59.5L: *Late-News Paper:* Evaluation of a Prototype Grating-Light-Valve Laser Projector for Flight Simulation Applications

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Abstract

An evaluation of a prototype grating light valve laser projector indicates it has properties well-suited to flight-simulation applications. Full-field luminance and contrast, spatial resolution, temporal resolution, and color stability were equal to or better than those of CRT projectors typically used in flight-simulator applications. In addition, this projector is capable of providing refresh rates greater than 60 Hz. The higher refresh rates eliminate perceived flicker, and greatly reduce (120 Hz) or eliminate (240 Hz) motion artifacts over the range of target speeds tested.

1. Introduction

Digital projectors, such as LCD, LCoS, and DLP projectors, typically provide better spatial resolution than CRT projectors. However, tracking blur, which occurs when an observer tracks moving imagery, is greater for most digital projectors due to a longer within-frame hold-time than that of CRTs [6, 7]. Digital projectors can be relatively easily modified to reduce their hold-time, and we have previously evaluated several such projectors for possible use in flight-simulator applications [12, 13]. Those evaluations verified the high contrast and spatial resolution of digital projectors, and also indicated that tracking blur could be reduced sufficiently for use in many simulator applications.

The potential benefits of laser-projector technology are generally well-known [11], and include high-pixel count, short hold-time, and expanded color gamut. However the development of a such a projector has, to date, proved problematic. Sony Corporation has recently developed a prototype laser projector: the GxL (G-by-L), which may be sufficiently stable to provide high-resolution images suitable for flight-simulator applications. In addition, the projector can provide refresh rates of 60 Hz, 120 Hz, and 240 Hz, by effectively exchanging spatial and temporal resolution. Based on previous studies [5, 10] we expected that high frame/refresh rates would reduce or eliminate many motion artifacts. Additionally, increasing refresh rate can produce the added benefit of increasing luminance and contrast [8].

We describe here an evaluation of the GxL prototype laser projector and discuss implications for flight simulation. The evaluation included instrument measurements of display luminance, contrast, spatial resolution, temporal characteristics, and color stability. In addition, psychophysical experiments were performed to assess the effects of higher spatial resolution on aircraft-orientation discrimination, and the effects of higher temporal resolution on perceived tracking blur, image flicker, and motion fidelity.

2. Methods

The GxL prototype laser projector evaluated here is based on grating light valve technology, and can produce images of 7680 × 1080 pixels at 60 Hz, 3840 × 1080 pixels at 120 Hz, or 1920 × 1080 pixels at 240 Hz (additional details on the GxL can be found in Kikuchi, et al., in press [4]). Although the GxL is typically demonstrated in curved (60 Hz) and flat (120 Hz and 240 Hz) front projection configurations, the current evaluation was conducted using a rear-projection configuration in order to facilitate comparison with previous evaluations. This configuration is similar to that currently used in Air Force flight simulator displays such as the Mobile Modular Display for Advanced Research and Training (M2DART). The display system was evaluated both in a 1.0 arcminute/pixel configuration (20 in ×11 in image), and a 2.6 arcmin/pixel configuration (52 in × 29 in image). These visual angles were calculated based on a viewing distance of 36 in.

The test imagery used to assess luminance, contrast, spatial resolution, temporal resolution, and color was obtained from a Display-Evaluation Test Suite that has previously been described [14]. These display characteristics were measured using a standard photometer (Minolta, Model LS100) and a CCD-based imaging photometer (Lumetrix, IQCam Model 500c). Color measurements were obtained using a Spider2-Pro colorimeter (Datacolor). The test imagery used for the aircraft-orientation, flicker, and motion-artifact measurements was obtained using either an L3 image generator (L3 IG, L3 Communications, Arlington, Texas), or software developed specifically for this evaluation. The 240 Hz update rate imagery was produced by using pre-rendered image sequences to play back at real-time rates of 240 Hz. Although not successfully demonstrated in this assessment, the GxL has the capability of projecting imagery rendered in real time at 120 Hz or 240 Hz by multiplexing individual DVI-I sources; two 60Hz DVI-I sources are required for 120 Hz, four 60 Hz DVI-I sources are required for 240 Hz.

2.1 Instrument Results

2.1.1 Luminance and Contrast Measurements

The maximum and minimum full-field luminances were obtained from measurements made at the center of full-field white (grayscale=0) and black (grayscale=255) images, respectively. The values were about 644 fL and 0.033 fL, for the 1.0 arcmin/pixel configuration, and about 96.2 fL and 0.007 fL for the 2.6 arcmin/pixel configuration. Additional full-field measurements were obtained for the 1.0 arcmin/pixel

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14. ABSTRACT **An evaluation of a prototype grating light valve laser projector indicates it has properties well-suited to flight-simulation applications. Full-field luminance and contrast, spatial resolution, temporal resolution, and color stability were equal to or better than those of CRT projectors typically used in flight-simulator applications. In addition, this projector is capable of providing refresh rates greater than 60 Hz. The higher refresh rates eliminate perceived flicker, and greatly reduce (120 Hz) or eliminate (240 Hz) motion artifacts over the range of target speeds tested.**			
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configuration in order to measure display gamma. The gamma measured for red, green, blue, and white was 2.24, 2.05, 2.75, and 1.96, respectively.

