less of a problem. If a laser-generated image is not projected onto a surface speckling does not occur. As a pendant to the Mura effect LBS has image areas where the laser beam moves slower, e.g. at the borders of the image, when the MEMS mirror approaches its turning points. Without compensating for that the image would get brighter. In state-of-the-art LBS there are several mechanisms implemented to correct color and brightness non-uniformity: For projection the laser pulse length is adjusted in the time domain. Independently of how long the laser scans over a certain area, it is switched on for the same amount of time, i.e. for the same amount of clock pulses. Using this technique, one can achieve a uniform brightness, without even touching the color space. In case one wants to correct an arbitrary color-nonuniformity, e.g. induced by a waveguide, one can use a brightness multiplier for each pixel.

With LBS individual pixels can be freely shifted across the FOV by timing individual laser pulses precisely[21], allowing for nearly perfectly calibrated images presented to the viewer's eye even when elements in the optical path (e.g. optical combiners) introduce distortions to the image. With the Trixel, image distortions are compensated within the TriLite Calibration Module[17,21]. Using correction vectors it compensates for nonlinear beam movement, geometric distortions caused by the MEMS mirror, angular offset between individual laser beams, parallel shifts of the beams or even for distortions caused by any optics (mirrors, lenses, waveguides) in the optical path between the LBS and the viewer's eye. Another advantage is, that unlike panel-based displays, LBS do not show a number of visual artefacts like the screen door effect or color break up during head movement: LCoS or mLED images are perceived as grid-like pictures like looking through a mesh screen. This is caused by their fill factors and worsened by the fact that XR optics are getting increasingly better such that small features are easily resolved. Countermeasures like mechanical motion[51] help, but reduce image sharpness on the other hand. In addition, the LCoS display constructs a single red, green, and blue (RGB) color frame by using field sequential color (FSC), i.e. it combines the color sub-frames sequentially. As LCoS uses FSC these displays exhibit color breakup during head movement if the field rate is too low[52]. With LBS there are no such problems.

One principle limitation of panel-based architectures like LCoS or mLED is their minimum pixel size (which is determined by various technological, manufacturing and efficiency constraints). This pixel size limits the achievable minimum display panel size for a targeted image resolution. Thus, an increase in resolution of mLED or LCoS also always leads to an increase in the size of the collimation optics to couple the light emitted by the display to the optical combiner and increases size and weight (cf. section user aspects). Available resolutions of up to 1080p were already reported for all three XR glasses display technologies by several vendors[23,41,42].

In Table 3 and Figure 4 we summarize our findings with respect to image quality based on the methodology as described in section 2.

Table 3: Image quality – benchmarking LBS, LCoS and mLED displays for XR glasses.

No.	Parameter	LBS (Trixel®)	Rating	LCoS	Rating	mLED	Rating
1	**Luminance**	6 x 10 ^{6} cd/m²	5	50 x 10 ^{3} cd/m²	2	350 x 10 ^{3} cd/m²	4
2	**Contrast ratio**	50,000:1	5	1,000:1	2	10,000:1	4
3	**Étendue**	≥ 2.31 mm²sr	5	≥ 5.5 mm²sr	3	≥ 8 mm²sr	3
4	**Color Depth**	≤ 10 bit	5	≤ 10 bit	5	≤ 10 bit	5
5	**Color Gamut**	≤ 214 % over sRGB	5	≤ 150 % over sRGB	3	≤ 185 % over sRGB	4
6	**Uniformity**	most favorable	5	favorable	4	average	3
7	**Distortion**	favorable	4	favorable	4	favorable	4
8	**Visual Artefacts**	favorable	4	average	3	favorable	4
9	**Resolution**	1080p	4	1080p	4	1080p	4
10	**Angular Resolution**	favorable	4	favorable	4	most favorable	5
		Total	47	**Total**	34	**Total**	39
		Total (in %)	93%	**Total** (in %)	67%	**Total** (in %)	77%

