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The effects of source resolution on resolution enhancement through shifted superimposition projection

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Abstract

Resolution in a projected display is traditionally defined by the number of pixels in the projector's spatial light modulator (SLM). In recent years, different techniques that increase the resolution on the screen above the number of SLM pixels have gained popularity. In one such technique, called pixel-shifting or shifted-superimposition, the display physically shifts every n^{th} frame on the projected screen, and the overlapping pixel grids forms a finer subpixel grid with a higher pixel count.

There is still an open question how much this method increases the resolution and how to quantify it. The resolution on the screen also depends upon the resolution of the input image fed to the projector.

In this work, we experimentally investigate how the projector performs with resolution enhancement through pixel-shifting and how this method relates to the source resolution. We also investigate some known methods of resolution measurement and evaluate how these methods perform for the shifted-superimposition case.

We find that the resolution enhancement through shifted-superimposition enhances the resolution to about 40% over native resolution, and we also find two different measurement methods (grille contrast and least resolvable line pair method) that is relevant for effectively measuring resolution within such systems.

KEYWORDS

display measurements, image processing, image quality, projected display, resolution, superimposition

1 | INTRODUCTION

Resolution is one of the key performance parameters of a projector, and the projector industry continuously aims to increase it. Superimposition of projected images is a cost effective way of enhancing the resolution in a projector above the native resolution of the spatial light modulator (SLM). Superimposition may be implemented either with a multi-projector setup,[1] with an optomechanical system within a single projector,[2] or as a static optical setup within a single projector.[3] As long as a superimposition consists of two or more images superimposed on one projected surface, the resulting image will be an additive function of the projected images.

Since the market drives for 4K and 8K images and video, resolution enhancement techniques in displays have gained some momentum. High resolution SLMs are seldom cost effective, and not all technologies have modulators available with such a high pixel count. For these kind of modulator technologies, it is appealing to push the resolution above the native resolution of the SLM. Even though the actual pixel count on the projected screen will increase, the resolution enhancement method also introduces some artefacts in the image. Because the optical overlap of superimposed images acts like a low-pass filter, some high frequency content is lost in the image.[4] The spatial artefacts manifest as blurring in the image, and these artefacts impacts both the visual quality and the resolution measurements. The introduced artefacts raise the question of how high resolution is actually achieved, and which factors do impact this resulting resolution.

In a projected pixel-shifted display, every n^{th} frame is displaced on the wall with subpixel precision. The two most common shift configurations are either half a pixel in one diagonal[2] (two positions as in Figure 1), or half a pixel in both diagonals (four positions).[4] By shifting in the diagonals, we are producing a new grid of overlapping subpixels where all pixels are of equal size and shape.

Pixel-shifted displays challenge the traditional sense of resolution as this is a computational display and not a traditional display[5]. Each resulting subpixel is made up of the sum of the SLM pixels illuminating the resulting pixel, and each subframe is contributing to this. Because different subframes may include different details from the high-resolution source image, there will be more details present on the screen than the native resolution would be able to represent without the pixel-shifting technology.

For the different subframes to be able to display different details from the source image, the source image must be of higher resolution and therefore contain more details than the native SLM resolution. This means that the resolution of the source image will affect the amount of available details for the projector to generate subframe details and will therefore also affect the perceived resolution of the resulting superimposed image. While the increased perception of quality and resolution in shifted superimposition have been proved,[6,7] the actual resolution gain itself have not been established. In this work, we experimentally investigate the relationship between source resolution and resulting superimposed resolution, and also how the resulting superimposed resolution is to be faithfully measured.

The rest of the paper is organized as follows: section 2 presents different definitions of resolution and approaches to how one may measure the display resolution. Section 2.1 includes which methods we choose to use in this work and also how we set up the experiments. The measurements themselves are presented in section 2.2 and discussed in section 2.3. Finally, the last section concludes on how the source resolution affects the resulting resolution and how the selected measurement methods perform.

2 | RESOLUTION MEASUREMENT

Display resolution is in its simplest form is defined as the number of pixels in the display available to form a image. This definition applies to all traditional forms of displays, and in a projected display, the resolution would be the number of pixels in the SLM. There are at least two aspects of the display that challenge this simple definition of resolution: the quality of the pixels and the physical build of the pixels.

The quality of the pixels may be seen as the pixels ability to represent different details. In most displays, the pixels are not completely independent of each other and will in some form affect the pixels in near proximity with their own value.

This may for instance be as nonperfect optics in projected displays, backlight bleeding in LCD monitors, or as fringe field effects in LCD and liquid crystal on silicon (LCOS) displays.[8] All of these effects make the value of a pixel interfere with the appearance of the neighbour pixels. Shifted superimposition as a resolution enhancement method will add dependencies between some neighbour pixels because of the optical overlap of the pixels and also because the SLM pixels illuminate a larger area than one resulting pixel in the superimposed pixel grid.

The physical build and geometry of the pixels may also affect the perceived resolution of the displayed image. Projected displays usually have a uniform pixel grid where the colors are superimposed on each other within the same pixel grid. But other displays may have different pixel geometry, for instance flat panels with subpixel rendering where colors are adjacent to one another and arranged in a specific pattern. Even though each pixel in Figure 2 [9] is made up of a red, green and blue sub-pixel, those colored subpixels may be individually controlled to form different pixel pairs to increase the apparent resolution when needed.

