

SEEING CLEARLY—THE EMERGENCE OF ULTRA HIGH-RESOLUTION DISPLAYS

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ABSTRACT

In the pursuit of eye-limited (20/20) training, simulation systems have been limited by display technologies. Displays used for simulation have typically been bulky and heavy, and their resolution capability has always lagged behind the image generator development curve. The tables are turning as display technology takes a giant leap with the emergence of ultra high-resolution (UHR) displays. The first UHR display technology has been demonstrated in a prototype projector developed by Evans & Sutherland. Displays built on this technology can be compact, lightweight, low power, bright, high-contrast, and ultra high-resolution. Advances in a variety of disciplines such as electronics, manufacturing, MEMS, optics, and digital video have made this technology possible. The challenge now is to satisfy the display's insatiable appetite for pixels with useful information.

Ultra high-resolution displays promise to advance flight simulation training to new heights. Military pilots will be able train on simulators to recognize targets, threats, and other objects that previously were not possible to identify due to lack of resolution and detail. Also, the risk of negative training will be reduced. The US Air Force, with their M2DART system, has recognized this advantage and seeks 5k x 4k (20 million pixels) per display.

This paper addresses simulation displays, the prototype projector technology, and the impact of ultra high-resolution displays on simulation.

ABOUT THE AUTHORS

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INTRODUCTION

Simulation systems are in constant pursuit of technologies that bring synthetic environments closer to reality. Display technology is a key element in this endeavor. Training systems to date are limited by display technologies. Displays used for simulation are typically bulky and heavy, and their resolution capability lags behind the image generator development curve. However, recent advances in a variety of disciplines such as electronics, manufacturing, micro-electromechanical systems (MEMS), optics, and digital video have made it possible to develop a new generation of displays. These new displays challenge image generators to satisfy their insatiable appetite for pixels with useful information.

Ultra high-resolution (UHR) displays promise to advance simulation training to new levels, providing clear, crisp, vivid images. Military pilots will be able train on simulators to recognize targets, threats, and other objects that previously were not possible to identify due to lack of resolution and detail.

The Air Force Research Laboratory/Warfighter Training Research Division (AFRL/HEA) recognizes the advantages of improved display performance and for many years has supported UHR display concepts. Evans & Sutherland (E&S) has partnered with the AFRL/HEA to develop displays for their Mobile Modular Display for Advanced Research and Training (M2DART) system, which requires 5k x 4k (20 million pixels) per display. In conjunction with this effort, E&S has developed the first prototype UHR display. Displays built on the technology contained in the prototype display can be compact, lightweight, low

power, bright, high-contrast, and ultra high-resolution. This paper addresses simulation displays and the AFRL/HEA effort to advance display technology, the prototype projector technology, and the impact of UHR displays on the simulation community.

DISPLAYS FOR SIMULATION

Displays for simulation are based on a variety of technologies including cathode ray tubes (CRT), liquid crystals (LCD), liquid crystal light valves, plasma, Texas Instrument's Digital Micromirror Device (DMD™), lasers, etc. For a given system, the display (as well as the image source) is chosen based on the application and the level of training. Since this paper addresses the high-end of simulation training, the following section will address only the technologies most commonly used for high-end simulation.

High-End Simulation Displays

Perhaps the most commonly used display device for high-end simulation is the CRT based projector. CRTs have been around for a long time and there has been a significant amount of engineering put into them over the years. CRTs have very high full-on/full-off contrast ratios because the black state (full-off) is truly black (no light). With appropriate drive electronics, a CRT-based display can be made to draw a raster image and then draw calligraphic (or stroke) lines and points. Calligraphic capability is essential to effectively simulate runway lights and other critical high-contrast items in an image. As any new display technology is developed, it is always compared to the CRT.

The major limitation in using a CRT-based projector for high-resolution is the attainable dot pitch. A pixel on/pixel off checkerboard pattern on most CRT-based projectors at their specified highest resolution generally produces an almost flat gray field.