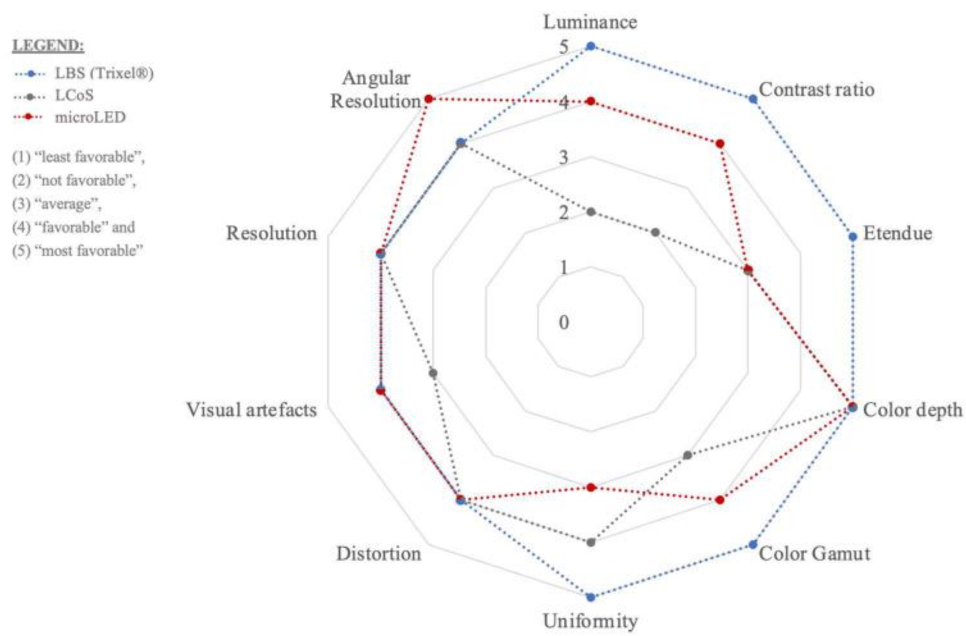

Figure 4: Image quality – benchmarking LBS, LCoS and mLED displays for XR glasses.

3.2 XR Display characteristics

Figure 5 illustrates the comparison of key indicators (cf. Table 4) with respect to XR display characteristics for the different display technologies under study. Some of these parameters are inter-dependent and an improvement in one characteristic impacts another (e.g. FOV, refresh rate and latency are a good example for this inter-dependency). For XR applications a FOV of around 50 deg diagonal is state-of-the-art[1], and can be achieved by using either of the three technologies. The combiner technology itself determines the upper limit for the FOV, which can be relayed to the eye. While a retinal display combiner can reflect a much larger FOV at the expense of a small eye box, waveguide-based combiners have a limited angular bandwidth for transmitting the image FOV but with the advantage of a larger eye box. It is important to note that for increasing the FOV, the size and the weight of panel-based displays will increase accordingly, but not with LBS technology. What is unique to LBS in respect of optical path/image redirection is its capability of retinal scanning[7,8,14,15].

Table 4: XR Display Characteristics– benchmarking LBS, LCoS and mLED displays for XR glasses.

No.	Parameter	LBS (Trixel®)	Rating	LCoS	Rating	mLED	Rating
1	**FOV**	≤ 40° x 30°	5	≤ 40° x 30°	5	≤ 30°	5
2	**Refresh Rate**	≤ 90 Hz	4	≤ 60 Hz	2	≤ 360 Hz	5
3	**Latency**	11 - 17 ms (with SW corr.)	4	18 - 30 ms	3	10 - 17 ms	5
4	**Power Consumption**	~ 0.1 W, all components	4	~ 0.3 W	3	~ 0.1 - 0.725 W per color	4
5	**Polarization**	linear or unpolarized	5	unpolarized (source)	2	unpolarized (source)	3
6	**Projection Flexibility**	flexible	5	not flexible	2	not flexible	2
7	**Technology Maturity**	pre-production	3	production implementation	5	pre-production	2
8	**Optical Path & Image Redirection**	favorable	4	average	3	average	3
		Total	**34**	**Total**	**25**	**Total**	**28**
		Total (in %)	**86%**	**Total** (in %)	**63%**	**Total** (in %)	**70%**

