Fundamental Microdisplay Metrics for Near-To-Eye Applications:
An Analysis of the Main Features of Microdisplays for Best Practice NTE Designs

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Abstract
Microdisplays are the enabling technology for head mounted and Near-to-Eye displays. In creating a colour image, FLC based LCOS technology is intrinsically and uniquely capable of a far more accurate rendering than any of the competitive technologies. LCD and OLED based technologies all suffer from fundamental limitations to image quality.

1. Introduction
Microdisplays are the enabling technology for Head Mounted Displays (HMD) and Near-to-Eye (NTE) displays for virtual reality, immersive gaming and military training and simulation applications. The very best HMD will use the very best microdisplays that are available, and with a wide range of microdisplays available it is important that the HMD and NTE manufacturer chooses the best display to meet their needs.

The following measurable and quantifiable features of a microdisplay are discussed with reference to high end NTE display systems where image quality is paramount and the needs of the end user are a display system which delivers as near to reality as possible.

2. Resolution
The native resolution of a microdisplay is the first choice criterion when choosing displays fit for the application. XGA (1024 x 768) resolution head mounted displays were a popular choice in the late 20th Century and from around 2002 the SXGA (1280 x 1024) resolution took over as the state-of-the-art. Since then, all new HMD and NTE displays have aspired to this resolution per eye.

In 2007, nearly all microdisplay roadmaps aspired to resolutions consistent with consumer television markets and were driven by High Definitions standards. 1920 x 1080 pixels (or resolutions with 16:9 aspect ratios) were an oft achieved resolution but this has little relevance to NTE display systems. In high end NTE display systems for training and simulation, for example, stereoscopic wide field of view (FOV) is the design aim. The human visual system (HVS) instantaneous field of view is 160^{o} in the horizontal by 120^{o} in the vertical direction [1] per eye. Microdisplays with an aspect ratio of 16:9 would result in a very wide horizontal resolution and a much lower vertical resolution. It is therefore a more appropriate approach to use microdisplays with a 4:3 or 5:4 aspect ratio.

3. Illumination
Liquid Crystal on Silicon (LCOS) microdisplays are not emissive and therefore require a separate illumination source which is modulated by the microdisplay giving full colour and grayscale. As the luminance is not linked to the display technology itself, the luminance options can be considered to be customisable for the application. Should a wide FOV be required then suitable illumination sources can be chosen to ensure that the correct luminance is achieved in the application. For an emissive display, boosting the luminance leads to a reduction in display lifetime. In that respect, LCOS microdisplays and transmissive liquid crystal displays (LCD) are best suited for wide field of view applications.

Emissive microdisplays are known to struggle to achieve suitable luminance characteristics for wide FOV NTE displays. A route around this is to tile multiple microdisplays to achieve higher resolution and wider field of view. However, reports have indicated that these tiled solutions can suffer from optical artifacts associated with colour and luminance variation between the microdisplays. As discussed in section 6, emissive type microdisplays have a fixed colour gamut whereas LCOS and LCD microdisplay have no native colour gamut or luminance (assuming they do not employ colour filters). Rather, the colour gamut is dependent on the illumination source and is therefore adjustable. It follows that an LCOS or LCD microdisplay may be a more applicable solution to a tiled type NTE display than an emissive type to negate the artefact issue of colour and luminance variation.

4. Pixel Fill Factor
Pixel fill factor (or aperture ratio) is an easily definable parameter for microdisplays and is a fundamental differentiator between technologies.

All microdisplay technologies strive for as high a fill factor as possible. Whether the colour is generated by sub-pixels or by colour field sequential techniques, the demand and need is to fill the pixel with as much colour as possible. The greater the fill factor of a display, the less distracting the visible structure of the inter pixel gaps becomes, which can detract from the sense of immersion.

For LCOS type microdisplays, all the pixel circuitry is located behind the pixel and does not interfere with the optical pathway. Therefore, the whole pixel is used in the creation of colour. This should be considered in comparison to microdisplay technologies which use sub-pixilation to achieve colour, as these only achieve 20 to 25% coverage of a single colour per pixel. The diagram in figure 1 demonstrates these differences.

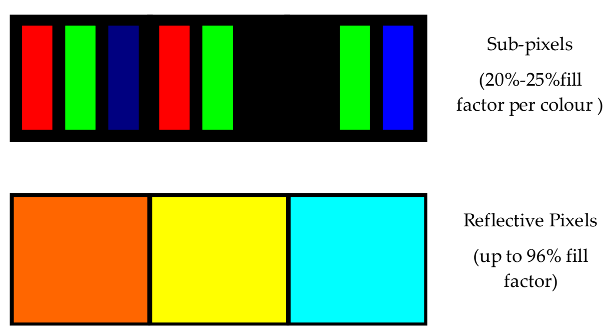

Figure 1: Pixel Fill factor

The high fill factor of the LCOS microdisplay is clearly shown in the image in figure 2, which is the magnified image of a 34x26 pixel area (note that this is only 0.07% of an SXGA resolution FLC LCOS microdisplay).

