THE IMPACT OF MOTION-INDUCED BLUR ON OUT-THE-WINDOW VISUAL SYSTEM PERFORMANCE

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Abstract

All visual display system technologies have visual artifacts, or perceptual features that would not be present in a naturally-viewed scene. The characteristics of certain light-valve technologies, specifically Liquid Crystal Display (LCD) and Liquid Crystal on Silicon (LCoS), exhibit a blurring artifact with image motion. In this paper, the causes of this artifact will be reviewed. Current knowledge regarding the impact of this artifact on both perception and simulator task performance will also be reviewed, and methods for reducing motion-induced blur will be discussed.

Introduction

The purpose of a simulator visual system is to render a computer generated image that simulates the image that would be available to the pilot when looking out of the vehicle windows. These systems while quite compelling particularly when well-designed, still fall far short of the real-world "stimulation" available looking out the window. On any level you use to compare, the visual system falls short of the real world: spatial resolution, temporal response, brightness, dynamic range, and depth cues are all different or minimized relative to the real world. However, even with these limitations, visual systems provide a highly necessary element for flight training.

The major components of visual systems have undergone significant advances in the recent past. The development of image generators for visual flight simulation has benefited from the rapid advances in graphics hardware and software that have been driven by consumer demand in broader market segments such as personal computers and computer gaming. These graphics innovations have allowed the visual simulation community to develop visual scenes with unprecedented levels of scene detail, as well as to significantly increase the update rates that can be achieved.

Similarly, consumer demand for higher quality visual entertainment, and availability of higher-resolution media, has driven many advances in large-screen displays. Some of these technologies have been adopted or are in the process of adaptation to visual flight simulation applications. The long-time mainstay of visual flight simulation projectors and displays, the Cathode Ray Tube (CRT), is now being replaced by other technologies such as LCD (Liquid Crystal Displays), LCoS projectors (Liquid Crystal on Silicon), and DLP (Digital Light Projection). Additional consumer markets for large-scale digital entertainment have yielded digital projectors with unprecedented pixel counts, such as the Sony SXRD and Evans and Sutherland Laser Projection Technology.

Each visual system component has specific capabilities. Image generators are typically defined by the resolutions and update rates they can support, and the amount of texture that can be applied. The performance of the image generator is modulated by the capabilities of the display. Displays are defined by the achievable resolution, luminance, refresh rate, color gamut, and other characteristics such as collimation or stereo capability. Additionally, the specific methods of visual image generation can create "artifacts", characteristics that aren't present in naturally viewed visual scenes but that are perceptible. Sometimes these artifacts can become quite apparent, rendering a technology unsuitable for certain flight simulation applications.

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This paper will address one particular artifact: motion-induced blur. First, underlying causes of motion-induced blur will be explained. Next, the perceptual consequences, and what is known regarding the effect on simulation performance, will be discussed. Finally, potential methods to reduce the artifact, and measurement issues related to achieving this reduction, will be considered.

Causes

Two different characteristics of current display technologies contribute the bulk of the motion–induced blur artifacts: the hold-type rendering mode of liquid-crystal based displays (LCD and LCoS); and a real (non-instantaneous) response time.

Hold time

Motion-induced blur due to hold-type rendering results from an interaction between the pixel illumination properties and human pursuit eye movements. Display systems that typically exhibit a long "hold time", or for which the pixel is illuminated for a large portion of a refresh, are subject to this type of blur. LCD and LCoS display systems are largely subject to this artifact. CRT and Laser displays, which very briefly illuminate a particular pixel, do not typically exhibit this artifact.