These aspects illustrate the point of having a more thorough resolution definition than just the pixel-count. For a given display, it will give direct information to measure the different specifications of the display thereby also the resolution. By using the same measurement methods, it will then also be possible to compare the performance of different displays. There is currently no measurement standard that is agreed upon by all display manufacturers in all markets, but there have been several measurement standards proposed. The International Committee for Display

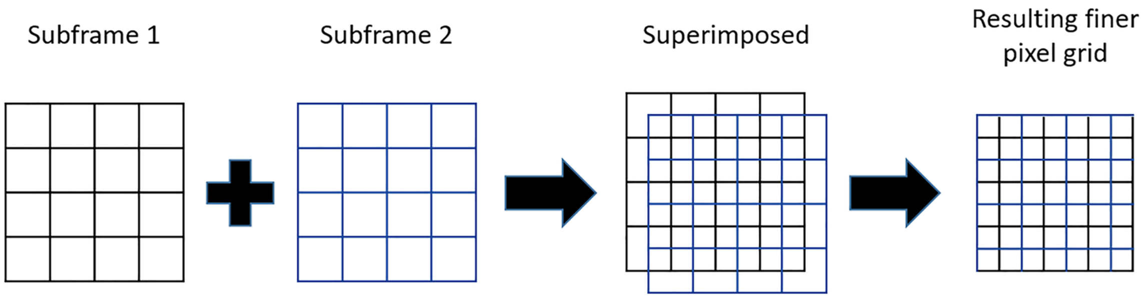

FIGURE 1 Subframe 1 and Subframe 2 shifted half a pixel diagonally from each other. The overlap results in a finer subpixel grid consisting of approximately twice the amount of pixels in both horizontal and vertical direction. The resulting finer pixel grid is illustrated at the far right with the edges trimmed off. In this illustration, we see that the new finer pixel grids have a pixel size of approximately a quarter of the original pixel size

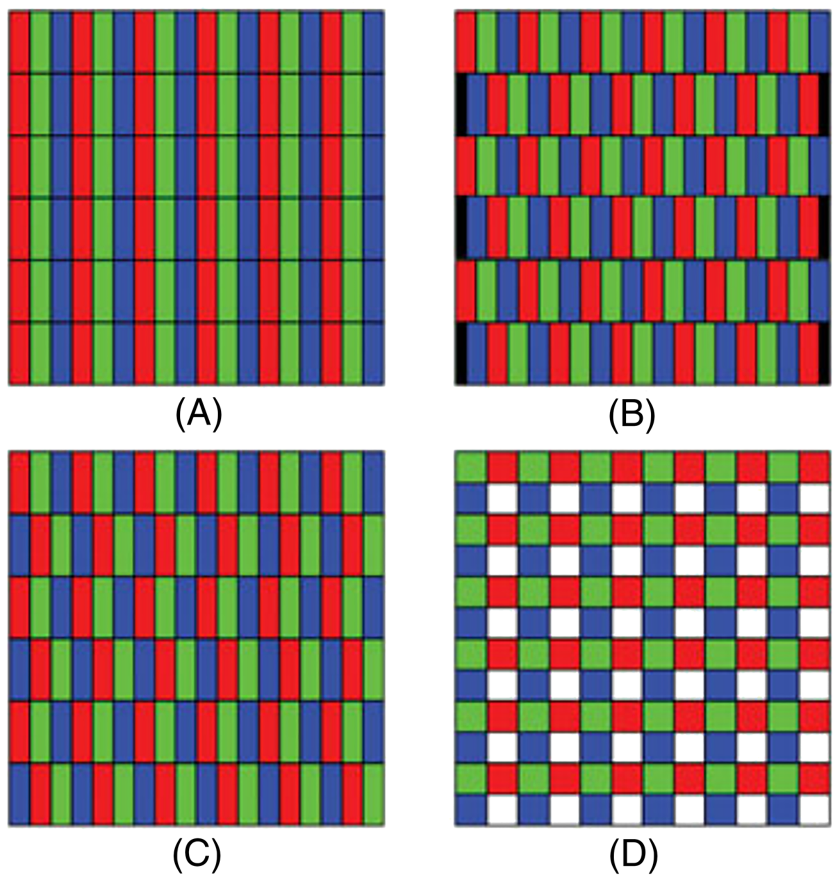

FIGURE 2 Examples of different pixel geometries in flat panel displays, and their sub-pixel placements. (a) RGB vertical stripe display, (b) RGB delta, (c) VPX (with three subpixels/pixels), and (d) VPW (with four subpixels/pixels).[9]

Metrology (ICDM) have included several proposals for spatial resolution measurement in the Information Display Measurements Standard (IDMS).[10]

2.1 | Least resolvable line pairs

The least resolvable line pairs measurement is an established method for determining resolution based on measuring a limited number of line pairs.[11] This is done by displaying an object in 3D-space consisting of a predetermined number of line pairs. The object is then pushed back in 3D space further and further away, apparently shrinking the line pairs. When the line pairs are at the limit where they are nearly not resolvable anymore, the physical size of the line pairs is measured. The size of the whole projected screen is then divided by the size of a single line pair. By doing these measurements both horizontally and vertically, the total resolvable resolution in the system may be obtained.

