Screen door effect reduction using mechanical shifting for virtual reality displays

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ABSTRACT

The Screen Door Effect (SDE) is a common complaint amongst users of Virtual Reality (VR) headsets. SDE is characterized by a mesh-like artifact, much like looking through a screen door, on an image due to the space between pixels having a large enough angular size to be resolved through the viewing optics. Current generation VR displays exhibit SDE, distracting the user and breaking immersion. There are solutions currently in use in commercial VR headsets that reduce SDE in the form of dispersive elements placed in front of the display that effectively blur images from the display. However, these solutions only reduce the SDE, and functionally the blur is equivalent to reducing the quality of the optical stack. A method of image enhancement is to "shake" the display using piezo actuators, effectively shifting the pixels to enhance the image. This method can increase the apparent size of the pixels, reducing the gaps between pixels and leading to a reduction of SDE. In this paper, we will explore the limits of SDE reduction using this pixel shifting method with a square pixel architecture on a 9.4 µm pixel pitch RGBW display, and how that generalizes to other display architectures. We will find how different stimuli change with screen door reduction, analyzing solid color, text, and natural scenes. We will also explore what parameters to use in order to minimize SDE, adding to the other benefits of this solution and generalizing the parameters to all displays.

Keywords: Screen door, Screen door effect, Displays, Virtual Reality

1. INTRODUCTION

1.1 What is the Screen Door Effect?

Put simply, the screen door effect (SDE) describes the ability to resolve the gaps between pixels. When looking at an image with SDE, the image appears as though it has been placed behind a screen door, hence the name. Placing a magnifier to a computer or phone screen, or getting uncomfortably close to such screens effectively showcases the phenomenon. Early projectors and rear-projection LCD TVs suffered from SDE due to the image-transferring optics having a pixel density that does not match that of the projected image while also magnifying the gaps, causing the meshed look.[1]

SDE is a commonly complained about problem in VR. VR headsets display SDE because of the fill factor of sources on the display coupled with ever-increasing quality of VR optics, magnifying the gaps between pixels and subpixels. The visibility of the gaps between pixels breaks immersion for users and causes a reduction in image quality. Current and future virtual reality headsets face this problem: the first Oculus Rift, first HTC Vive, and the PSVR all suffer from SDE. Current Oculus Quest headsets also show screen door. One solution to this problem includes the use of diffraction gratings, which effectively reduces the image quality gained from better VR optics and introduces a trade-off between the amount of SDE and image quality.[2]

The goal of this paper is to quantify screen door to set a metric for reducing SDE using mechanical pixel shifting.

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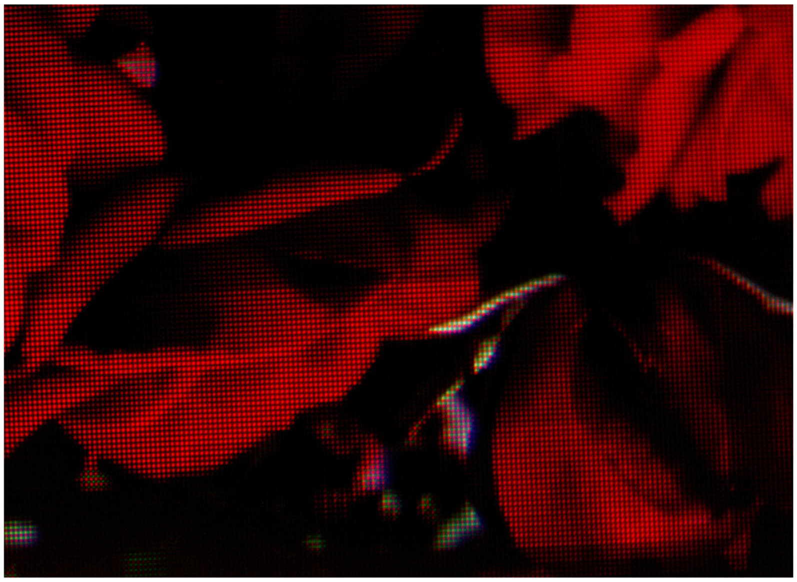


Figure 1. An image taken of a micro OLED display with SDE prominent.

2. SYSTEM ARCHITECTURE

2.1 How do we reduce screen door?

The idea of shifting pixels for better image quality has been explored before. Hewlett-Packard used a method of subframe shifting to increase image resolutions from SLM projection systems, known as "Wobulation". The data in any given frame is taken and split into subframes that are projected rapidly in a sequence of shifts that are shifted slightly from one another to increase detail.[3] This method also had the benefit of mitigating pixel fill factor issues, namely screen door. Thus shifting a single pixel should also lend itself to the reduction of SDE.