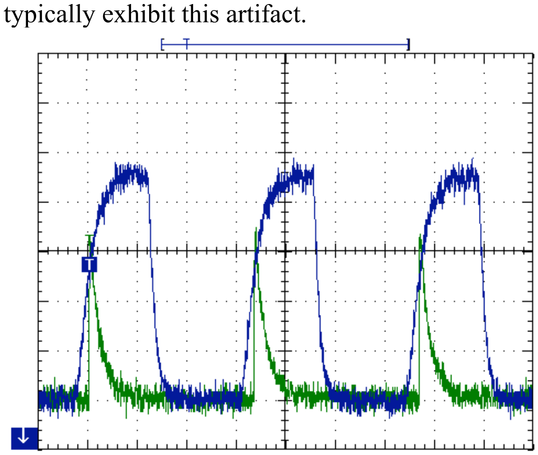

Fig. 1 – Overlay of CRT response (green) to the LCoS response (blue) to a flashing square stimulus of 1/60sec on, 1/60sec off.

A simple side-by-side comparison test illustrates this difference. Fig. 1 contains the measured luminance, as a function of time, of a VDC Marquee 9500 CRT projector and typical high end LCoS projector. A CRT projector uses a single electron gun to illuminate only a single spot on the screen at a time; the illumination decays rapidly, such that the period of time in which the pixel is actually illuminated is quite small in comparison to the LCoS projector.

The perceived blur results when the observer's eyes track or follow the apparent motion of the image. The continuous illumination of the pixel on LCoS/LCD systems, while the eye is in motion, results in a blurring or smearing of the light on the retina (see Fig. 2). This retinal smear, and resulting blur, does not occur with CRT systems because of the relatively brief illumination.

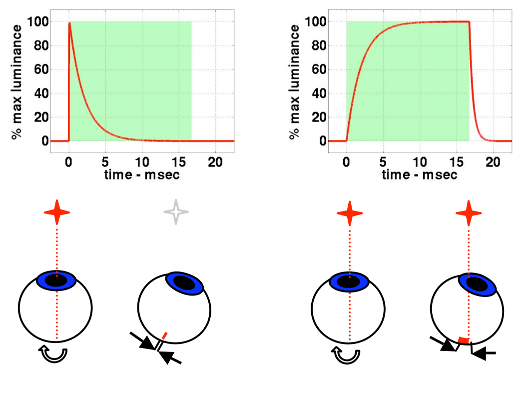

Fig. 2 – As shown in (a), the relatively brief illumination of the CRT pixel stimulates a small visual angle of the retina even when the eyes are engaged in smooth pursuit eye movements. The long illumination of the LCD or LCoS pixel (b) stimulates a large portion of the retina when the eyes are moving, resulting in blur.

Response time

The perception of a pixel is related to the temporal integration, or area under the curve, of the light output. The difference between the perceived and the desired luminous levels increases as more of the pixel's signal is dominated by the response time. When the pixel's decay in luminosity begins at the end of a frame, and this luminance continues into the next frame, motion blurring will result (Fig. 3).

The technology behind LCD displays lends itself to motion smearing issues. For an LCD display, light passes from the light source through the electronic circuitry components for controlling pixels, and all the way through the liquid crystal (LC) panel. Higher contrast images are achieved through relatively thick LC panels; and, the thicker the panel, the slower the response time. LCoS technology uses a much thinner LC panel on top of a silicon mirror. The light travels through the liquid crystal, bounces off the mirror then travels back through the liquid crystal. The optics are a bit more complicated, but because the light travels through the LC twice, high contrast can be delivered with a much improved response time.

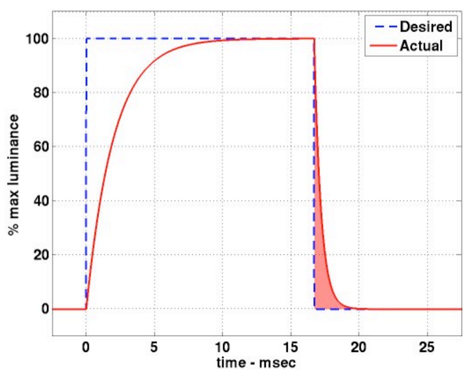

Fig. 3 – Representative non-instantaneous response for an LCD/LCoS pixel. The persistence of illumination after the end of the refresh cycle (shaded in red) produces motion-induced blur.