Full-field contrast, defined as the ratio of the full-field white and black luminance levels, was approximately 19,500 for the 1.0 arcmin/pixel configuration, and approximately 13,700 for the 2.6 arcmin/pixel configuration. Checkerboard contrast, measured using a standard ANSI 4×4 checkerboard pattern, was defined as the average luminance of the two center white checkerboard areas divided by the average luminance of the two center black checkerboard areas. The checkerboard contrast was approximately 113 for the 1.0 arcmin/pixel configuration, and approximately 91 for the 2.6 arcmin/pixel configuration. These contrast measurements are quite good, however they were likely reduced to some degree by ambient illumination.

2.1.2 Spatial Resolution

Display spatial resolution was characterized using procedures adopted from accepted measurement standards [3, 9]. Briefly, a full-field, square-wave pattern with a grayscale contrast of 1.0 (i.e., black=0, white=255) was generated, and the displayed image was captured by an imaging photometer. The captured image was then used to determine the average luminances of the maxima (L_{max}) and minima (L_{min}) of the displayed grille pattern. These values were then used to compute the Michelson contrast of the grille pattern as: $(L_{max}-L_{min})/(L_{max}+L_{min})$.

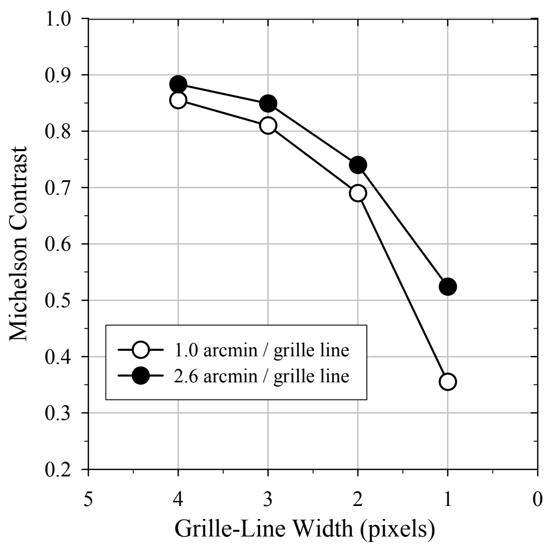

Figure 1. Contrast modulation versus line width for vertical grille patterns for each laser-projector image size tested.

Figure 1 shows Michelson contrast for a series of vertical grille patterns with line widths corresponding to 1, 2, 3, and 4 pixels for both the 1-arcmin/grille-line and 2.6 arcmin/grille-line configurations. For all grille-line widths, contrast remains well above the 25% criterion recommended by VESA. Thus, the number of resolved pixels is equal to the number of addressed pixels, in this case 1920 × 1080. It should be noted that the rear-projection screen used in this evaluation significantly decreased displayed contrast for the GxL laser projector. The measured contrast of a grille pattern imaged directly on a camera sensor (i.e., with no projection screen), was near 1.0 even for the single-pixel grille pattern (Sony, personal communication).

2.1.3 Color Stability

We also compared the color stability of the GxL laser projector with a CRT projector. Chromaticity (x, y) and luminance were measured at various times over a period of 60 min. The measurements were converted to tristimulus values (X, Y, Z) and the average of the tristimulus values after stabilization (t ≥ 15 min) determined the white-point used in the CIELAB calculations. The CIE 1976 $L^*a^*b^*$ color space [15] has a lightness dimension (L^*) and two color-opponent dimensions (a^* and b^*), and it is uniform in that the distances between points in the space are approximately proportional to perceived color differences.