One major drawback with this method is that it is very prone to subjective biases and measuring errors. The action of establishing when the line pairs are at their resolvable limit is in itself very subjective. In addition to that, any inaccuracy when measuring the physical size of

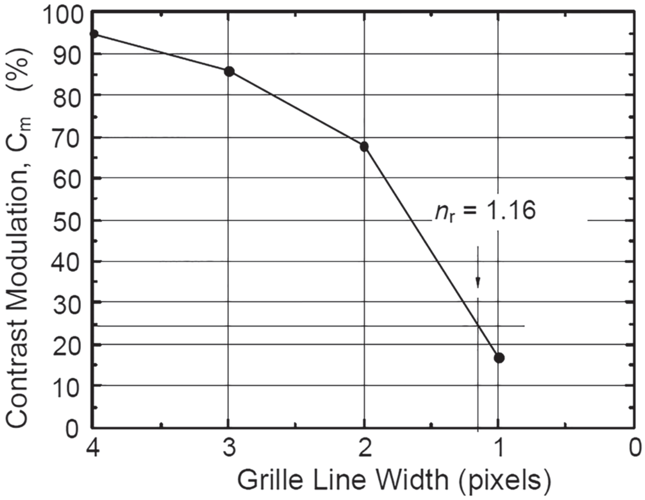

FIGURE 3 Contrast modulation example as shown in the Information Display Measurements Standard (IDMS) standard. Measurements are done with Grilles of 1, 2, 3 and 4 pixels width, while linear interpolation makes up the intermediate values

the line pairs may have a major impact on the total resolution number. Another trait of this method is that it is measuring the system performance of the image generator, the projected display, and the screen at the same time. This fact may be a feature for a system integrator, but for measuring the display itself, it introduces uncertainties.

Another drawback is that the results of this method will be dependant on the image generator. This could make this as a characterization method hard to compare objectively over different test sites and technologies. On the other hand, it is a good system-level resolution measurement method for fixed installations with in-system image generators. For these reasons, it is a method often applied in the simulation industry where the display is a fixed component in the system.

2.2 | Grille contrast modulation

The grille contrast modulation method is to measure the Michelson contrast with grille patterns (alternating black and white stripes) with different widths. The intermediate values between these points is extracted from linear interpolation between neighbour points as shown in Figure 3. This approach was proposed by The ICDM within the Society for Information Displays (SID) in 2012 when they released the IDMS.[10]

The contrast vs line pair curve gives an indication on what contrast the display is able to reproduce for different detail sizes. In this sense, the curve gives not only a resolution measurement, but also a quality factor to that given resolution. It is debatable what contrast factor that is really needed for different display applications. IDMS proposes that the display itself should have 50% contrast modulation for text applications and 25% contrast modula-

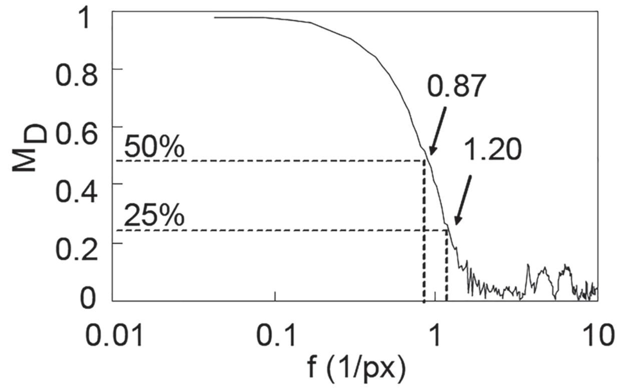

FIGURE 4 Spatial Frequency response example curve from Information Display Measurements Standard (IDMS). M_D is the frequency modulation for the display

tion for image applications. This means that the resolvable resolution at 25% contrast modulation is

$$ResolvableResolution = DisplayedResolution/n_r \quad (1)$$

In the example given in Figure 3, the calculated grill line width n_r is 1.16, making the resolvable resolution lower than the input resolution to the display with a factor of 1.16.

2.3 | Slanted edge measurement

The slanted edge method is to measure the spatial frequency response (SFR) as an approximation of the modulation transfer function (MTF). This method has become widely used within fields of optics, and has been adopted by multiple international standards within optics, including International Organization for Standardization (ISO) and Institute of Electrical and Electronics Engineers (IEEE). The slanted edge approach for displays is described in the IDMS chapter 7.7.[10]

In this method, we measure the luminance of vertical or horizontal step patterns on the display with a slightly tilted camera so that the sampled image captured by the CCD camera oversamples the slanted edge. The SFR is then calculated as described in chapter 7.7 of the IDMS to obtain the $M_D(f)$ curve. An example of such a curve is shown in Figure 4.

The SFR obtained by the slanted edge method give a continuous spectrum without the linear approximation as introduced by the Grille Contrast Modulation method. This means that the resolvable resolution numbers at 25 and 50% contrast modulation are calculated more precisely than those methods that use linear approximation between measured points.

For both the slanted edge method and the grille contrast method, there is an ongoing debate regarding the appropriate contrast modulation required for different applications. In the IDMS, 25 and 50% for images and text respectively is suggested as points of interest in the slanted edge method also.

3 | EXPERIMENTAL SETUP

In our experimental setup, we used a Barco F70-4 K pixel-shifted projector equipped with a Barco EN41 lens. This projector has a native Wide Quad Extended Graphics Array (WQXGA) (2560 by 1600 pixels) digital micromirror device (DMD) as an SLM and a pixel-shifting mode where every other frame is shifted half a pixel diagonally. To capture the test scenes, we used a Nikon D5100 SLM camera with a 23.6 × 15.6 mm 16.2 megapixel complementary metal-oxide-semiconductor (CMOS) sensor. The captured images was stored in Nikon's uncompressed raw format Nikon Electronic Format (NEF). The setup is shown in Figure 5.

One purpose of these tests is to explore the relationship between the source resolution and the resulting measured resolution. To this end, all of these experiments are performed for different source resolutions, starting at the native WQXGA resolution. Then the experiment is redone several times with steps of 10% increase in the source resolution all the way up to 120% over the native resolution.

3.1 | Line pair measurements

To perform the least resolvable line pair measurements, we used a regular PC as the source connected to the projector. On this PC, we had a program rendering a 3D object consisting of three black/white line pairs. This object could be moved back in 3D space to increase the distance between the viewpoint and the object thus also decreasing the size of the object on the screen. This will be viewed as the line pairs is shrinking all the way down to not being distinguishable anymore. The measurement setup was as illustrated in Figure 6A where there is an observer who determines if the line pairs are resolvable or not.