2.1.1 The display

The main display used for this paper is a micro OLED display with a RGBW pixel architecture. The pixel pitch of the display is 9.4 µm x 9.4 µm, with the subpixel pitch being 4.7 µm x 4.7 µm (Fig. 2). Only a 640 x 120 pixel portion of the display is used to achieve a 480 Hz refresh rate for test images.

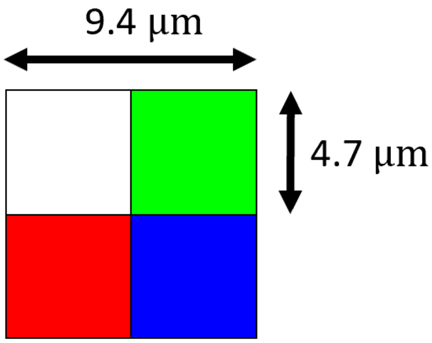


Figure 2. The subpixel structure of a single pixel on the micro OLED display.

Shifting the pixels mechanically will cause the pixels to smear, filling the gaps between pixels contributing to SDE. Controlling the shift diameter, coupled with controlling the refresh rate of the display, is what leads to reduction of SDE. For example, with the micro OLED display a single pixel can be shifted in a circle at a rate of 120 Hz with a display refresh rate of 480 Hz. This results in that single pixel appearing to contribute to four locations during the circle shift (Fig. 3).

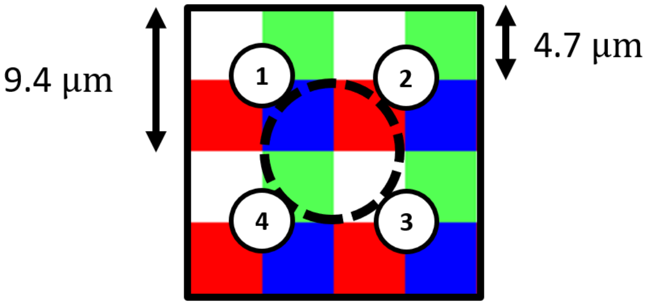


Figure 3. Example of a full pixel pitch circularly shifted and appearing to contribute to four locations, including the pixel's start location.

For this project, the circle shift diameter was limited to ten microns, which is just larger than the pixel pitch of the display.

Pixel shifting is not limited to a circular shape. Indeed, an elliptical path or even a figure-eight path could be used by controlling the amplitude of each axis' movement. Paths can be traced in many ways to explore screen door reduction. For the micro OLED display, a circular path was well-suited to the square pixel and sub-pixel layouts. This path is used to balance the length of the path with the fill factor, minimizing the speed the actuators must operate at.

2.1.2 Pixel path

Non-Redundancy uses a single image, which can be displayed as multiple identical subframes or as a single frame with 100% duty cycle. The Non-Redundancy mode in this paper used four subframes, causing the pixel to appear in four different locations during a single rotation. The pixel trace looks like four smeared arcs in a circle.

Redundancy is a more complex driving scheme. Not only is the display being shifted, the image itself is converted into four unique subframes, with each subframe shifted from the original to compensate for the display shift. The trace of this shift appears to be a curved x-shape, with the arcs tracing as if they originated from the pixel center.

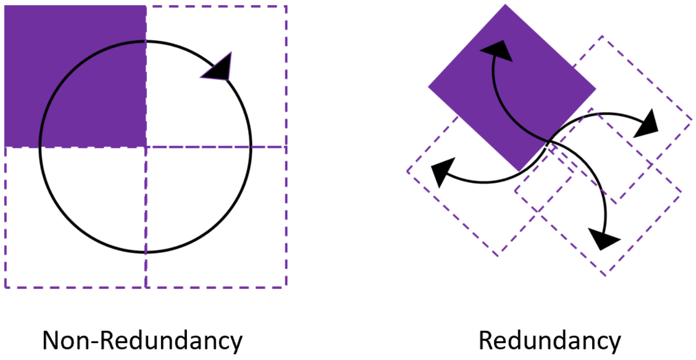


Figure 4. Non-Redundancy pixel trace (left), and Redundancy pixel trace (right).

2.2 Mechanical design

A custom parallel kinematic XY translation stage was used to physically move the display in a circularly oscillating motion within a small package size (Fig. 5). The stage was designed to achieve a travel of 10 µm of travel in X and Y to produce

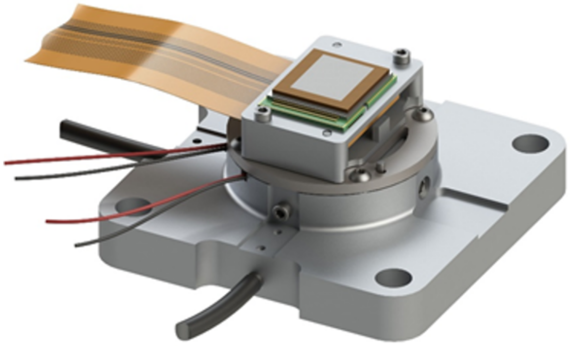


Figure 5. The prototype stage for shifting the display.

a circular translation motion profile moving at 120 Hz without rotation. The achieved repeatability of the motion path was a small fraction of the desired ∼300 nm path repeatability tolerance.