In the past few years, more and more liquid crystal light valve and DMD based projectors have made their way into high-end simulation. These devices present new engineering challenges such as edge-blending of multiple projectors, reducing/eliminating smearing effects, reducing visible pixel boundaries, etc. There is (and has been) a significant amount of engineering effort placed on these problems and many fine projection systems based on these technologies are in use today. The limitation in using this type of technology for UHR display development is in the manufacturability of the devices. These devices consist of a two dimensional array of elements, one for each pixel, to modulate light. As the number of pixels increase, the manufacturing yield of these devices drops below acceptable limits.

Other types of displays, some of them laser-based, have also been considered for use in high-end simulation. However, their scanning bandwidth and light modulation techniques have prohibited them from achieving ultra-high resolutions.

In order to achieve the resolution required to provide adequate training by today's standards, many high-end simulation systems use several tiled projectors to collectively produce an image. This tiling creates boundaries in the image that are difficult to remove and can be distracting.

Advancing Display Technology

The AFRL/HEA located in Mesa, Arizona, has been supporting the development of UHR projector technology since the mid 1990's. A major laboratory goal is to provide Air Force fighter pilots with eye-limited resolutions during their simulator training scenarios. Based upon display geometry of the Boeing Visual Integrated Display System (VIDS) and the Air Force's Mobile Modular Display for Advanced Research and Training (M2DART), a UHR projector capable of displaying 5,120 x 4,096 pixels at a 60 Hz frame rate is required.

Achieving these high resolutions is a challenge in and of itself, but to do so while avoiding the perceptual issues related to various types of modulation techniques and scan architectures further complicates the task. This feat is being accomplished through coordinated AFRL/HEA team efforts involving human factors and visual systems engineers and one of the laboratory's industry partners, Evans & Sutherland.

Investigation into emerging display technologies and requirements has been, and continues to be, instrumental in defining an optimized display system. Early hypotheses and subsequent substantiating research have, in effect, defined the selection of incorporated technologies by ruling out unacceptable perceptual artifacts produced by competing technologies. For instance, display technologies that involve extended pixel "on times" of several milliseconds are deemed to be unacceptable for fast jet simulation applications because "the perceived target during tracking will always be a 'smeared' version of the actual target" (Lindholm & Scharine, 2000). In addition, the tiling of small displays or sets of beams was considered, but these concepts were discarded mainly due to the anticipated large temporal offsets between adjacent panels and the necessity to blend seams. It was concluded that "of the multibeam and multipanel scan architectures considered, a linear array scanned once per refresh period would be least likely to introduce image distortions of perceptual significance" (Lindholm, 2001).

The Silicon Light Machines linear array spatial light modulator technology to date is the most likely to succeed in meeting UHR projector requirements. This modulator's switching speed exceeds the requirements of a UHR projector and has the added benefit of not requiring pulse-width modulation, thus allowing for greater gray scales within the associated time frame. It is also a technology that has been successfully demonstrated with exceptional results. While the current version of the modulator only has 1,088 pixels in its length, it can produce a swath of 1,088 pixels by 8,192 pixels at 60 Hz. Although impressive, this format is quite wide and contains less than half the pixels required by the UHR projector (5,120 x 4,096). The linear array needs to be a minimum of 4,096 pixels in length to paint a 5,120 x 4,096 swath of video.

There are several promising methods being investigated that may allow this modulator technology to be used to achieve UHR projector performance requirements. If there is a downside to using this particular spatial light modulator technology, it is the requirement to use laser light as an illumination source. This laser source requirement is the direct result of the geometric etendue, which is the limiting function of system throughput based upon its ability to accept light. Laser light has the positive characteristic of being able to produce a much greater color gamut than those of traditional displays and can increase the depth of focus, qualities that are advantageous to the flight simulation community. However, the requirement for a laser light source creates an additional set of technical challenges as well as cost considerations.

PROTOTYPE PROJECTOR TECHNOLOGY

E&S is developing a family of UHR displays for use in simulation. A prototype display has been demonstrated at a resolution of 8192x1088 (8.9 million pixels) running at 60Hz.

Overview

The prototype projector technology is based on the Grating Light Valve™ (GLV™) developed by Silicon Light Machines. The GLV is a linear array of MEMS “ribbons” that can be controlled electronically to modulate light. Presently, six ribbons are used to create a pixel and the array contains 1088 pixels. The prototype projector uses red, green, and blue lasers for light sources. The laser sources are optically directed onto the GLV devices where the ribbons are positioned to modulate the light for a column of the desired picture. The modulated diffracted light is collected and re-combined to produce a column of the image. A galvanometric mirror is used to sweep the column of light horizontally across the screen. As the mirror moves, the ribbons are updated to modulate the light for the current screen position so that the desired image is displayed (Figure 1).