The experiment itself was performed as described in section 2.1. The object with the line pairs was moved away from the viewpoint until the three line pairs was not resolvable anymore. Then the object was moved towards the viewpoint one step again to make them resolvable. At this point, the physical size of the line pairs on the screen was measured. The total size of the projected surface was then divided upon the line pair size to calculate the number of line pairs that would fit within the projected area. This number is the measured resolution for this method at this given source resolution. The measurements in this paper is done by a single observer, who is a professional from the display industry.

The least resolvable line pair measurement is redone for source resolutions ranging from native SLM resolution up to 220% of the native SLM resolution.

3.2 | Grille contrast measurements

The grille contrast measurement experiment setup was per section 2.2. On the PC, we had a program rendering three black/white line pairs of controllable width, and we did the measurements with 1-, 2- , 3-, and 4-pixel-wide lines. Measurements were done using the camera and dcraw was used to convert raw image files to Description Tagged Image File Format (TIFF) format. The images were then filtered and analysed in MATLAB as described in IDMS chapter 7.2.

The measurement setup was as illustrated in Figure 6B where the camera is capturing the test scene.

3.3 | Slanted edge measurements

The slanted edge measurement experiment was setup as per section 2.3. On the PC, we had a program rendering a black/white step pattern. The measurements was done with the camera that we tilted 5 degrees relative to the edge of the step pattern. The raw image files were converted to TIFF images with dcraw before they were filtered and analysed in Matlab as described in IDMS chapter 7.7.

The measurement setup is the same as for the Grille contrast modulation method as illustrated in Figure 6B, but with a different test image displayed and with the camera tilted 5 as described in chapter 7.7 of the IDMS .

There are several commercial software solutions available for calculating the slanted edge response of an image, but we did not find any that suited this use case. The nature of the DMD makes the projected pixels very distinctive with dark gaps in between, and the available software solutions required a solid line edge to calculate the response. For this reason, we developed our own solution that took the distance between the pixels into account, and sampled one line for each pixel in the area of interest. Even though the shifted superimposition reduces the screen-door effect significantly, Figures 11 and 14 illustrates that the resulting subpixels also are distinguishable. So for calculating the slanted edge of the shifted superimposed scenes, we took the resulting pixelsize into account, which in this case is half the size of the projected DMD pixel of the native image in Figure 14A.

4 | RESULTS

4.1 | Least resolvable line pairs

The least resolvable line pair measurement was executed as described in chapter 2.1. In these measurements, the source resolution is set to WQXGA, the native resolution of the projector, and then increased in steps of 10 up to 120% over the native resolution.

FIGURE 5 Lab setup measuring the projected contrast with a camera

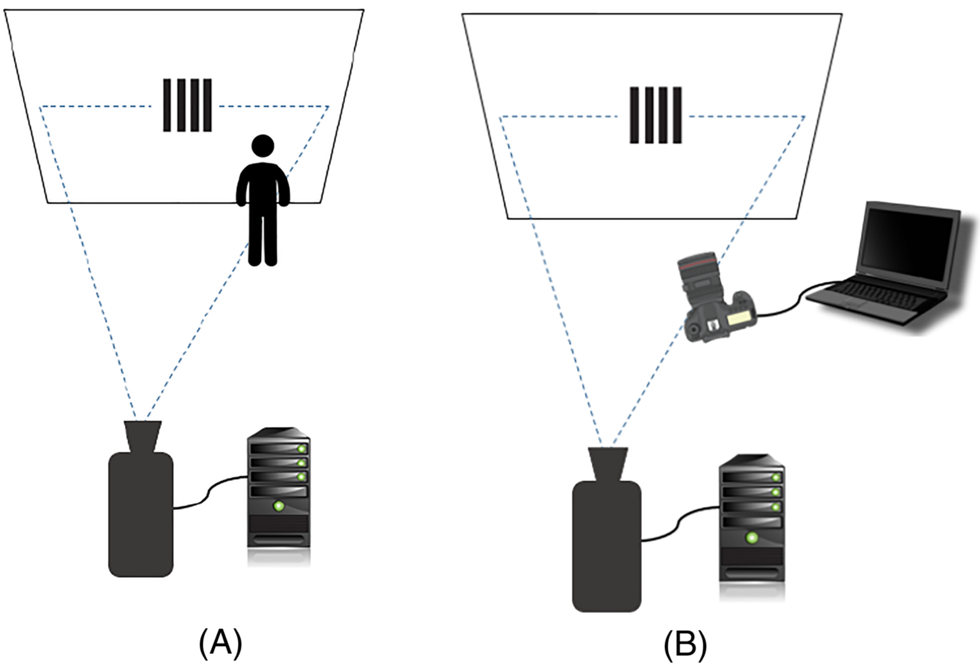

FIGURE 6 A, Test setup for the least resolvable line pair method. B, Test setup for the grille contrast and the slanted edge methods

Figure 7 illustrates four different measurements, where A and B show examples on resolvable line pairs, while C and D are not resolvable because two of the line pairs are melted together. The linepairs are deemed to be not resolvable anymore when it is not possible to discern a black line between two white pines or when the two of white lines build up to a single local maxima instead of two local maximas.