The stage was actuated by two piezoelectric stack actuators; one for the x-axis and one for the y-axis. The displacement of each piezoelectric actuator was amplified through a titanium scissor-jack style strain-amplification sub-assembly to achieve the necessary travel of one pixel pitch on the display. Each axis's actuation sub-assembly then acted upon a center column through low-friction alumina contacts that allowed sliding translation transversely between the two axes to reduce over-constraint and reduce potential angular error. The piezoelectric actuation sub-assemblies were then preloaded from the other side of the column for each axis using compression springs and set screws for adjustability (Fig. 6).

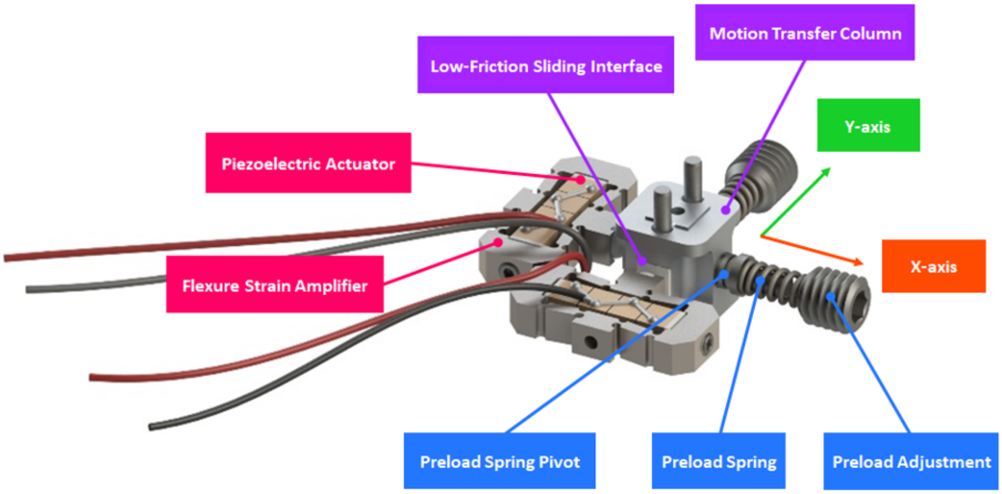


Figure 6. Detailed view of the piezoelectric stack subassembly.

The output motion from the two strain-amplified piezoelectric sub-assemblies was then guided using a top and bottom titanium waffle flexure to increase rotational stiffness and improve the quality of motion. A capacitive sensor was used to measure the displacement of each axis and then used to adjust preload and close the loop for position control. The display was then mounted onto the mechanism, completing the mechanical assembly (Fig. 7).

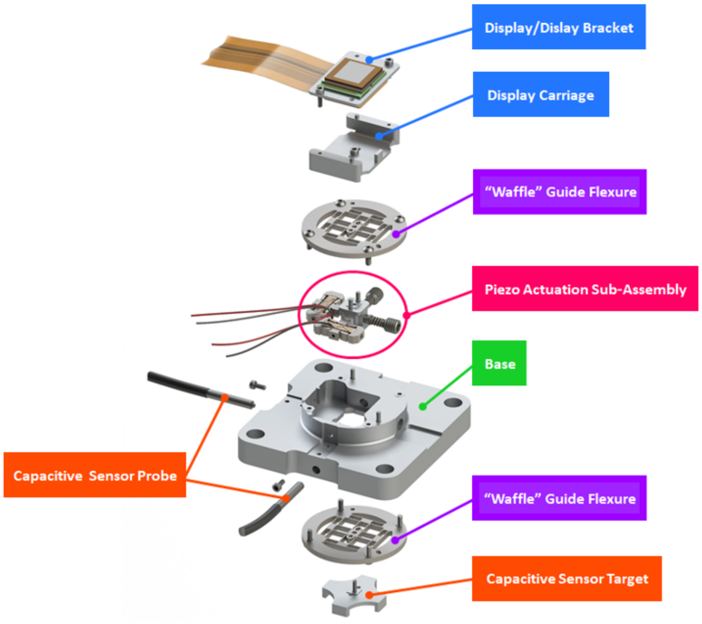


Figure 7. Detailed view of the entire mechanical assembly.

2.3 Electronic design

By default, the micro OLED display used for this paper operates in rolling shutter mode, with an update speed limited by a pixel line clock (60 Hz with all pixels in use). To achieve a refresh rate of 480 Hz, we limited the our test images to 120 horizontal lines. With four subframes, the observed full-frame refresh rate was 120 Hz, which is fast enough to prevent flicker in stationary scenes.