Advantages of Linear Modulation

The underlying technology for many display devices is a two-dimensional array of elements. This becomes a limiting factor for high-resolution because the arrays become increasingly difficult to

manufacture as the number of elements increase. For example, to produce a 640x480 device the manufacturing process must yield 307,200 perfect elements. To increase the device size to 1280x1024, the process must yield 1,310,720 perfect elements. To equal the size of the prototype projector (8192x1088), the process must yield 8,912,896 perfect elements.



Figure 1. Scanning an Image Using a GLV.

The original GLV device was conceived as a two-dimensional array of elements. In fact, some experimental devices were manufactured and demonstrated (Bloom, 1997). However, as high-resolution capabilities began to be investigated, it became evident that the device was fast enough to operate as a linear array making them much easier to manufacture (Amm & Corrigan, 1999).

Regardless of the horizontal resolution, the manufacturing process need only yield 1088 perfect elements for a GLV. For a 33.6 million pixel display (8192x4096) the process only needs to yield 4096 perfect elements. That's 75 times fewer elements than is required for a 640x480 array!

Another advantage of a linear array of elements is that there are no vertical pixel boundaries. The ribbon architecture of the GLV removes any horizontal pixel boundaries, so the resulting image created by a GLV based projector is made up of smooth continuous light.

The Requirement for Laser Light Sources

The GLV requires that a very narrow line of light be directed at the linear array of ribbons.

Typically, this line of light is about 27 mm long and less than 25 μm wide. It would be nice if an arc lamp could be efficiently directed to this required geometry, but due to the random nature of the light, only a small percentage of the light output would be usable. A coherent light source is necessary and, with today's technology, that leads to lasers.

Unfortunately, there are not very many high-power lasers in the visible spectrum that have the necessary characteristics to be packaged as part of a GLV-based projector. Those that are capable tend to be expensive. Lasers also exhibit speckle and bring up safety issues. For these reasons E&S is developing low-cost, safe, efficient, high-power lasers with excellent beam quality for use with UHR projectors.

Lasers do have advantages. One of the major advantages of lasers is that the primary colors (red, green, and blue) can be chosen to provide a color gamut much greater than can be produced by current display technologies. Figure 2 shows the color gamut available from a typical CRT vs. lasers.

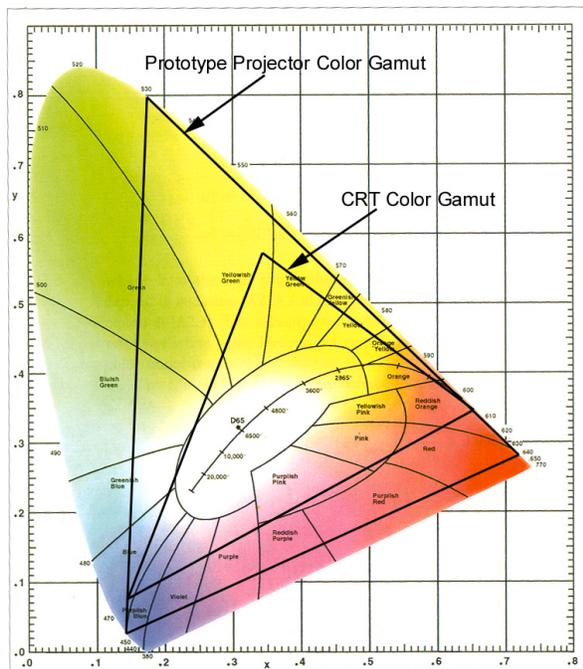


Figure 2. Color Gamuts on CIE 1931 2° Chromaticity Diagram.

The Horizontal (Time) and Vertical (Physical) Axes

The horizontal resolution of the prototype projector is limited by the switching speed of the GLV ribbons (the time it takes the ribbons to deflect) and the width of the line of laser light on the GLV.