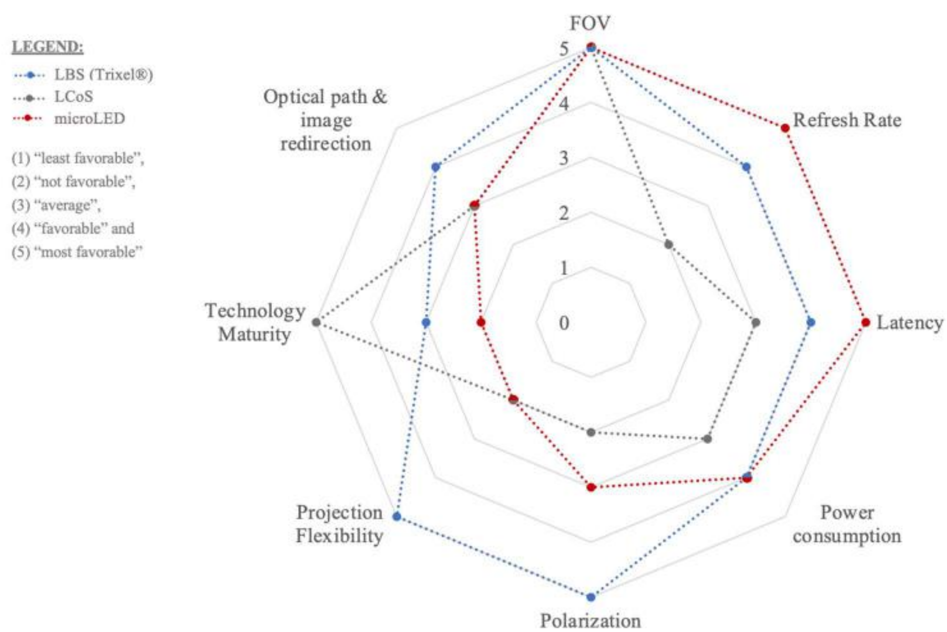

Figure 5: XR Display Characteristics– benchmarking LBS, LCoS and mLED displays for XR glasses.

Refresh rate is an important factor in XR displays for moving scenes and images. The refresh rate has a direct effect on the motion-to-photon latency[53] in addition to the contributions of other components in the display pipeline such as sensors, tracking and rendering (cf. Table 5). As the displays, are used to augment real world images which are highly dynamic (because the user moves the head in an application environment), it is critical that the delay between the refreshed image in the display is minimized to produce a consistent virtual image superposed on the see-through image at any time. LCoS displays in that sense have inherently a longer latency because of field color sequential mode operation.

Table 5: Overall latency of an XR pipeline[54]

Criteria	LCoS	mLED	LBS
sensors	15 ms		
tracking	25 ms		
rendering	17 – 50 ms		
display	18-30 ms	10-17 ms	10-17 ms

The efficiency of the different display types varies with different combiners. As both LCoS and mLED displays are matrix panels with essentially Lambertian light sources, the collection and direction of the photon energy to form an image at the eye becomes a challenge unless a larger amount of photon energy is generated by increasing electrical power. This is due the Étendue limitation of these technologies. In that sense, LBS is extremely efficient (cf. section 3.1). Laser sources with their small beam divergence are best in generating very directional light with a high efficiency compared to other Lambertian sources. The collection efficiency of the generated photon energy is a huge advantage for LBS as it has a direct impact on low power consumption when compared to LCoS and mLED displays. Additionally, LBS uses a single beam which can be temporally and spatially controlled, thereby increasing power efficiency compared to a whole display matrix. For example, LCoS is illuminated entirely during all times and only works with polarized light. Therefore at least 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 state-of-the-art mLED displays is also higher than LBS, especially as the pixel size is reduced to reduce the display footprint. In this case mLED efficiency goes down because of crosstalk between pixels and the effect on the collection efficiency of photon energy from these pixels.

A unique advantage of using LBS as a single beam painting an image is the ability to modify the FOV through software and to compensate for non-uniformity and distortions[17,21], which we denoted as projection flexibility in our study.

All display technologies analyzed here have different level of maturity. To date, LCoS has been in the market for a while and is widely commercially available. LBS display technology is currently gearing to be mass produced soon as the technology is maturing[1,55]. On the other hand, mLED displays are a promising technology but still in their infancy with respect to some technical issues, e.g., intensity-variation free RGB color, heat management or efficiency. As already stated in section 2.1, our benchmarking methodology explicitly excludes dynamic aspects including price, which changes with scale. However, price and the ability to scale depend on the yield, which increases with decreasing technological complexity. Software-driven hardware architectures like the Trixel take advantage of laser and MEMS mirror control (cf. TriLite Calibration Module[17,21]) to compensate for non-idealities caused by hardware. First, it enables unique, simplified LBS assembly process flows, e.g., by reducing the number of active and passive alignment steps. Secondly, it allows for looser alignment tolerances, improving the assembly yield. The combination of both aspects allows for a significant reduction in manufacturing costs by increasing yield due to relaxed manufacturing tolerances. It also reduces the generation of waste through high reliability during manufacturing and decreases the generation of pollution during production[55].