The results from the least resolvable line pairs measurements on all source resolutions is plotted in Figure 8. At the native resolution, the measured resolution is below the native resolution, and the measured resolution increases

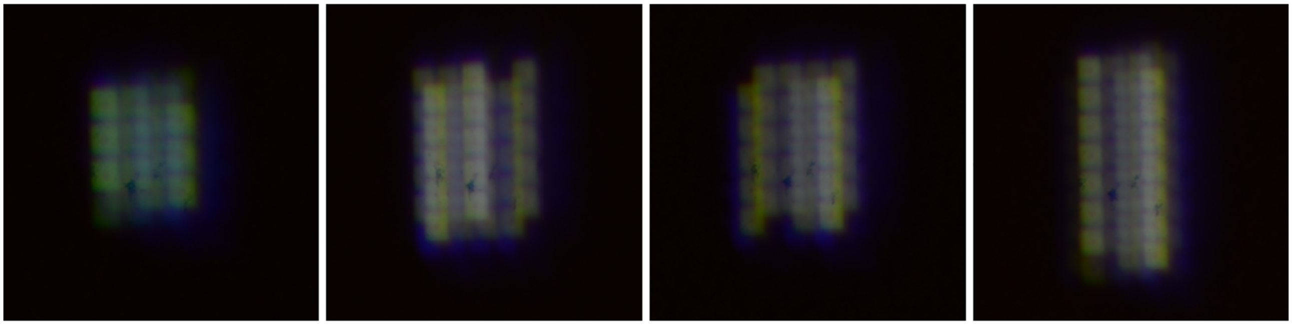

FIGURE 7 Results from least resolvable linepair test. Horizontal source resolution is A, 4352. B, 5120. C, 5376. D, 5632

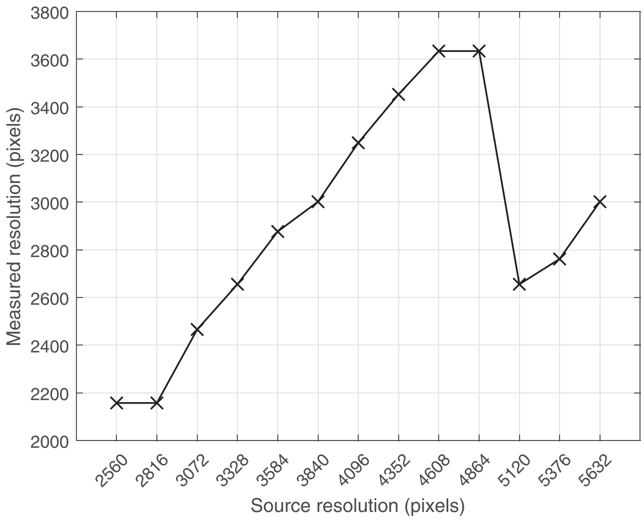

FIGURE 8 Horizontal measurement results from the least resolvable line pairs experiment on a pixel-shifted projector with WQXGA (2560) native resolution

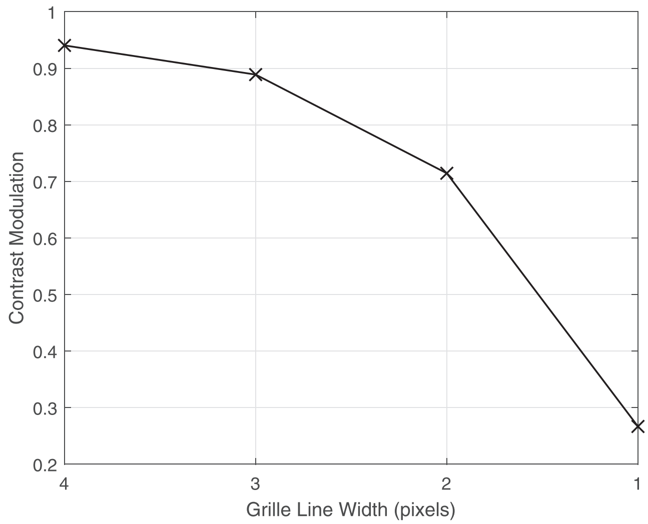

FIGURE 9 Grille contrast measurements for the source resolution 3328 × 2080

steadily until the measured resolution reaches about 40% above the native resolution.

When the source resolution reaches and goes beyond double the native resolution, the measured resolution drops down below the maximum measured resolution. This is because the regular nature of the subframe generation is to handle the process as a case of upscaling instead of downscaling.[12] Figure 1 illustrates that the resulting pixel grids resolution is doubled in both horizontal and vertical direction. Given the narrow nature of upscaling algorithms, it is natural that one may lose single pixel details when going above double the native resolution because the sampling grid of both the subframes combined will then possibly miss some single pixel details.

4.2 | Grille contrast

The grille contrast measurement was executed as described in section 3.2. In these measurements, the source resolution is set to WQXGA, the native resolution of the projector, and then increased in steps of 10 up to 120% over native resolution.

Figure 9 shows the grille contrast measurement for 3328 × 2080 (30% over native resolution), and such a measurement was obtained for all the given source resolutions. The usage of such a curve is to look at the intersection point between the desired contrast value and the contrast curve of the display.

According to the IDMS, a typical desired contrast value for displaying images is 25%, and extracting the measured resolution for 25% contrast value gives us the measured resolution curve shown in Figure 10.

The measured curve is monotonically increasing with input resolution equal the source resolution as long as the desired contrast is less than the measured contrast at grille1 (single pixel width line pairs). When the measured contrast at grille1 goes below the desired contrast, we start to go up the contrast curve, and n_r in Equation (1) goes up. This leads to the measured resolution dropping at that point such as at source resolution of 3580 in Figure 10.