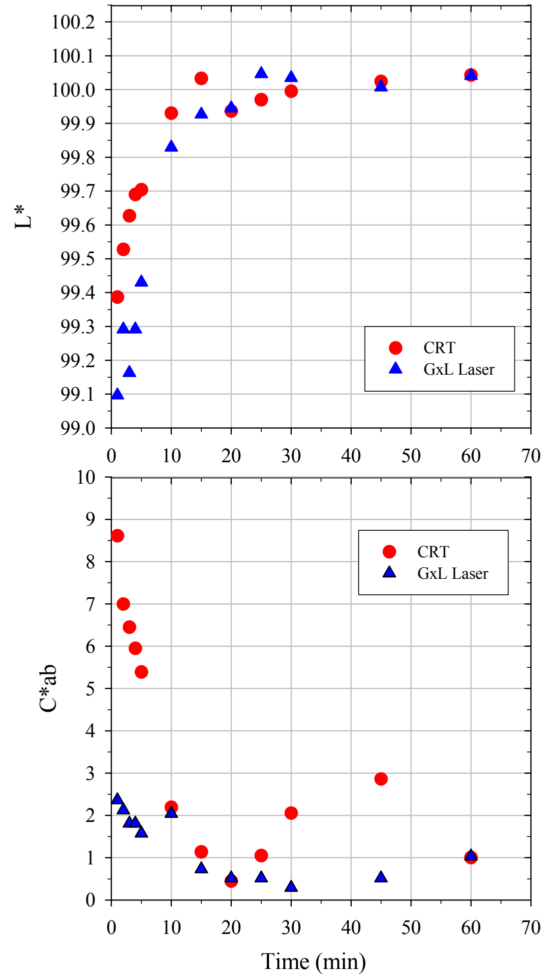

Figure 2. L* and C*ab measured at various times following a 15-min warm-up period for the laser projector and a CRT projector.

Figure 2 (top) shows L^* values as a function of time for both projectors. The procedure used to determine the white-point ensures that the mean of the stabilized L^* values is 100. The maximum of the absolute value of the differences between the L^* values and the mean were 0.07 for the GxL laser projector, and 0.06 for the CRT. Figure 2 (bottom) shows C^*_{ab} (a measure of chroma) values as a function of time for both projectors. These values were obtained using the same white-point, and they represent the Euclidian distance between the measured value and the origin in the color-opponent plane (a^*=0, b^*=0). The maximum of the stabilized values for the laser projector was 1.03

and the mean was 0.60. For the CRT, the maximum of the stabilized values was 2.86, and the mean was 1.42.

Based on these measurements, color stability of the laser projector was equal to or better than the CRT projector. Note that a color difference of 1.0 in the CIE 1976 $L^*a^*b^*$ color space corresponds approximately to one just noticeable color difference. The average differences in L^* for both the GxL laser and CRT were less than 0.1 which is well below threshold. The average C^*_{ab} value for the laser display was slightly below threshold (0.60) and that of the CRT was slightly above threshold (1.42). These differences are inconsequential for most simulator applications.

3.1 Behavioral Results

3.1.1 Aircraft-Orientation Discrimination

In addition to simple spatial resolution, we also measured observer performance on a task relevant to operational Air Force training that is dependent upon image detail. A total of eight observers participated in this experiment which involved identifying the orientation (either left or right) of an F-16 aircraft model. Further details concerning this procedure can be found in Geri and Winterbottom [2]. Figure 3 shows the results of this experiment for each image-size configuration tested on the GxL laser projector. Also shown in Figure 3 are comparable data obtained using a CRT projector that is similar to those used in many flight simulators. Recognition ranges were about 11.5 km (7.1 mi) and 5.5 km (3.4 mi) for the 1.0 and 2.6 arcmin/pixel GxL laser-projector configurations, respectively, and about 2 km (1.2 mi) for the CRT. The aircraft orientation recognition ranges obtained for the laser projector are the best we have obtained with this procedure to date, and approach or exceed real world aircraft recognition ranges.

3.1.2 Tracking Blur

Six observers participated in this experiment, which was a simplified application of the moving-line test that we have previously described [12]. In the modified procedure used to evaluate the GxL projector, observers tracked a pair of white, 20 pixel wide bars with a 1-pixel gap between the bars against a black background and reported if the gap was detectable. All six observers reported detecting the gap at all tracking velocities tested (18, 26, and 63 deg/sec). These results, which represent the minimum measurable gap width, are plotted in Figure 4. Also shown in Figure 4 are moving-line data obtained from a CRT projector, a standard LCoS projector, and a modified LCoS projector. The modified LCoS projector was equipped with a shutter that reduced the hold-time to 3.8 msec. As shown, the tracking blur for the modified LCoS is similar to that of the CRT, but still greater than that of the laser projector.

Tracking blur is a consequence of the fact that a digital display represents motion as a temporal sequence of still images whereas an eye that tracks the motion moves continuously. Therefore, within a frame, a stationary display element is imaged by a continuously moving eye. This eye movement blurs the retinal image and the magnitude of the blur increases with both the speed of the tracking motion and display hold-time. For a rectangular pulse and a perfectly tracked screen element, the tracking blur is equal to the product of tracking velocity and hold-time. The hold-time of the GxL is approximately 2.0 microseconds and, at a 60 deg/sec tracking speed, the retinal image blur will be approximately 60 deg/sec × 0.000002 sec = 0.00012 deg = 0.0072 arcmin, which is inconsequential for practical purposes. In addition, this amount of blur cannot be measured using our moving line test because it is lower than the minimum possible gap width in this moving line test (1 pixel = 2.6 arcmin).