3.3 User aspects

With respect to durability, LEDs as photon source have a larger lifetime compared to laser diodes[56] although laser diode reliability can be improved by optimizing operation conditions, e.g. temperature. Durability of a display is not only defined by their photon source lifetime but also by the shortest lifetime of its components. Literature reported values for the lifetime of LCoS displays to be above 20,000 hours[42] and lifetime of a mLED display to be about 50,000 hours[57]. For evaluation of LBS durability, the most sensitive components such as laser diodes and MEMS mirror should be taken into account. Laser diode lifetime can be up to 100, 000 hours[58], whereas lifetime of a MEMS mirror is above 60,000 hours. Thus, among the leading display technologies LBS has the longest lifetime to date and LCOS has the shortest one. Decreasing brightness over the lifetime of all light sources and increasing maturity of mLED nevertheless has to be taken into account.

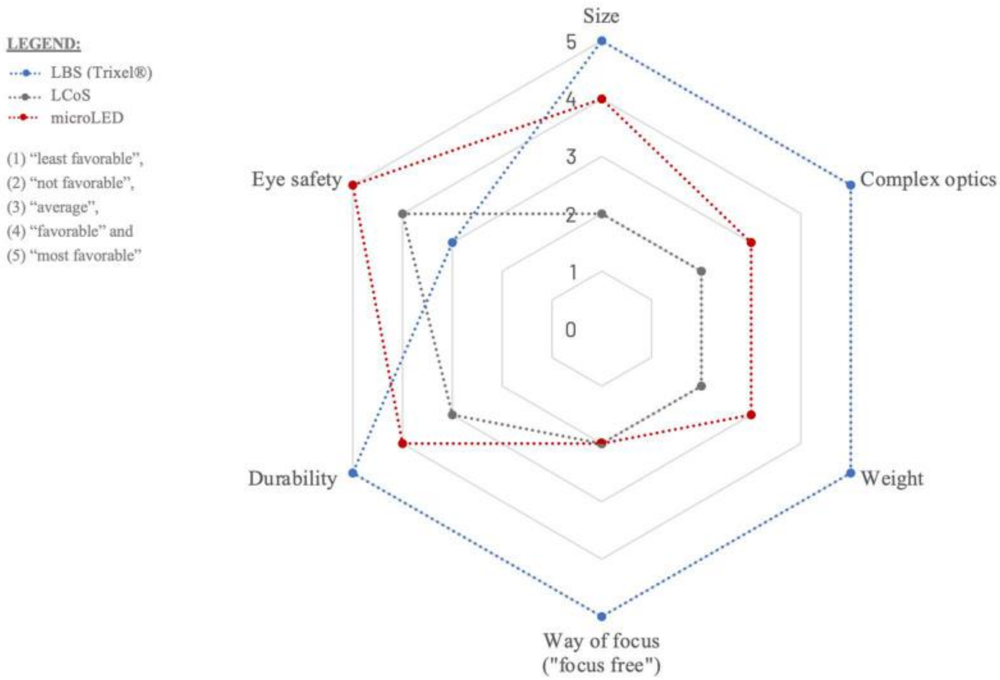

Figure 6: User aspects – benchmarking LBS, LCoS and mLED displays for XR glasses.

The use of an inherent bright and coherent light source such as a laser in LBS has potential challenges in terms of eye safety. Thermal effects (i.e. heating by the laser), photochemical reactions (i.e. the laser introduces a chemical change in tissue), or phototoxic effects (i.e. an excessive luminance dose in the visible wavelength region for a certain extent of time) can be omitted by keeping the laser light power below a certain limit and by implementing additional safety measures[59]. With the use of active mitigation, eye safety for LBS can be established. As an example, smartphone face scanning concepts have implemented active mitigation against the potential complications caused by laser radiation[1]: Indium tin oxide (ITO) layers are running through the diffractive element. If those ITO lines are broken the laser is shut off. For the Trixel, lasers are shut off when the MEMS mirror stops moving. As LCOS and mLED typically use LEDs as a light source which are considered to have no potential hazard for vision, those techniques bring no issues for eye safety. For recently reported ultrabright mLED displays eye safety topics still need to be addressed accordingly.

LBS have the unique advantage of free-focus projection. The projected image stays focused for an observer while the image plane is shifted. Panel-based displays using LED have a fixed focus. Focus free projection of LBS has further advantages, as the beams are typically collimated before they are delivered to the scanning MEMS mirror. This allows to project image onto flexible areas or omit distorted focus. It also has a particular advantage for retinal displays, as the displayed image is in focus regardless of user eye accommodation or presence of a contact lens.

Size, weight and optics complexity are important key factors when it comes to the user aspects of XR glasses. According to customer surveys and user studies, XR devices should be as lightweight as common eyewear. Increasing the FOV with LBS technology does not necessarily increase the size of the laser display. Panel-based displays with their 2D array of pixels on the other hand are using additional optics to convert the linear display into angular space. So, the FOV is directly proportional to the size of the micro-display and inversely proportional to the collimation optics focal length. For larger FOV, a larger micro-display is required to maintain a given pixel resolution. Conversely, collimation with smaller focal length is required. However, maintaining acceptable optical performance of the collimation optics over the FOV and small f-number would be challenging.