Rolling shutter display operation is incompatible with a constantly-moving display due to artifacts caused by different lines being shown at different times, and thus, incorrect relative locations. To operate the display in global shutter mode, custom electronics were designed to keep the cathode voltage off while waiting for the subframe data to be loaded onto the display, and for the display to reach the appropriate location. Once the sub-frame is fully loaded and the display reaches the correct position, the cathode voltage is turned on for a period of time, displaying the entire image. Once the cathode voltage is turned back off, the next sub-frame begins to load.

The 'on' duration for the subframes is set by the operator and can be changed during operation, with a longer duration creating a brighter image. The normal subframe duration is approximately 200 µs, corresponding to a 10% duty cycle. The subframe rise and fall time caused by turning the cathode on and off was measured to be less than 10 ns, which is negligible compared to the subframe 'on' time and is not a source of artifacts.

3. QUANTIFYING SCREEN DOOR

There are multiple stimuli that could be used to try to quantify screen door. Monochrome screens, for example, should be smooth and uninterrupted. If the screen door effect were to affect a swath of solid color, that would break user engagement and lower image quality for the user. Text is another example; the more disjointed text is, the more difficult it may be to read. Lastly, an important stimuli would be a natural scene, as users would have more enjoyable and immersive experiences when natural scenes look, simply put, natural. Gaps causing jarring contrast in objects in a scene would also reduce image quality and the effect of the overall VR experience.

3.1 Quantifying a threshold

A threshold for where the gaps between pixels begin and end would be useful in characterization. To establish a threshold, images of the pixels were taken and measured with camera software. Two definitions were tested: the full width half maximum (FWHM) definition and the 1/e definition. The gap was indistinguishable with the 1/e definition as shown in the line trace taken across two pixels. The FWHM definition gave a gap measurement of 3.7 µm, which does not match visual observation. The subpixels should measure close to 4.7 µm, and while the FWHM line data gives a gap almost the same size as a subpixel, the gap on the image is not at all near the same size as a subpixel (Fig. 8).

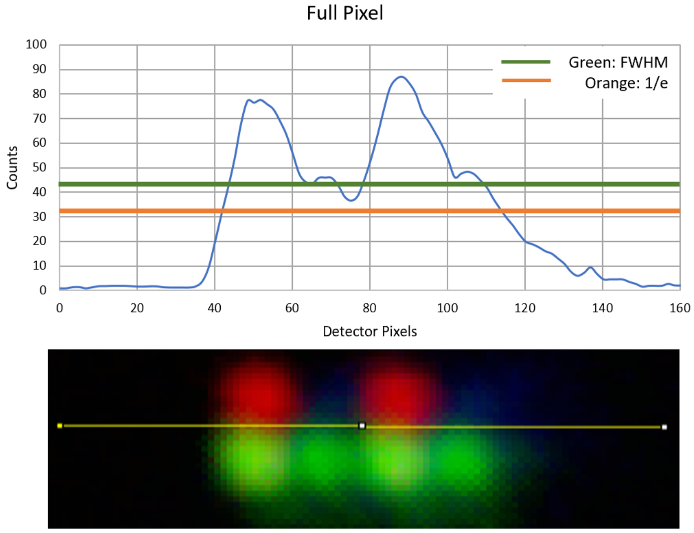


Figure 8. Line measurement taken of two pixels.