Perceptual Consequences

Winterbottom et. al. (2004) have developed a technique that directly measures the perceptual effect of the type of blur resulting from pixel hold time. This method has been used to study the relationship between motion-induced blur and hold time.

Winterbottom et. al. (2006) examined the properties of a shuttered LCD projector. Two hold times – 11.3 and 8.3 msec – were examined. In the baseline condition (11.3 msec hold time), the amount of blur was approximately linearly proportional with the rate of image motion, resulting in blur of approximately 10 pixels for image motion of 800 pixels/sec. The 8.3 msec hold time was associated with an approximate 50% reduction in blur, although the reduced hold time condition still exhibited significantly more blur than a CRT display.

Geri and Morgan (2007) examined the effect of display hold time on perceptual blurring using an FLCoS (Ferroelectric Liquid Crystal on Silicon) helmet-mounted display. Hold times of 13.4, 8.0, 6.0, 4.0, and 3.0 msec were evaluated at motion rates ranging from 9.8 to 59.1 deg/sec. The longest hold-time condition, 13.8 msec, was associated with blur that was proportional to the motion, with approximately 20 pixels blur resulting at image motion of 60 deg/sec (approximately 0.2 pixels of perceived blur per deg/sec of image motion). When the hold time was reduced to 8 msec, the perceived blur dropped significantly in all conditions. At the fastest image motion, the perceived blur was 13.5 pixels for the 13.4 msec hold time, as compared to 5 pixels for the 8.0 msec hold time. Other reductions in hold time resulted in modest reductions in perceived blur, to values on the order of 1 to 3 pixels for the minimum hold time (3.0 msec). However, even the lowest levels of perceived blur on the FLCoS display was above that experienced with CRT, which was in the range of zero to 1.0 pixels of blur.

The levels of blur encountered in the baseline condition of this study would likely produce very salient and objectionable differences in perceived resolution as a function of image motion. For the FLCoS experiment, each pixel subtended 3 arcmin. At the highest image motion rate, 60 deg/sec, this would result in blurring of a full degree of visual angle! While human visual acuity does degrade somewhat with image motion, the degradation is very small in comparison to the motion-induced blur. Brown (1976) measured changes in human visual acuity as a function of both stimulus motion and contrast. He found that in general, visual acuity degraded linearly as a function of image motion; at contrast levels of 23%, visual acuity varied from 1.8 arcmin with no stimulus motion, to 6.0 arcmin at 80 deg/sec stimulus motion. At contrast levels of 36%, acuity varied from 1.5 arcmin (with no stimulus motion) to 4.5 arcmin (at 80 deg/sec).

Simulator Performance Implications

In essence, this motion-induced blur artifact has the characteristic of reducing the perceived spatial resolution of the image when the image is in motion.

Simulation tasks in which spatial resolution becomes critical include the detection and identification of small (or detailed) features, airborne or ground-based. One example is the detection of airborne targets in air-to-air combat.

Geri and Winterbottom (2005) studied the effect of display resolution on the discrimination of the orientation of a target aircraft. They determined the orientation detections thresholds[2] for two levels of spatial resolution, approximately 4 arcmin/line and 8 arcmin/line. With the high-resolution display, subjects were capable of detecting aircraft orientation at greater distances in comparison with the low-resolution display (approximately 7000 ft distance for high-resolution, 5000 ft for low-resolution).

It is likely that motion-induced blur would introduce a highly salient and objectionable level of variation on target detection and identification tasks conducted as part of a simulation scenario. Even at the relatively modest image motion rates of 20 deg/sec, Geri and Morgan (2007) found blurs on the order of 4 to 7 pixels, or 12 to 21 arcmin. For the aforementioned aircraft orientation discrimination task, targets with sizes in the range of 6 to 18 arcmin were identified; even small levels of motion-induced blur would likely significantly change performance on this task.