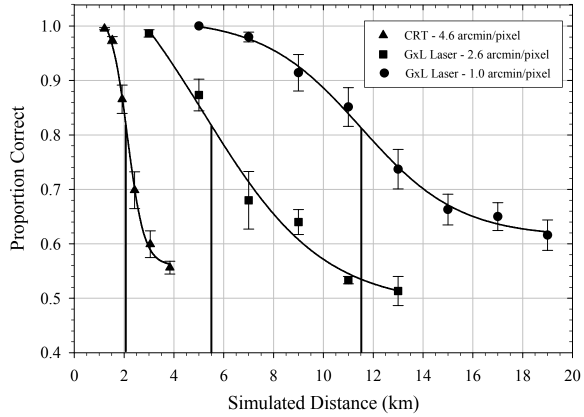

Figure 3. Proportion of correct left/right discriminations as a function of simulated aircraft distance.

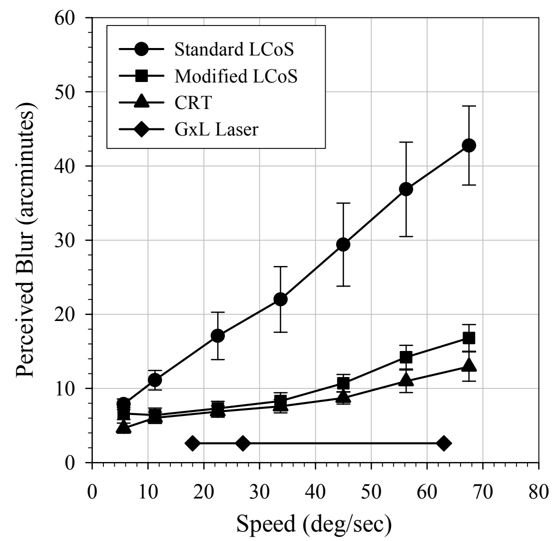

Figure 4. Mean just-perceptible distance between two, vertical moving lines as the speed of the moving-line test stimulus was increased. This distance is taken as a measure of tracking blur.

3.1.3 Flicker

Observations of the perceived flicker of a uniform field white field, displayed by the GxL laser projector, were recorded from several people who were familiar with the projector. All observers reported flicker with a 60 Hz frame rate, but none reported flicker with the 120-Hz or 240-Hz frame rates.

3.1.4 Motion Fidelity

Image sequences were generated in which an F-16 aircraft was moved horizontally across the display at three different speeds (10, 20, and 40 deg/sec) and frame rates (60, 120 and 240 Hz). Observers were instructed to maintain fixation at a point along the flight path and report motion artifacts which appeared as a variation in speed, or in false (i.e., aliased) replicas of aircraft features. For the 60-Hz refresh rate, all observers reported motion artifacts, even at the lowest speed. For the 120 Hz refresh rates, motion artifacts were reported only at the highest speed. No motion artifacts were reported for 240-Hz refresh rate condition.

4. Discussion

The results of this initial evaluation of the GxL laser projector indicate that it has properties well-suited for simulation applications. Specifically, full-field contrast, spatial resolution, and temporal resolution were high, and color stability was equal to or better than the CRT projector evaluated here. Performance of observers for an aircraft-orientation discrimination task was significantly better than has previously been measured for CRT projectors, even for an image size similar to that typically used in flight-simulator applications. Additionally, expected reliability is also high, as demonstrated by 185 days of nearly continuous operation in Aichi, Japan in 2005 [4].

The very short hold-time of the GxL laser projector (~2 μsec) effectively eliminates tracking blur, but it has the potential for maximizing perceived flicker for typical refresh rates [1]. Our results on this issue are preliminary, but they suggest that a 120 Hz (or higher) refresh rate will eliminate perceived flicker and greatly reduce (120 Hz) or eliminate (240 Hz) motion artifacts for a range of target speeds representative of those used in Air Force flight simulation applications. These results are consistent with those of Watson, *et al.* [10], who reported an approximately linear relationship between the speed of a line that can be displayed without perceived motion artifacts and the frame rate.

In order to fully take advantage of these higher refresh rates, new image generator architectures and/or new video interfaces will need to be developed. In the near term, 120 or 240 Hz real-time rendering and projection are most likely to be achieved through the multiplexing of multiple 60 Hz IG channels described in the Introduction, rather than with faster IG update rates. This approach, while increasing computational resources, could enable faster refresh/update rates without sacrificing scene complexity. It is anticipated that eventually graphics processors could directly support faster update rates.

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