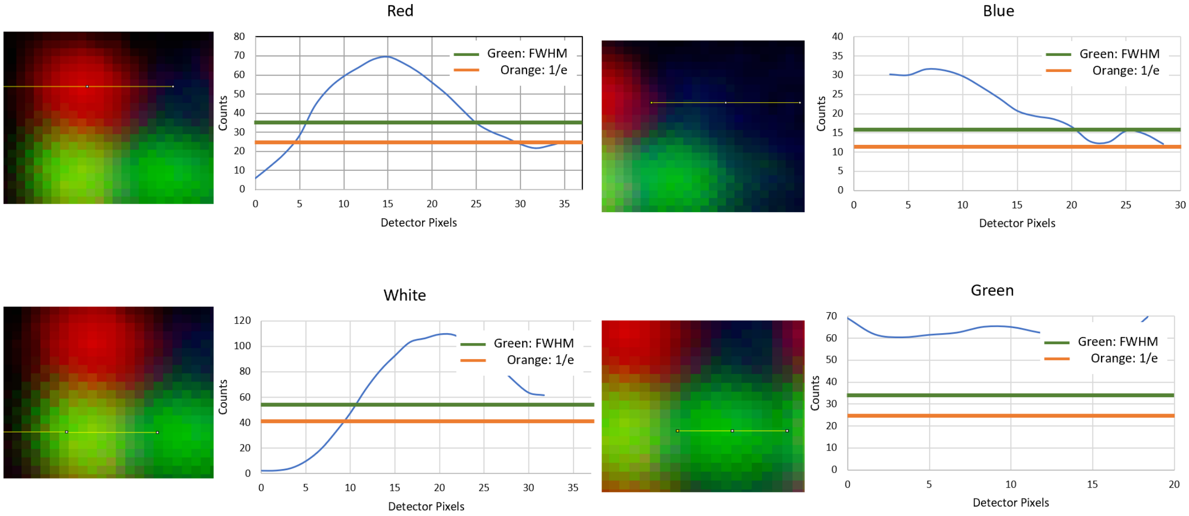


Figure 9. Subpixel line measurements. Green, white, and blue show pixel bleed that invalidates the use of FWHM or 1/e as definitions for a subpixel baseline.

Trying to find a subpixel baseline proved difficult as well, as the resolution of the camera was not fine enough to prevent the bleed of the brighter subpixels into the darker subpixels. For the darker subpixels, no clear line could be drawn to differentiate the borders around them, and neither the FWHM definition nor the 1/e definition could be used to define them (Fig. 9).

A different method must be used to quantify screen door. It is important to note that human perception of the display may not match that of the camera and that brighter sources can look larger to the human eye. Reducing the exposure or gain on the camera to reduce subpixel bleed will not necessarily result in a measurement that more accurately represents the appearance of the gaps between pixels or subpixels.

3.2 Monochrome screens

Using a microscope and camera with measurement software, line contrast data was taken for red, green, blue, and full white screens with and without screen door reduction in Non-Redundancy and Redundancy modes. Images were also taken at different magnifications. For each combination of parameters, five lines of data were taken and the maximum and minimum brightnesses were averaged separately to calculate an average contrast ratio.

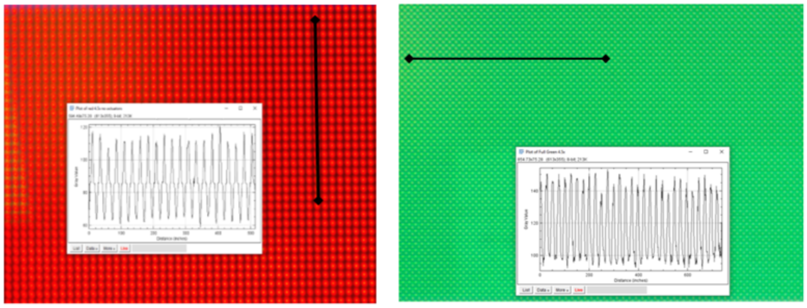
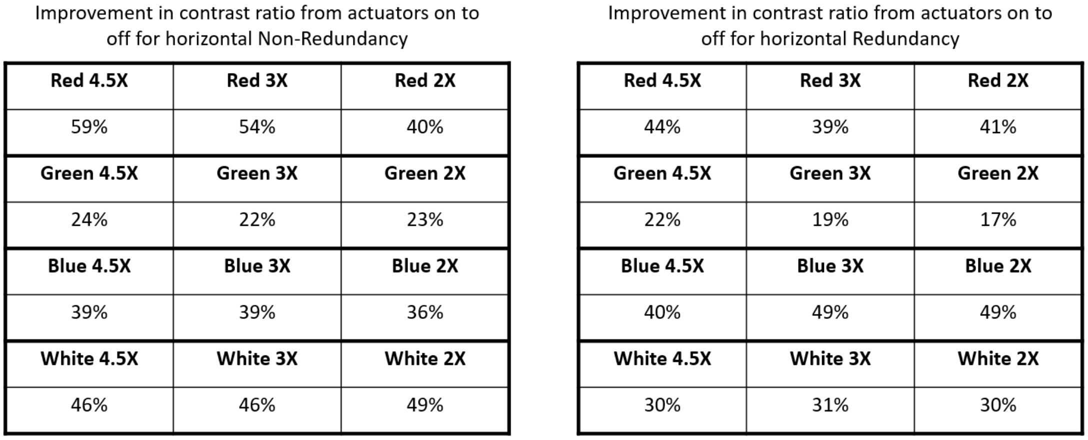


Figure 10. Examples of the methodology used for finding line contrast for monochrome screens.

For monochrome screens, a lower contrast implies the screen door effect is harder to see. As previously discussed, the camera images do not necessarily reflect what a human would observe, so these numbers are not a quantitative evaluation of screen door visibility; however, the numbers should provide an indication of the relative visibility of screen door under different conditions. The results show that, with pixel shifting active, the contrast decreases in all cases. In Fig. 11, average improvement in the contrast ratio with the actuators on and off is reported for Non-Redundancy and Redundancy. Only the horizontal line trace results are shown for brevity; the camera optics did result in an asymmetry between horizontal and vertical, but this did not affect the conclusions taken from the data.