GLV devices have been made that switch in 20ns (Bloom, 1997). For perspective, a GLV that can switch from full-on to full-off (or full-off to full-on) in less than 200ns would allow about 80,000 pixels in the horizontal direction at 60 Hz. The prototype projector, at a resolution of 8192x1088, switches the ribbons in 1.6 μs at 60 Hz. As technology continues to grow, it is possible that displays with greater than 8K pixels in the horizontal direction can be designed using today's GLV technology.

The width of the line of laser light on the GLV also affects the maximum horizontal resolution. The wider the line on the GLV the wider the pixels are in the image. If the scan mirror does not move a full pixel width before the next column of data is presented, then the pixels will overlap and effectively reduce the image quality. Figure 3 illustrates this effect. Typically the line width is around 25 μm or less which allows for square pixels. However, the desired shape of the pixel, the GLV geometry, the number of ribbons used per pixel, and the horizontal scan distance ultimately define the line width.

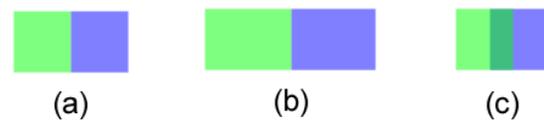


Figure 3. Horizontally Adjacent Pixels Where
 (a) Scanning Rate Matches Pixel Width,
 (b) Scanning Rate is Faster than Pixel Width,
 (c) Scanning Rate is Slower than Pixel Width.

The vertical resolution is physically constrained by the geometry of the GLV. The number of ribbons in the array and the number of ribbons used to define a pixel determine the vertical resolution. The prototype projector utilizes a GLV with an array of 6,528 ribbons, where 6 ribbons define a pixel, so it is limited vertically to 1088 pixels.

Extending the Vertical Resolution

Since the vertical resolution is physically constrained, it is much harder to extend than the time-constrained horizontal resolution. However, there are ways to extend the vertical resolution.

One method is module stacking. Multiple GLVs can be stacked vertically and optically combined to extend the vertical resolution of the display. This method requires complex optics. It is important to note that this method is different than tiling, with respect to human perception, because all adjacent pixels contain data from the same time stamp (Figure 4).

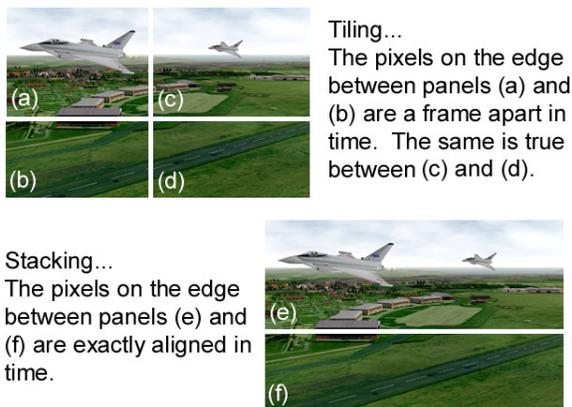


Figure 4. Tiling Vs. Stacking.

Another method is vertical shifting. A single GLV, or the modulated light produced by the GLV, can be shifted up and down by one-half pixel each field to double the vertical resolution (essentially drawing odd and even fields). Two fields would be required to present a complete image. This method has a couple of downfalls. First, since a GLV-based projector does not have any pixel boundaries, vertically adjacent pixels in the odd and even fields will overlap (Figure 5). Second, it introduces all of the visual artifacts associated with interlacing.

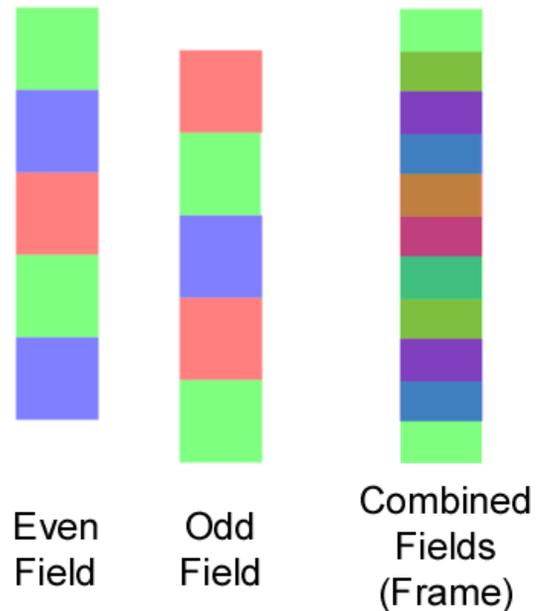


Figure 5. Effect of Combined Fields on a Single Column Using Vertical Shifting.