In addition to determining the perceived blur of the shuttered LCD projector, Winterbottom et. al. (2006) also evaluated the suitability of the projector for simulation and training applications, specifically for fighter applications including aggressive maneuvering. Pilots felt that the unshuttered (11.3 msec hold time) condition would inhibit training, while they commented that the shuttered projectors (8.3 msec hold time) recovered faster during aggressive maneuvering, and required more rapid rolls and maneuvering for blur to become noticeable.

Aircraft orientation determination is not the only type of simulator task that could be impacted by the motion-induced blur. Any task in which the finest spatial resolution of the display is necessary to convey an important cue or data would be impacted by this artifact; other examples include aircraft identification (through planform presentation and markings), detection of airport/landing site markings, and legibility of signage.

[2] Detection thresholds were defined as the distance at which aircraft orientation could be determined at a criterion threshold of 0.816, indicating correct discrimination 81.6% of the time.

One last factor should be considered regarding the suitability of display systems with motion-induced blur. The blur is a result of the interaction of two parameters; 1) pixel hold time, and 2) pursuit eye velocity. It is unlikely that the blur would be significantly affected by the actual spatial resolution of the display – whether a pixel is "big" or "small": both light sources would sweep out the same visual angle on the retina for a given hold time and pursuit rate. It is anticipated that the relative saliency of this artifact (specifically the difference in perceived resolution between a static image and a moving image) will significantly increase with higher-resolution displays.

Potential Solutions

Hold time and response time are the two factors that affect motion-induced artifacts. Solutions that improve these artifacts address one of the two factors.

Hold Time

Several different solutions have been proposed to reduce motion-induced blurring in sample-and-hold type display projectors (LCoS and LCD). Some of these proposals include: black data insertion, light modulation schemes (Fisekovic, 2001), higher frame rates (Itoh, 2004), and pre-display video processing (Klompenhouwer, 2004).

Light modulation schemes attempt to chop the light output of the projector, and thus reduce the effective hold time for each pixel. Modulation of the light source itself can be used to reduce the effective hold time of these projectors. Typical lamp modules cannot be modulated at sufficient rates to produce a shuttering effect on the hold time of the image. In contrast, LED and laser type illumination sources *could* be modulated at rates sufficient to reduce the effective hold time. Although gaining in popularity, currently very few commercially available projectors utilize LED lighting as the illumination source.

Another solution places an external shutter in the optical path, effectively reducing the hold time of the projector. As Streid (2007) pointed out, significant reduction of motion blurring can be achieved with this method on LCoS projectors. The shutter must be synchronized with the refresh rate of the display and made to scroll with the refresh rate of the projector. LCD shutters exists that may fit this need, but the shutter refresh rate and its resolution must be sufficient to not introduce additional artifacts. Mechanical optical choppers exist that offer alternatives to implement the scrolling behavior necessary. This type of solution can cause large-area flicker and ghosting within the image caused by a stepping artifact. Streid (2007) proposes that these negative impacts of scrolling shutters can be mitigated in the next-generation LCoS materials and displays.

Increasing the refresh rate is another option for reducing hold time. This is an attractive alternative for two reasons. First, increasing refresh rate rather than shuttering will not produce the inevitable loss of overall achievable luminance that shuttering, or hold time reduction alone, would produce. Second, the experiments performed to-date on shuttering and perception (Winterbottom et. al. 2006, Geri and Morgan, 2007) suggest that hold times in the range of 8 msec or less produce significantly less motion-induced blur, more improvement than was predicted. Doubling of current typical refresh rates (60 – 72 Hz) would achieve this.