Improvement in contrast ratio from actuators on to off for horizontal Non-Redundancy

Red 4.5X	**Red 3X**	**Red 2X**
59%	54%	40%
Green 4.5X	**Green 3X**	**Green 2X**
24%	22%	23%
Blue 4.5X	**Blue 3X**	**Blue 2X**
39%	39%	36%
White 4.5X	**White 3X**	**White 2X**
46%	46%	49%

Improvement in contrast ratio from actuators on to off for horizontal Redundancy

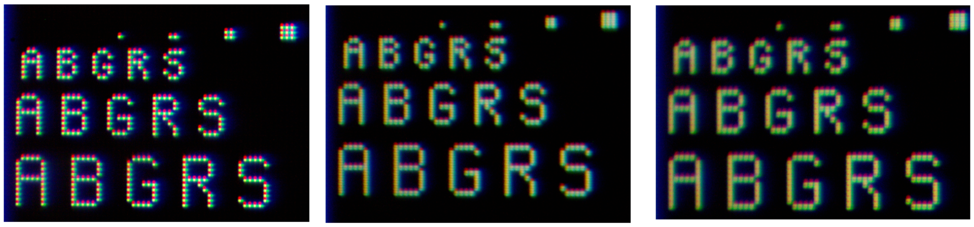
Red 4.5X	**Red 3X**	**Red 2X**
44%	39%	41%
Green 4.5X	**Green 3X**	**Green 2X**
22%	19%	17%
Blue 4.5X	**Blue 3X**	**Blue 2X**
40%	49%	49%
White 4.5X	**White 3X**	**White 2X**
30%	31%	30%

Figure 11. The average improvement in contrast ratio (the difference between actuators being off and then on) for both Non-Redundancy (left) and Redundancy (right) for several magnifications.

While monochrome screens were useful in demonstrating that pixel shifting should reduce screen door, this method does not lend itself well to quantification of SDE.

3.3 Text

What the monochrome screen contrast ratio cannot take into account is high spatial-frequency objects like text, where spurious dark lines may mask or be mistaken for real features. Screen door effect could cause problems in accurately identifying both individual letters and the separation between letters. Different sizes of text and different pixel shift diameters were used to attempt to qualify screen door through text for the display in the three test modes: Redundancy, Non-Redundancy, and No Actuators.



No Actuators 6.8 µm (72.3% pixel pitch) 7.2 µm (76.6% pixel pitch)

7.6 µm (80.8% pixel pitch) 8.4 µm (87.5% pixel pitch) 9.4 µm (100% pixel pitch)

Figure 12. Different pixel shift diameters for white text used in qualitative observation of screen door in Non-Redundancy mode.

First, observations were made with white text (Fig. 12). Even with strong SDE in the text with the screen door reduction off, the text was still readable and, arguably, not bothersome. Depending on personal preference, the text may be qualitatively better without SDE reduction. Objectively, for the individual pixels that make up each letter, connectivity of pixels is achieved for pixel shift diameter larger than approximately 80% of the pixel pitch.

Monochrome text becomes significantly more affected by screen door due to the subpixel structure. White text uses the full 9.4 µm pixel pitch as it uses up all four subpixels. For any single color like red, the gaps between each red pixel become larger than that of white pixels. Observation of the red text with the same pixel shift diameters showed a surprisingly similar result to the white text (Fig. 13). Screen door once more was not bothersome without screen door reduction, even with the enlarged gaps between pixels. A larger diameter is necessary to achieve connectivity between letters, at least 90%.

At 100% pixel shift diameter in Non-Redundancy mode, the circular path of each red subpixel results in a hollow circle visible in the center of the path at higher magnifications. Similarly, an X shape appears in Redundancy mode. These non-screen door artifacts should be taken into account when pixel shifting, meaning a balance must be struck between connectivity between pixels and the appearance of a new artifact when reducing screen door. The results of monochrome text suggest that artifacts may be visible in both Non-Redundancy and Redundancy mode due to the reduced fill factor when only one sub-pixel is lit. To completely eliminate gap-related artifacts, a different motion path would be required.

These initial observations suggest that text is not useful as a way to quantify screen door. Text is artificial, and in many cases is meant to look pixelated. It is possible that screen door reduction may be useful for some types of text, such as serif fonts or text that is scaled down below its intended resolution, but screen door reduction did not appear to improve the sans serif font used in this paper. This exploration did establish that a pixel shift diameter equal to roughly 90% of the pixel pitch will minimize artifacts on the display used in this paper.