Designing and manufacturing displays with smaller pixel pitch is also challenging as they are limited by the lack of efficiency and pixel crosstalk effects which get worse as pixels get smaller. Collection optics are usually added to improve efficiency, but they are limited in what can be achieved. Some leading mLED manufacturers already produce relatively small micro-display panels with a pixel pitch of 1.3 µm[60] and up. Those are mainly monochromatic and of low resolution. So at least three panels would be required for an RGB display which will then require, e.g., an x-cube prism to combine them. In addition, a collimation optics is required which makes these designs bulky. The overall size of such mLED displays becomes relatively larger and in the case of using an x-cube with monochromatic mLED panels additional color non-uniformity issues arise (cf. section 3.1). LCOS displays are also available in different pixel resolutions and have a typical pixel pitch of, e.g., 4.5 µm. An analysis of a 1280 x 720 pixel (5.76mm x 3.24mm) panel used to generate 30 deg FOV shows that a collimation optics of 12.3 mm focal length is required. The diagonal dimension of the active area panel is 6.6 mm. In addition, the LCoS display requires both illumination and projection optics which more than doubles the overall size compared to a self-emissive display. If these micro-displays are to be scaled up from say 30 deg to 50 deg diagonal FOV applications while maintaining the same pixel resolution, the micro-display panel will have to increase by 74 % diagonally.

All of its components in general define the size of the display engine, not only the display technology itself. In particular size is defined by the optical system required to project an image. LBS shows the following advantages in terms of size, weight and form factor: Unlike any other micro-displays used for XR, the 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 additional external projection optics. Increasing the FOV with LBS technology does not increase the size of the laser display. The Trixel especially is characterized by its capability of direct coupling into different combiners[61]. This reduces the complexity of the optics as the LBS projector and minimum aberrations are introduced. Avoiding large and bulky optics due to software beam calibration and compensation measures[21] leads to a small-sized and lightweight LBS display engine for look-through XR glasses. The overall comparison of key performance indicators with respect to user aspects is shown in Figure 6 derived from Table 6.

Table 6: User aspects – benchmarking LBS, LCoS and mLED displays for XR glasses.

No.	Parameter	LBS (Trixel®)	Rating	LCoS	Rating	mLED	Rating
1	Size	no optics for illumination or for projection required	5	optics for illumination and optics for projection needed	2	optics for projection needed	4
2	Complex Optics	low	5	high	2	medium	3
3	Weight	no optics for illumination or for projection needed	5	optics for illumination and optics for projection needed	2	optics for projection needed	3
4	Way of focus ("focus free")	free-focus	5	fixed	2	fixed	2
5	Durability	~ 60 x 10^3 hours	5	~ 20 x 10^3 hours	3	~ 50 x 10^3 hours	4
6	Eye Safety	active mitigation requested	3	depending on light source active mitigation requested	4	no issue	5
		Total	**28**	**Total**	**15**	**Total**	**21**
		Total (in %)	**92%**	**Total** (in %)	**49%**	**Total** (in %)	**69%**

4. SUMMARY

In this paper, we present an extended benchmarking addressing the potential benefits and pitfalls of using LBS as a display technology in look-through XR glasses. Using systematic literature research assessing 96 selected publications we analyze 25 key performance indicators, comparing LBS to passive and active panel-based display technologies like LCoS or mLED, respectively. The normalized benchmarking results are presented in the three categories of (i) image quality, (ii) XR display characteristics and (iii) user aspects. It is found that LBS which replace cumbersome hardware beam combination by mere software solutions - like our Trixel - show superior performance in many aspects. Compensating LBS hardware non-idealities via software, e.g. by reducing the number of active and passive alignment steps and loosening the requirements for alignment tolerances, provides substantial benefits in terms of assembly yield and therefore manufacturing costs. High luminance in combination with very favorable étendue properties (leading to low waveguide input coupling loss) promise suitability for outdoor XR glasses. Being more or less on a par with panel-based displays in respect of image quality, LBS show unique benefits like their flexible projection capabilities, focus-free operation or a wide RGB color gamut space up to 214% over sRGB. With their technological maturity continuously increasing, our analysis shows that LBS in combination with software beam calibration and compensation measures – thereby avoiding large and bulky optics – is one of the most promising small-sized and lightweight display technologies for look-through XR glasses to date.

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