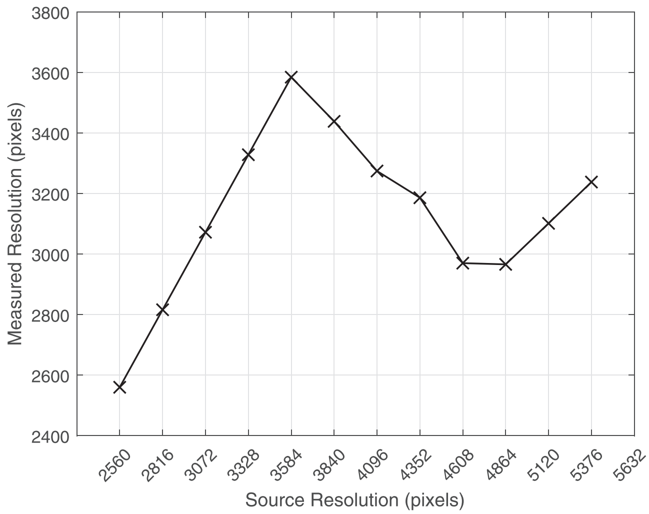

FIGURE 10 Resolution measurements versus source resolution, given 25% contrast

Because the source resolution grid and the SLM resolution grid do not match each other in even numbers, the source pixels may be represented by an uneven number of overlapping pixels in the projected image. This means that the line pairs will sometimes be unevenly represented, which again leads to uneven contrast measurement between the different line pairs as shown in Figure 11. When this occurs, the resolution measurement is open for interpretation because the different line pairs have different contrast ratios.

Figure 10 have used the biggest local line pair contrast while Figure 12 shows how the resolution measurements is when also using the smallest local line pair contrast instead. Figure 13 illustrates examples of different local contrast where Figure 13B have different contrast measurements for the line pairs while Figure 13C show that the first line pair is almost not detected.

4.3 | Slanted edge

The slanted edge measurement was executed as described in chapter 3.3. In these measurements, the source resolution is set to WQXGA, the native resolution of the projector, and then increased in steps of 10 up to 120% over native resolution.

As seen in Figure 14, the shifted edges are blurred because of the overlapping pixels; Figure 15 shows that the frequency response of the shifted images is lower than the native unshifted edge.

The slanted edge MTF curve of each measurement is calculated from the camera captured scenes, and the results of these is presented in Figure 15.

5 | DISCUSSION

Increasing source resolution gives more details in the source image to include in the subframes that makes up the resulting projected image on the screen. There are several different ways the subframes may be generated, but the subframes are always more than one frame and are always generated at the SLM resolution. So for the different subframes to have different information in them, the source resolution needs to be higher than the SLM resolution to provide enough details and information. Therefore, it is intuitive that higher source resolution also results in higher measured resolution.

But the shifted superimposition technique also has some physical limitations. The optical overlap of the pixels as shown in Figure 1 makes up the new and finer pixel grid, but it also illustrates that these new pixels are not independent of each other. Each resulting finer pixel in Figure 1 are made up of two overlapping SLM pixels from different subframes, and each of these SLM pixels are also influencing three other resulting pixels in the finer pixel grid. This dependency makes the optical overlap function as a low-pass filter, attenuating the highest frequencies of the resulting image.

These physical limitations ensure that even though the resulting resolution in the shifted superimposed image is increasing with increasing source resolution, there must be some limitations in how high resolution that may be obtained. When counting the resulting pixels in the new overlapping pixel grid shown in Figure 1, we see that the number of separable pixels have doubled in both horizontal and in vertical directions. But because of the inter-pixel dependency each of these new pixels are not independently controllable, and the low-pass filter behaviour of the optical overlap will attenuate the highest frequencies. These aspects affect the resulting resolution so that the ideal double resolution will not be fully achieved.

The high frequency attenuation should be measurable, so the method we use to measure the resolution will also have an impact on the measured result. The least resolvable line pair method makes use of subjective observations to see when the line pair is at the resolvable limit. The idea here is that the resolution represents the amount of separate distinguishable details, and to find this resolution number, we need to see how small details the display is able to reproduce. This procedure is well known in the industry and is widely adopted in some professional markets of projected display using the Johnson's criteria to design and verify their display systems.[11] The least resolvable line pair method is often used as a system resolution measurement rather than a display resolution measurement, but there is no reason not to use this method also as a pure display measurement. The results are dependant

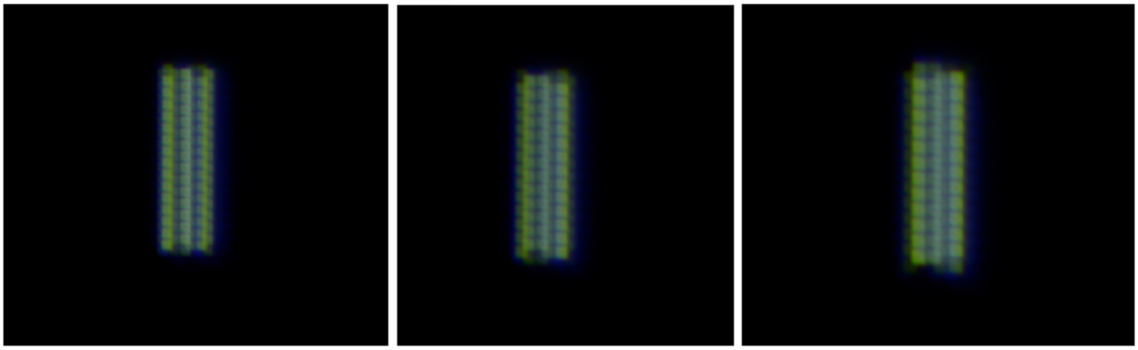

FIGURE 11 Images taken of the grille1 measurements for A, 3328. B, 3840. C, 4096

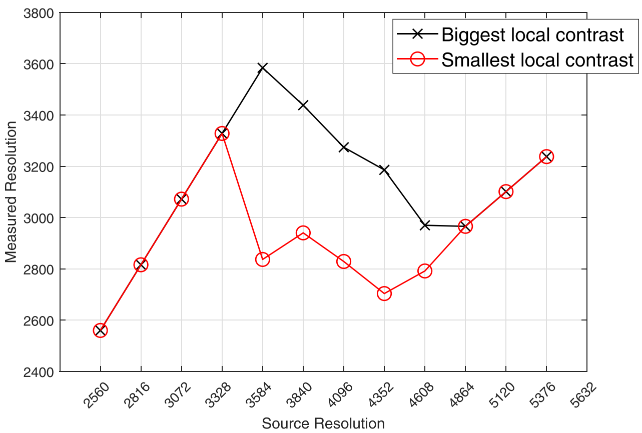

FIGURE 12 Resolution measurements versus source resolution, given 25% contrast. This figure illustrates both the best case measurement and the worst case measurement

on the performance of the source and the projected screen, but the same can be said for the results from the other measurement methods.