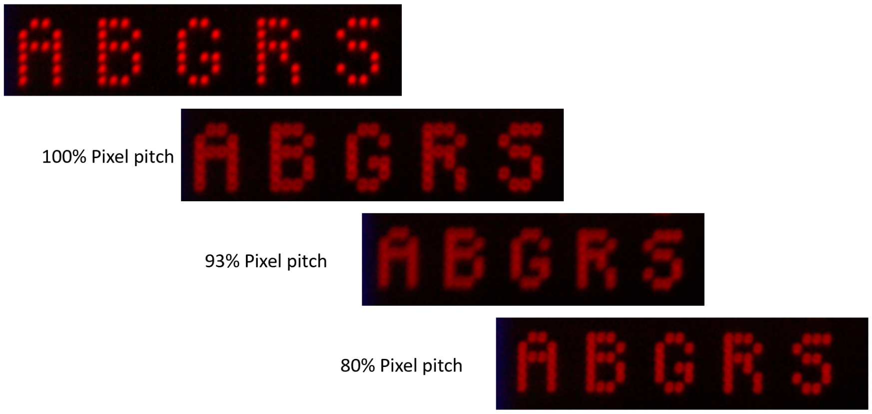


Figure 13. Red text observed with differing pixel shift diameters in Non-Redundancy mode.

3.4 Natural scenes

It is important for natural scenes to show minimal screen door effect to keep users immersed in content. Screen door can cause details of images to look unrealistic. Thus, testing screen door using natural scenes might be the way to best quantify the phenomenon.

Our proposed metric for screen door visibility is the difference in image magnification, when viewed through a stereo microscope, at which screen door or screen door reduction artifacts become noticeable with and without a visibility reduction technique. Our test conditions are Redundancy, Non-Redundancy, and No Actuators, and our test images are chosen to include features with a variety of colors, spatial frequencies, and categories of subject matter.

The test image of Cork, Ireland (Fig. 14) is used for three details: the high-frequency brick; the low-frequency sky; and the irregular, distinctive shape of the car. This variety of features is useful to test how different details and spatial frequencies are affected by the screen door reduction. The other test images are shown in Fig 15.

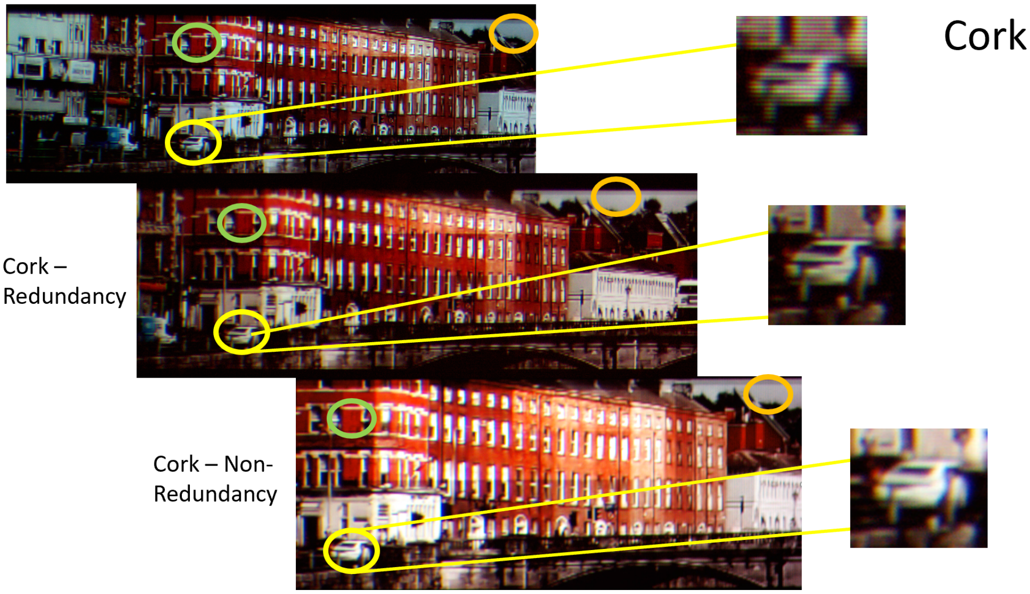


Figure 14. Test image of Cork, Ireland in the three test conditions. From top to bottom: No Actuators, Redundancy, and Non-Redundancy. Three distinct features are circled, and a magnified view of one of these features is shown for each test condition.

Figure 15. Three test images depicting a variety of natural scenes.

Upon visual inspection of specific regions of these test images, artifacts in the Redundancy condition generally became noticeable at magnifications roughly 33% greater than in the No Actuators condition, and artifacts in the Non-Redundancy condition generally became noticeable at magnifications roughly 60% greater than in the No Actuators condition. While not a controlled study, these preliminary observations suggest that screen door reduction through mechanical motion could allow gaps between pixels on VR displays to be significantly larger without causing noticeable artifacts.