Although this is an attractive solution, it is technically difficult to achieve. Although *short* response times of the liquid crystal (LC) could potentially improve blur, a doubled driving frame rate would yield less improvement with *longer* LC response time (Klompenhouwer, 2005). This method does not seem to induce large area flicker and the projector luminance ratings are not significantly impacted. However, increased frame rates reduce the hold time only if the incoming frames are not simply repeated, but interpolated using motion estimation and/or compensation techniques – which can introduce other artifacts into the images. In order to achieve higher frame rates, LCoS panel performance specifications – such as shorter line address times – must be improved.

Response Time

In earlier LCD-based displays, the response time (on-time + off-time) of the display dominated the moving picture induced artifacts. However, in the past 10 years, liquid crystal technology has improved to a point where only about 30% of the motion blurring is caused by the response time. The other 70% of the blurring is due to the "sample and hold" type display of the technology. Further improvements in response time in-and-of-themselves will have little impact on overall motion blurring until improvements in the hold time can be realized. That being said, some of the improvements in hold time rely upon improvements to the response time of the technology (LCD or LCoS).

Measurement

One challenge to improving moving picture induced artifacts is the current lack of an accepted standard by which to measure and compare the different technologies and displays. Two basic types of methods have been developed: sensor-based; and perception-based. The appendix contains an overview of measurement techniques currently in use to quantify the effects of motion-induced blur.

Sensor-based measures are attractive because of the potential for stability and repeatability of these measures. However, the current implementations of the measures do not provide a methodology that is applicable for the majority of projection and display devices. Assumptions appear to be built into the standard that the response time of the display is the dominant factor for causing motion induced blur – an assumption that is not true with today's display technology. Additionally, as noted in the appendix, there has been relatively little success at correlating sensor-based measures and perceptual measures.

Watson (2006) has proposed that existing sensor-based measurements are lacking in that they do not take into account the potentially complex shape of the temporal step response, and demonstrated the potential impact of varying response characteristics with human perceptual models. He proposes a metric that more accurately accounts for the effects of human vision processing on the resulting perception of blur.

Conclusions

The CRT projectors' performance with rapid image motion is often used as a comparison standard for other technologies. Other technologies offer advantages beyond CRT projectors that make them attractive; however, these projectors need to improve their moving picture response to validate the continued interest by the simulator industry.

Motion-induced blur is likely to be a highly salient and objectionable visual system artifact; the severity will likely be very dependent on the specific vehicle/application and task, as well as other display characteristics. This artifact is likely to be more objectionable on higher resolution display systems.

Reduction of hold time has been shown to be an effective mechanism to reduce motion-induced blur artifacts. In order to achieve this, optics driving mechanisms and/or illumination schemes need to be improved in the next generation of projectors to realize significant improvements in motion-induced artifacts. Research indicates that hold times of 11 ms or less can yield significant reduction of perceived blur; additionally, hold time reductions below 8 ms provide very small additional improvement in blur reduction. Reducing hold time to a fraction of the refresh, rather than illuminating the pixel for the duration of the frame, will inevitably result in losses of luminance and contrast, so hold times in the vicinity of 8 to 10 ms are probably optimal. Reducing hold time through an increase in refresh rate offers advantages over shuttering, but is more difficult to achieve. Implementation of increased refresh rate would also require improved image generator performance (or other compensatory video processing techniques) in order to achieve any improvement in blur.

A common measurement standard must be developed to allow side-by-side comparisons of the different models and technologies of today, and to allow more cogent discussions on projector performance. Additionally, in order for these standards to be usable to inform design decisions, a clear correlation needs to be established between the sensor-based measurement metrics and human perception, across varying levels of contrast, luminance, and resolution.

Appendix

Two measurement approaches have been developed to quantify the characteristics of blur; sensor-based, and perception-based.