The grille contrast modulation measurements is straightforward and not as open to interpretation when the measurement results follow the criteria in the IDMS. But this method will be open for interpretation when the measured data behaves as shown in Figure 13B,C. The problem with the data in Figure 13B is that the line pairs have different contrast ratios, and the measurements will be heavily dependent on which of these contrast ratios is used. The reason for this difference in contrast is that the pixel grid of the resulting pixels shown in Figure 1 do not necessarily correlate to the pixel grid of the source resolution. In these instances, rows and columns of the source image will be represented by different geometric compositions in the resulting pixel grid, as evidenced by the different widths of the line pairs shown in Figure 11. In Figure 11B,C, we see that the line pairs have different widths, so the contrast measurements of these examples will be of the nature in Figure 13B. In these cases, it is not given which contrast to use, and the difference between using the best and the worst line pair contrast is illustrated in Figure 12. There is a significant difference in these resolution numbers, and it must be defined in such cases how to interpret the contrast measurements when the geometry of the line pairs are not consistent.

Figure 13C shows another interesting phenomena. When the source resolution is closing in on double the SLM resolution (and beyond), one may end up losing a whole line. This is because the source resolution goes above the resolution of the resulting pixel grid caused by the pixel overlap, which is double the SLM resolution in both horizontal and vertical direction. When the source resolution goes above this limit, there are more details represented in the source resolution than we have pixel elements on the projected screen. So some of these details will then be lost, and it is therefore possible to lose whole line pairs. The least resolvable line pair test will disqualify these results as one of the line pairs will be lost. But the grille contrast modulation method will still calculate a contrast ratio based on the remaining line pairs, and as we see in the measured resolution in Figure 12, the measured resolution actually goes up again at the higher resolutions even though we are starting to lose a line pair in the Grille measurements.

In Figure 11, we see three line pairs in both A, B, and C, so all of these examples would pass the least resolvable line pair test. In the grille contrast measurement however, both figure 11B,C fall below 25% contrast and would therefore not pass that measurement. This raises the question if 25% really is a wise choice or if the target contrast should be lower. In older applications, like CRT monitors for the professional market, the target contrast limit was set between 2 and 10%,[11] so the 25% target contrast may seem a bit too strict to measure the general resolution of a display. It is good to have a target contrast if you have a specific application that needs a given contrast to perform satisfactorily. But as a measurement for general resolution, this method disqualifies details that are perfectly distinguishable just because the contrast does not reach this tests desired contrast levels.

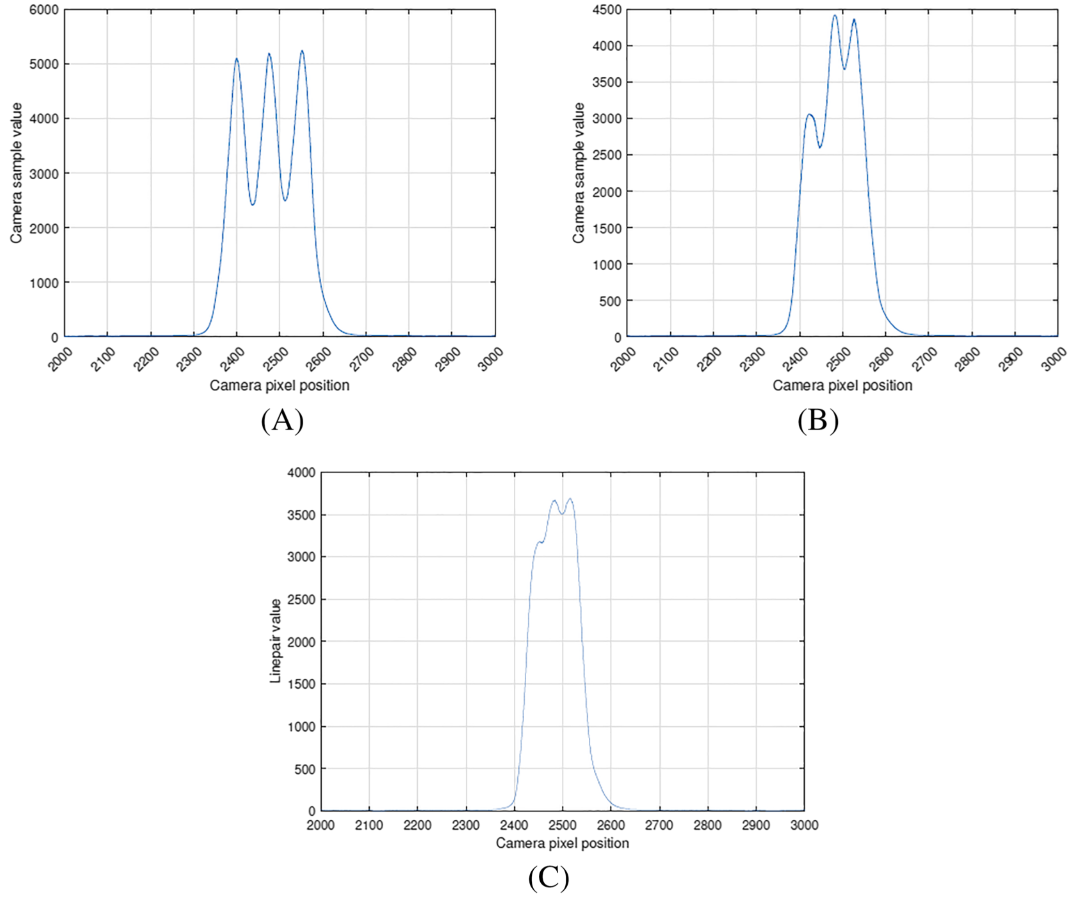

FIGURE 13 Grille plots of three different source resolutions: A, 2560. B, 3584. C, 5120