4. GENERALIZING AND NEXT STEPS

4.1 Using an LCD

Another display panel was used to extend the results from the micro OLED microdisplay to other displays. This panel is a liquid-crystal display with a pixel pitch of 47.25 µm in a RGB vertical stripe layout. This LCD is continuously backlit; when observed during actuation at different frequencies, there were no obvious desync issues. As shown in Fig. 16, the vertical gap between white pixels is virtually nonexistent compared to the horizontal gap, but both the vertical and horizontal gaps are significant when only a single color is being displayed.

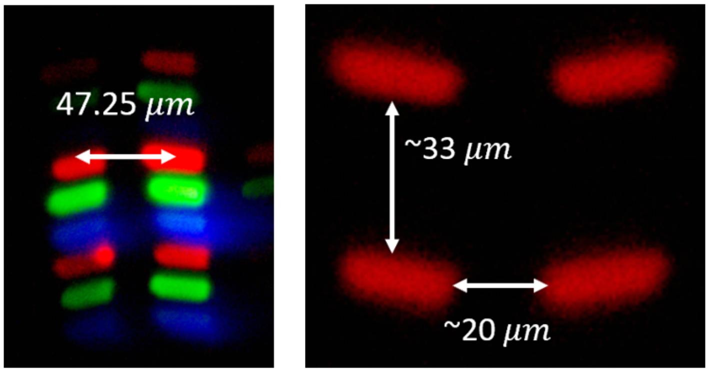


Figure 16. Close-up images of the LCD pixel architecture with measured dead space between pixels.

The LCD was tested on the same mechanical platform as the OLED, still with a maximum actuation distance of 10 microns. Although the LCD pixel pitch was several times larger than the actuator range, turning the actuators on still produced a minor, but noticeable, reduction in gap visibility at certain magnifications. The current architecture does not allow for a larger shift, but if the system were capable, a circle would not be the ideal path shape for this display; rather, an elliptical shift matching the maximum dead space of the monochromatic red subpixels would better reduce SDE for this display without significantly increasing path complexity.

4.2 Perception-based analysis

Our initial observations of screen door reduction in natural scenes suggest that a full user study would provide valuable quantification of SDE visibility and reduction for a given display. The study participants would begin at a display magnification low enough that SDE is not visible, and then gradually increase the magnification until they notice artifacts. This process would be repeated across each test image and screen door reduction mode to determine the efficacy of different solutions and how the displayed content changes the visibility of SDE and reduction artifacts. While this paper focuses on screen door reduction through mechanical motion of the display, this visibility reduction metric should apply to other screen door reduction methods, including optical diffusers and alternate pixel and sub-pixel layouts.

A perception-based analysis using Fourier techniques could be a useful addition to this experiment, as SDE is a periodic phenomenon. Fourier transforms of photos of natural scenes in the three test modes can be used in conjunction with human contrast sensitivity curves to extract the frequencies corresponding to the screen door effect and to predict whether subjects will be able to resolve the spatial frequencies corresponding to screen door at specific magnifications. This same approach could also be used to predict the visibility of any new artifacts introduced by screen door reduction. A Campbell-Robson grating can be used to define each subject's unique contrast sensitivity curve which can then be applied to Fourier data.[4] The Fourier-based artifact visibility predictions can be compared to the data from the direct observation study to determine whether Fourier analysis alone is sufficient to accurately predict the impact of artifacts such as screen door.

Future perceptual considerations include flicker and other spatio-temporal effects that may accompany normal VR use. Head movements, eye movements, and image movements are likely to cause artifacts that have not been taken into account in this study.

5. CONCLUSION

In using mechanical shifting of pixels for screen door reduction, the dead space of the display needs to be characterized to define the path shape and shift distance required of the mechanical shifting system. With appropriate application of mechanical motion, SDE can be qualitatively reduced. A promising method of screen door visibility quantification uses natural scenes and human subjects to determine the magnification at which SDE and screen door reduction artifacts become noticeable.

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REFERENCES

[1] Cho, J., Kim, Y., Jung, S., Shin, H., and Kim, T., "78-4: Screen door effect mitigation and its quantitative evaluation in vr display.," in [*SID Symp. Digest Tech. Papers*], **48**, 1154–1156 (2017).

[2] Sitter, B., Yang, J., Thielen, J., Naismith, N., and Lonergan, J., "78-3: Screen door effect reduction with diffractive film for virtual reality and augmented reality displays.," in [*SID Symp. Digest Tech. Papers*], **48**, 1150–1153 (2017).

[3] Allen, W. and Ulichney, R., "47.4: Invited paper: Wobulation: Doubling the addressed resolution of projection displays.," in [*SID Symp. Digest Tech. Papers*], **36**, 1514–1517 (2005).

[4] Campbell, F. and Marr, D., "The physics of visual perception.," in [*Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*], **290**, 5–9 (1980).