Yet another method, and perhaps the optimal solution, is changing the geometry of the GLV device. GLV devices using 4 ribbons per pixel have been demonstrated (Bloom, 1997). Using 4 ribbons per pixel (instead of 6) on the current 6,528-ribbon array would increase the vertical pixel resolution from 1088 to 1632. Using 2 ribbons per pixel can double the resolution again to 3264 pixels. The current GLV is not limited by manufacturing processes. It is possible to make a GLV device with more ribbons in the array.

Electronic Interface

The prototype projector interfaces to image generation (IG) devices through multiple Digital Visual Interfaces (DVIs). The data received from the DVIs is required to be frame synchronized within a few active lines. This means that each video stream can begin active data for a frame at different times within a few lines (Figure 6). However, for zero delay, all data streams must begin active data at the same time. The electronics wait until all data streams are supplying active data for a frame before processing begins. Depending on the order in which data is received, it is either sent immediately to be displayed or is buffered for up to one frame. The amount of buffering required is determined by the data order.

The electronics are very flexible and can accept data from the multiple DVI interfaces in almost any order.

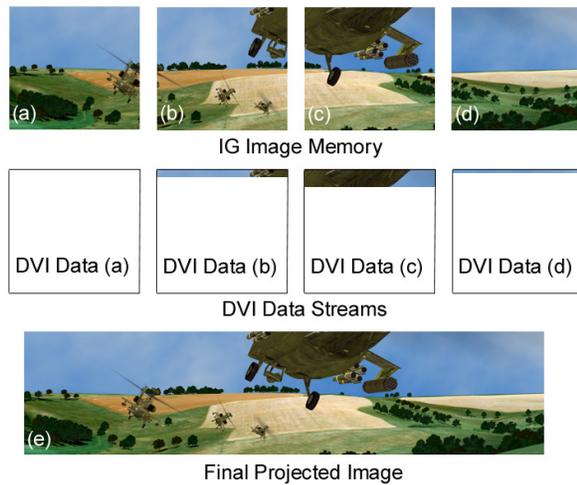


Figure 6. Transfer of Data from IG Image Memories (a)–(d) via DVI Streams to Produce Image (e). The DVI Streams Need Only be Frame Synchronized within a Few Active Lines.

Calibration

Perhaps the most challenging issue in obtaining the best picture from the prototype projector is calibration. Compensation must be provided for an uneven laser line profile, contaminated optics, GLV driver imbalance, and the position of the GLV ribbons after the sacrificial layer below them is removed.

The prototype projector uses a fully automatic procedure to calibrate the image. First, the calibration hardware is automatically placed into the optimal range for detection. Next, the drivers are balanced. Finally, each pixel is tested and corrected for proper intensity output. The results are stored in files and the appropriate parameters are downloaded into the projector control hardware.

The calibration block diagram is shown in Figure 7 below. An integrating sphere is set to collect all the light output from the projector. The detector on the integrating sphere sends a signal back to custom calibration acquisition hardware. The acquisition hardware performs both analog and proprietary digital filtering and returns values to the control hardware. The control hardware uses this

feedback to determine how to correct the light output from the projector.

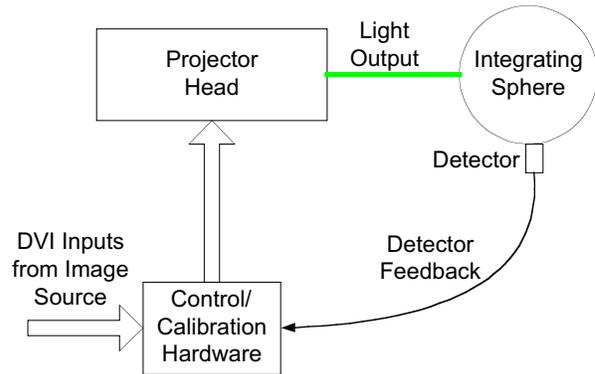


Figure 7. Calibration Block Diagram.