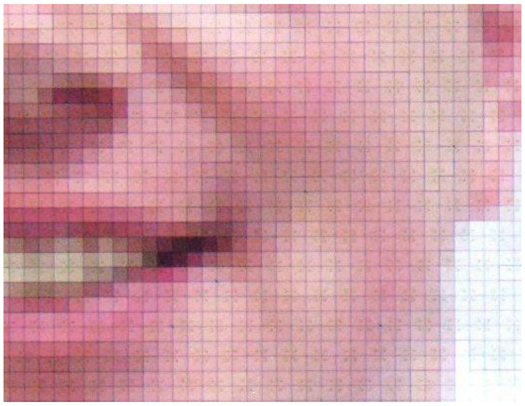

Figure 2: Magnified image of a section of an SXGA resolution FLC LCOS microdisplay

5. Field of View

The previous three sections have discussed points which are important to the NTE display and can be brought together when considering one of the main criteria for high end immersive HMD systems, namely field of view.

Close to (or as near as possible to) reality is a goal of all high end gaming and training and simulation virtual reality NTE systems. The reason FOV is important to immersive HMDs is that the closer the FOV and spatial resolution is to the HVS, the more immersive the user will find the experience. Examples of the field of view of two leading high end head mounted displays versus the HVS FOV are illustrated in figure 2.

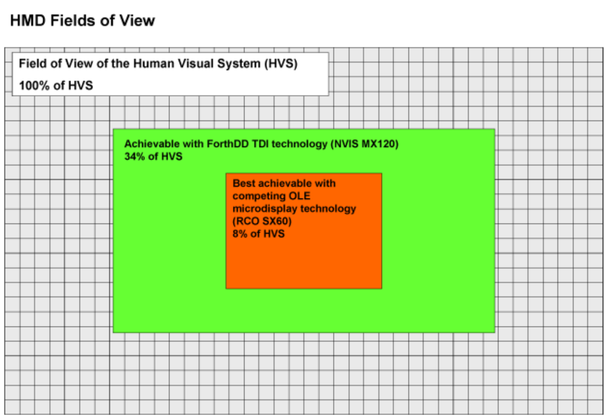

Figure 3: HMD FOV vs. HVS FOV

To achieve a high performing HMD with wide FOV, a high resolution, high fill factor display coupled with scalable illumination must be designed into the final solution.

An emissive display may not be capable of offering sufficient luminance when projected onto a virtual image with greater than 60^{o} diagonal FOV. However, as previously discussed, tiling can offer a solution, albeit with know optical artifacts.

Similarly, when using a large FOV, the gaps between pixels can become viewable and the "screen door effect" reduces the optical performance. Further to this, the colours in a sub-pixilated microdisplay can become separated and de-pixelisation films and diffusers may be required in the optical pathway to remove this effect. This would reduce the luminance and ultimately reduce the resolution by introducing a blurring effect.

6. Colour Gamut

The colour gamut achievable on a microdisplay is an essential consideration for virtual reality applications so that accurate rendering of images is achieved. Microdisplays which are emissive or use sub-pixels with colour filters for colour generation have a fixed colour gamut, often much less than the NTSC gamut. LCOS microdisplays with separate illumination sources have user selectable colour gamuts and white points which can be changed as per the end application. Therefore, the fidelity of the reflective microdisplay is higher than the sub-pixilated types due to the matched colour gamut. This is a desirable goal for immersive HMDs as well as for electronic viewfinders (EVF) which are replacing optical viewfinders (OVF). An example of OVF replacement is in the cinematography industry where OVFs associated with film based cameras are progressively being replaced with EVFs associated with digital cameras.

An example CIE 1931 chart showing NTSC and HDTV colour spaces are shown in figure 4. Also shown is the measured colour space for a LCOS microdisplay which uses a leading off-the-shelf illumination source (Osram O-Star).

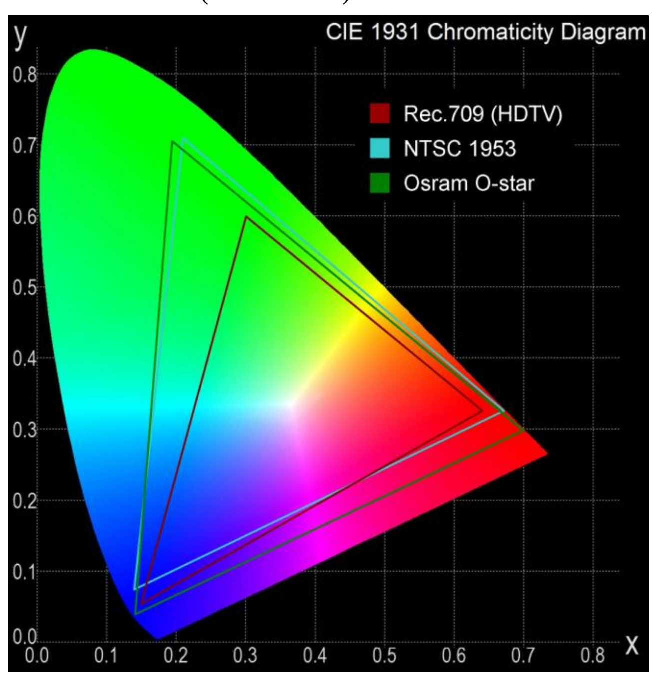

Figure 4: CIE 1931 chart

Also, wide colour gamut displays (greater that Rec. 709 for example) can produce more natural and preferred image reproduction than by displays limited to Rec. 709 or less [2], as Rec. 709 does not cover all colours occurring in nature