<u>Sensor-based measures.</u> A number of sensor-based measures have been developed. The Motion Picture Response Time (MPRT) – also called Moving-Edge Blur (MEB) or Moving Edge Response Time (MERT) – is gaining acceptance to quantify the blur in flat panel displays (Streid, 2006). The Flat Panel Display Measurements standard is produced by the Video Electronics Standards Association (VESA). The MPRT measure from this standard currently makes some assumptions that are true for flat panel displays but not for projector displays. However, several research efforts are exploring modifications to the standard MPRT to allow it to effectively evaluate both flat-panel and projection type displays (Streid, 2006; Pan, 2005; Someya, 2007).

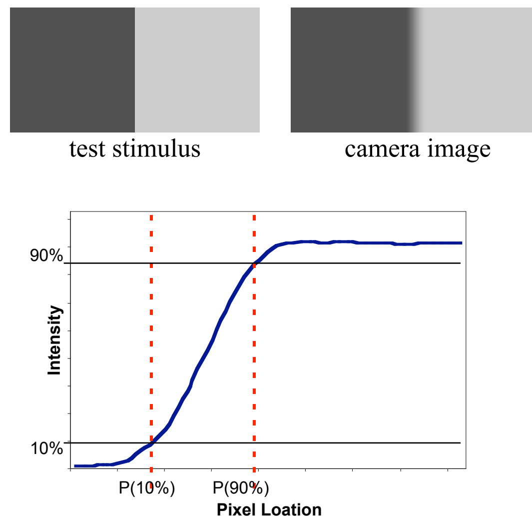

Figure 4. Example of MPRT measurement technique. A test stimulus (upper left) consisting of two luminances is moved from left to right. A camera or photosensor tracks the movement of the edge and records the image (upper right). Pixel locations at 10% luminance change and 90% luminance change are measured to determine resulting MPRT.

The MPRT, as proposed by VESA's Flat Panel Display Measurement (FPDM) Standard, version 2.0, is designed to quantify the motion blur perceived by the eye when viewing an image moving on a display during smooth-pursuit eye tracking. In this test, the display is initially filled with a constant, uniform luminance level. An edge of a second luminance level is scrolled from left to right at a constant pixel/frame rate until the entire display is filled with the second luminance level. A camera indexed to track the motion of the moving edge captures images of the edge in motion – as the camera is moving at the same speed as the displayed luminance edge, the edge does not move within successive camera images and any blur is theoretically due to the display device, and not the integration of the camera device.

The MPRT of the luminance transition region is calculated with different transition levels. As shown in Fig. 4, the camera-pixel locations, P(90) and P(10) respectively, of 90% and 10% of the peak luminance level are obtained, and 125% of the difference is reported as the extended blur-edge width (EBEW).

$$EBEW = 1.25 * |P(90) - P(10)| \qquad \text{(Eq. 1)}$$

The VESA Flat Panel Display Measurements Standard Version 2.0 (FPDM2) suggests a minimum of 21 measurements across 7 different grayscale transitions be taken. The EBEW measures are averaged to obtain the MPRT measure.

In separate research, Streid (2006) suggests using the MPRT scores across a range of motion speeds, expressed as a fraction of the MPRT for static motion to better adapt the standard to current projection displays.

The FPDM standard does not specify the type of sensor to be used for the measurement – the technique described here represents one of several different sensing methods that can be used. For instance, a photo-diode based circuit can be statically positioned inside the range of the moving test images, or a smooth-pursuit camera can be used to follow and capture the moving test images. Either the relatively instantaneous acquisition time of the photo-sensor or the zero motion of the camera relative to the image motion, minimizes the distortion effects of the sensing device.

The FPDM2 standard includes placeholders – to be defined in FPDM3 – for measurements of additional motion artifacts including: Horizontal Box Motion Blur, Moving Line Spreading, Moving Line Flicker, and Motion-Induced Grayscale and Chromatic Aberrations [FPDM2 2005]. Through the quantification of additional motion induced artifacts, these testing procedures will allow for a more complete and consistent dialog concerning performance of display devices.

Perception-based measures. Perception-based measures utilize a human subject in place of the sensor, and the subject makes adjustments to the stimulus until a particular characteristic is achieved, or the stimulus matches a reference.