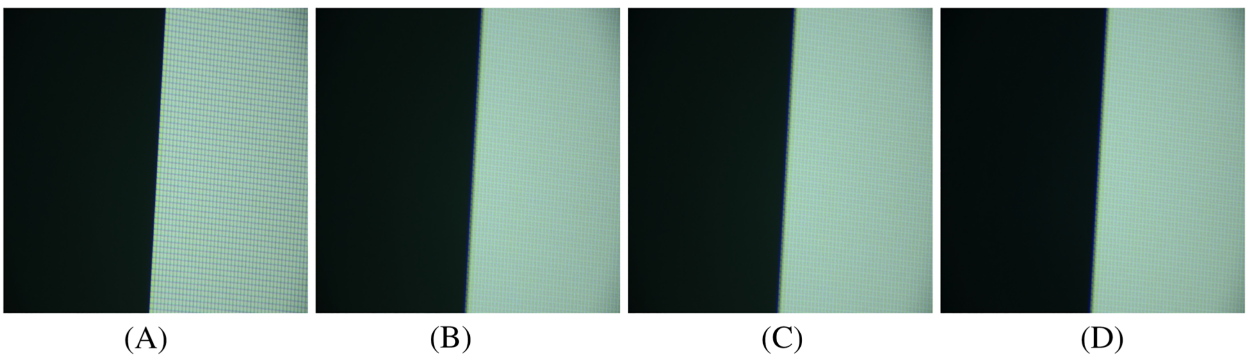

FIGURE 14 Slanted edge measurements at horizontal source resolutions A, unshifted 2560. B, 3584. C, 4352. D, 5376

The slanted edge measurement is a very good measurement for optical performance, but as we see from Figures 14 and 15, the shifted slanted edge does not change significantly as a function of the input resolution. This is logical because the source image in this case is a step pattern that will be interpreted the same way in all of these resolutions. This makes the slanted edge measurement method an unsuitable method to measure the effect of input resolution on a shifted superimposed display.

The least resolvable line pairs and the grille contrast method both show that the measured resolution increases with the source resolution up until approximately 40% over the native resolution. The differences in the measurement method give some differences in what source resolution that gives the best measured resolution, but they both indicate that the maximum gain of this resolution enhancement method is around 40%.

The least resolvable line pair method measures the smallest perceivable line/detail in the current configuration, while the grille contrast method measures the contrast between neighbour lines/details in the image. So even though both these methods agree on the maximum res-

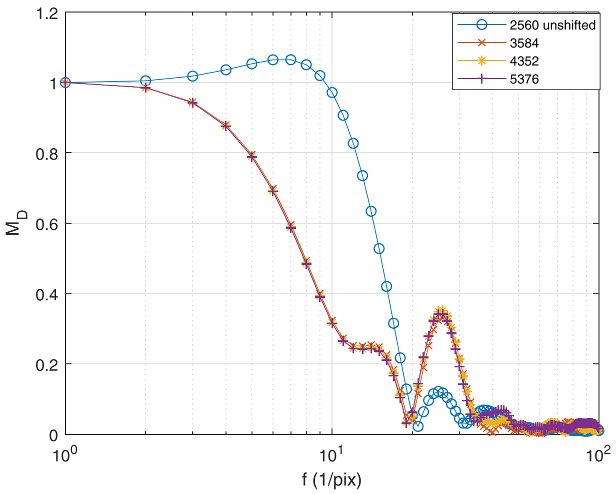

FIGURE 15 Slanted edge modulation transfer function (MTF) calculations

olution gain of the shifted superimposition method, they differ on the ideal source resolution. This is because of the different features they analyse in the image, and the ideal source resolution may differ depending of the applied application and thus what definition of resolution is most suitable for that specific use case.

Approximately 40% resolution increase also matches the number of pixels actually projected on the screen, because we are using two different subframes in two different positions for these measurements. With our WQXGA projector, this gives us 2560 × 1600 × 2 number of pixels on the screen. Keeping the aspect ratio, this will equal the number of pixels in a 3620 × 2262 image which is 41% (square root of two) above the native resolution.

6 | CONCLUSION

The achieved resolution with the shifted superimposition technique does increase as we increase the source resolution. This is valid up to a certain threshold, where the shifted superimposition method reaches its limit because of the physical size of the projected SLM pixels and the overlap of these pixels in different positions. The resolution enhancement limit seems to be about 40% above the SLM resolution.

There are still open questions on how to measure this resolution increase in the best way. We have utilized the least resolvable line pair test, the grille contrast modulation method, and the slanted edge method in this work. All these methods have their shortcomings, but the two best methods for this use case both measure a maximum resolution increase at 40% while the slanted edge method is found to be unsuitable for this measurement. The least resolvable line pair method seems to be better suited to measure the achieved resolution increase, because the grille contrast modulation method takes too many assumptions on what attributes the measurements should have to be defined as resolution.

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