7. Flicker

Flicker is an image quality issue which is often seen on displays which have a persistence of image (such as the phosphor on cathode ray tubes) or on microdisplays which gate the illumination to create grayscale and colour. The magnitude of flicker is a function of the frequency, duty cycle and amplitude variation (difference between illuminated and non-illuminated periods) of the illumination for these latter "flicker susceptible" microdisplays. The visibility of flicker is further complicated by the variation in observers' sensitivity to flicker [3].

Microdisplays which split the illumination into very small, sub millisecond pulses are known to show little or no flicker, especially when a refresh rate above 60Hz is in operation. Only reflective microdisplays which use a ferroelectric liquid crystal (FLC) are capable of higher refresh rates as the FLC is the only type of liquid crystal available which can switch fast enough to show more than 6 sharply definable colour fields per frame. By showing 24 accurate colour fields at a refresh greater than 60Hz, each with field a maximum of the 500 microseconds in length, the gating of the illumination is so swift that the flicker effect is reduced to near zero.

Where no gating of illumination exists, specifically in LCD and OLED display systems, no flicker occurs. These solutions are therefore easily used for long periods of time where flicker can influence viewing comfort.

8. Image Smear

In a similar mechanism to the aforementioned flicker, image smear is not seen on FLC LCOS. FLC switching speeds are in the order of 40 microseconds and each colour field used to create colour and grayscale are accurately defined and therefore grayscale production is not affected by liquid crystal switching speed. This slow switching leads to a reduction in image reproduction accuracy [4] and will have serious implications for high end NTE applications such as fast-jet flight simulation.

One method of counter acting this is the so called "black frame insertion" where illumination is switched off for part of the video frame thereby creating distinct black periods in the image rendering which reduces the sample and hold artefact. This is now finding favour in consumer display applications and has been part of the image smear deterrent in FLC LCOS displays since their conception.

9. Colour Break-Up

It would be incorrect to mention motion blur and flicker without addressing the image artifact colour break-up (CBU). CBU can occur when a field sequential colour (FSC) generation method is used, as is often associated with LCOS display solutions in NTE applications. Red, green and blue illumination flashes are separated in time to generate full colour and the observer may track their eye across a microdisplay "catching" the separate colour fields which are therefore not integrated correctly by the eye to produce the intended colour. This observation of the separate primaries results in the "rainbow effect" of CBU.

Again, similar to flicker, it has been proposed that increasing the frame frequency is the most obvious way to reduce CBU[5]; however, this is limited by the incoming video refresh rate and ability of the microdisplay to switch fast enough between primary colour fields without influencing the next frame due to slow switching speed (thereby reducing grayscale accuracy).

A further reduction in CBU can be achieved by reducing the colour field on time to an absolute minimum whilst maintaining proportionality of each colour to ensure correct colour reproduction. Here, individual colour fields could be so short that the effect would be similar to increasing the frame frequency (as long as the colours are shown in the same section of the frame) but can be achieved without the difficulty of increasing the incoming video refresh rate. This de-coupling of colour field on-time with the incoming refresh rate has resulted in some FLC based LCOS microdisplays having reduced CBU over other LCOS technologies.

Note that the reduction in the on-time has effects to the duty cycle and this reduces system luminance. However, as the illumination is scalable for LCOS displays, reduced duty cycle can be countered by increasing the output of the illumination source.

Finally for CBU, the visibility is often further complicated by the variation in observer's sensitivity to the effect.

10. Conclusion

A number of metrics have been discussed which should be considered when choosing which microdisplay is correct for HMD and NTE systems, for applications which include 3D gaming and military training and simulation.

It is clear that high fidelity is achieved in a NTE system via a number of parameters and not one in particular (such as resolution, fill factor, colour balance, no image smear and low flicker). The table below summarises the performance of different types of microdisplay for the parameters considered:

Parameter	FLC LCOS	AMLCD	OLED	LCOS
Resolution	SXGA	XGA	SXGA	WXGA
Scalable Illumination	Yes	Yes	No	Yes
Pixel Fill Factor	Very high	Low	Low	High
Colour Gamut	Customisable	Fixed	Fixed	Customisable
Flicker	Low	None	None	High
Image Smear	None	Yes	No	Yes
Colour Break-Up	Low	None	None	High

11. Acknowledgements

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12. References

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