Winterbottom et. al. (2004) developed a relatively simple test that utilizes human observers to quantify the degree of blur. In the test, the observer adjusts the displayed gap between two parallel lines in motion until there is no perceptible gap; the separation of the lines when the observer reports no perceived gap describes the amount of blur present, in pixels. This test is performed for a range of motion values, both vertical and horizontal.

Someya (Someya, 2005; Someya and Sugiura, 2007) presents a perceptual measurement strategy that performs side-by-side comparison of an LCD monitor with a CRT monitor. The CRT monitor is held as the standard and the blur of its moving images are manually adjusted to match the blur of the LCD monitor. The amount of adjustment required to match the CRT to the LCD is deemed the blur of the LCD display. Pan (2006) proposes a similar matching strategy however he presents the observer with a static image and a moving image. Pan utilizes his model of blur and the input of the observer to increase the "blur" on the static image until it matches the viewed blur on the moving image. Again, the amount of adjustment required is deemed the amount of blur for the moving image.

Correlation of methods. Many attempts have been made to correlate sensor-based measures and perceptual measures. Winterbottom et. al. (2006) developed a model to predict perceived blur using the previously described perceptual measure (Winterbottom et. al., 2004). Simulated perceived spatial blur profiles were developed by transforming the measured temporal response into retinal coordinates (based on the pursuit eye movement velocity). The width of the blurring was predicted through selection of a "criterion height", a level of intensity above which the blur was predicted to be perceptible. The model demonstrated good correlation for the unshuttered condition, but the same criterion height did not exhibit good correspondence for the shuttered condition. The authors speculated that several factors could contribute to this result; a primary factor was thought to be the fact that the model did not reflect how the retinal image is represented in the human visual system.

Someya (2007) demonstrated correlations between perceptual measures and predicted perceptual performance that exhibited a high degree of variability. He found that by altering the threshold levels used to define the MPRT metric of the sensor-based measurements, he was able to improve the correlation between the sensor-based and perception-based measures. However, the thresholds producing the best correlations were different for the two monitors evaluated (monitors with different liquid crystal response times were assessed).

Pan (2006) demonstrated good correlation between perceived blur and modeled blur, but the model was based upon theoretically derived point spread functions rather than actual measurements of the display's temporal characteristics.

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Authors Biographies

Dr. Barbara Sweet works in the Human Systems Integration Division at NASA Ames Research Center. Since joining NASA in 1984, she has worked in helicopter handling-qualities research, simulation facility development and management, and human-factors research. Her research has focused on the use of visual cues to accomplish vehicular control (such as piloting an aircraft). This work has included the development of models of human control behavior that account for perspective scene viewing. Dr. Sweet received a Ph.D. in Aeronautics and Astronautics from Stanford University in 1999, and B.S. and M.S. degrees in Aeronautical and Astronautical Engineering from Purdue Univeristy in 1982 and 1986, respectively. She is a member of the AIAA. She is also a pilot, with commercial ratings in both airplanes and helicopters, and flight instructor and instrument flight instructor ratings in airplanes.

Dr. Timothy M. Hebert is a Computer Engineer Ph.D. with 8+ years of experience designing and implementing software platforms for visual inspection and integrated control applications. As the Principal Software Development Engineer for VDC Display Systems, he is responsible for the software projects that support the company's primary product line of projectors. Over the past three years, he successfully integrated full resolution CCD cameras into the projector line to allow automatic correction of the projector's geometry, color convergence, and electrical focus. Dr. Hebert developed image analysis routines to locate, classify and compensate for geometric inconsistencies within the projected image (e.g. keystone, pincushion, skew, etc). His current research focuses on the developments necessary to being new projector technologies into high-end simulators. He earned his Doctoral degree in Computer Engineering from the University of Louisiana, Lafayette in 1998. He is a member of IEEE, SID, and ACM.