Calibration is performed for each laser color separately. This makes sense for two reasons. First, the detection hardware cannot distinguish between different light sources. Second, each light source is associated with a separate optical path and GLV.

It is possible to use this method to continually monitor/correct the picture calibration during normal operation. At the end of each scan a sample of the light being output can be directed to the integrating sphere and checked by the control hardware. The control hardware can update the projector hardware to compensate for any discrepancies found.

Results

The development of the prototype projector has demonstrated that, using the GLV device, a UHR display can be made to provide a new level of training in the simulation industry, and that it can have the following attributes:

- Smooth image with no pixel boundaries.
- Low power.
- Fast pixel response to minimize/eliminate smearing artifacts.
- Lightweight relative to existing high-end projectors suitable for simulation.
- Bright with high-contrast.
- Large color gamut due to laser light sources.
- Standard interface that works with today's image generators.

IMPACT OF HIGH-RESOLUTION DISPLAYS ON SIMULATION

The giant leap from 1 or 2 million pixel displays to 9 to 32 million pixel displays most certainly has impact on the simulation community. Simulation environments have the potential to look more realistic and provide training previously unattainable. This potential is realized only if other components of the simulation system such as databases and image generators are able to provide more detailed information.

Overall Systems

Simulation systems are continually improving and providing synthetic environments that are coming closer and closer to reality. UHR displays provide the means to make a giant leap toward reality. Sharper, clearer images mean better training. Eye limited (20/20) images become a possibility. A single lightweight UHR projector can replace multiple bulky projectors and eliminate the need for edge-blending. In short, the door to a whole new set of possibilities is opened.

Databases

UHR displays place the challenge of making more realistic objects with high quality pixels onto the database designers. It doesn't make much sense to use a UHR display with low-resolution images. There is a balance between the database, the image generator, and the display device that must be maintained to provide the best simulation environment without over-processing (generating information that is useless or more detailed than can be realized).

Image Generators

UHR displays have a greater impact on image generators than on any other component of a simulation system. In the past, image generators have challenged display technology, but now display technology is exceeding image generator capabilities. UHR displays are pixel hungry and today's image generators are not capable of supplying millions of pixels per frame. Many image generators have difficulty supplying HDTV (1920x1080) resolution display devices with high quality pixels. It is common practice to lower the resolution and place more processing emphasis

on pixel quality. Pixel quality is obviously important. As image resolution goes up, pixel quality cannot be sacrificed. Image generators must meet the pixel resolution and quality challenges that UHR displays present in order to create advanced simulation systems. In the near term, multiple image generators will need to work together to provide quality pixels. The prototype projector accepts multiple data streams so that multiple image generators can drive it. Perhaps as technology advances, a single image generator will be able to drive a UHR display.

The prototype projector also challenges image generator architects to rethink data output format capabilities. The prototype projector requires data to be presented in columns (rather than rows) and in a specific pixel order to minimize any buffering delay in the projector.

Interfacing

UHR displays require high bandwidth. A true color (24-bit/pixel) 8192x1088 display with 15% blanking (effectively 9424x1088) at 60 Hz has a transfer rate of 1.85 gigabytes/sec., or a 615 MHz pixel clock. Processing pixels in parallel and low voltage differential signaling technology make it possible to transfer this huge amount of information. However, as the display resolution increases these technologies may not be sufficient on their own. Simulation systems may need to incorporate digital video and real-time image compression and decompression techniques to support ultra high-resolution displays.

CONCLUSION

Ultra high-resolution displays are beginning to emerge. The E&S UHR prototype projector demonstrates that recent advances in technology have enabled the development of these types of displays. Although this technology is mature enough to be useful in UHR displays today, improvements in light sources, modulation devices, and driving techniques are still being developed. In the near future, displays approaching eye-limited resolution will be available to the simulation community.

UHR displays enable training that was not possible before, and reduce the possibility of negative training. Displays, which have typically

been a bottleneck in simulation systems, are now challenging image generators to satisfy their demanding pixel capacity.

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