Methods for Measuring Flat Panel Display Defects and Mura as Correlated to Human Visual Perception

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Abstract

Human vision and perception are the ultimate determinants of display quality, however human judgment is variable, making it difficult to define and apply quantitatively in research or production environments. However, traditional methods for automated defect detection do not relate directly to human perception – which is especially an issue in identifying just noticeable differences. Accurately correlating human perceptions of defects with the information that can be gathered using imaging colorimeters offers an opportunity for objective and repeatable detection and quantification of such defects. By applying algorithms for just noticeable differences (JND) image analysis, a means of automated, repeatable, display analysis directly correlated with human perception can be realized. The implementation of this technique and typical results are presented. Initial application of the JND analysis provides quantitative information that allows a quantitative grading of display image quality for FPDs and projection displays, supplementing other defect detection techniques.

Keywords: mura, display defects, just noticeable differences, JND, imaging colorimeter

Introduction

Human perception is the ultimate standard for assessing display quality. However, the use of human inspection as a metrology method in display evaluation for either development or production is problematic because of the statistical variation between observations and observer. In particular, human vision is subjective, difficult to calibrate and difficult to replicate from observer to observer.

This imprecision makes it difficult to apply standards consistently from inspector to inspector. This has implications for comparison of various display designs and technology, especially over time, within a development environment. In a production environment this variability also makes it particularly difficult to uniformly apply standards to multiple sources throughout a supply chain. Depending on the tolerances applied, this either increases the risk of accepting defective displays or failing good displays – both of which represent added cost. Also missing is detailed quantitative information on defects, especially as human observers tend to only classify the most obvious defects.

The difficulty in applying automated defect detection using image analysis has been the lack of clear algorithms for defect classification directly correlated to human perception. Recent advances in modeling human visual sensitivity to display defects have allowed the development of a system for the automated detection of just noticeable differences (JND) for various display technologies. Based on sampling of human observers, the JND scale is defined so that a JND difference of 1 would be statistically just noticeable; on an absolute scale, a JND value of 0 represents no visible spatial contrast and an absolute JND value of 1 represents the first noticeable spatial contrast – which for display technologies allows the grading of display defects. By using a computer controlled imaging colorimeter to capture accurate data on spatial distribution of display image luminance and color and then analyzing the data to create a JND map of the image, mura (or blemish) defects in a display image can be graded with a direct correlation to human visual perception.

Display defect detection performed using this system demonstrates that JND analysis is an effective means of obtaining additional information about display image quality that extends other analysis techniques. This analysis system can be applied to any display type, including LCD, OLED, and plasma FPDs, and front and rear projection displays.

Just Noticeable Difference Characterization

Currently, there are a number of commercial systems available that utilize imaging colorimeters to identify display non-uniformities in color and brightness, and discontinuities such as line and point defects. However, the problem of creating an automated system for the detection of more subtle defects that is well matched to human perception has so far proved less tractable. This is in part because human perception of just noticeable differences in display artifacts is dependent on contextual factors, and standard display defect analysis algorithms, based on methods such as setting thresholds and edge detection, are not directly correlated to human perceptions in these cases.

Recent advances in modeling human visual sensitivity to display defects have allowed the development of a system for the automated detection of just noticeable differences (JND) for various display technologies.

The Spatial Standard Observer (SSO) is a software algorithm developed by NASA that incorporates a simple model of human visual sensitivity to spatial contrast [1]. It was specifically created for display metrology applications, and identification of display "mura," or blemishes. Factors that are included in this model are spatial frequency (how fast spatial contrast varies), orientation (the angular orientation of the spatial contrast relative to the viewing plane defined by human eyes), and the observer's distance from the display being viewed.

This algorithm has been adapted for use in Radiant Vision Systems ProMetric image analysis software to allow ready application to arbitrary display data captured by an imaging photometer or colorimeter. In general the analysis technique can be applied to either a photopic or colorimetric measurement image; because the analysis method generates useful data for both brightness and color, so we will generally refer to colorimetric images.

A short synopsis of the SSO algorithm is as follows:

- The input to the algorithm is a pair of images, the test image and a reference image.
- The test image is an imaging colorimeter measurement, possibly containing mura.
- The reference image is computed from the test image as a low-pass filtered version of the test image designed to eliminate the mura.
- The difference between test and reference images is filtered by a contrast sensitivity function (CSF).
- The filtered image is then multiplied by an aperture function.
- The final step is a non-linear pooling of the resulting image over space to produce the JND image.

The CSF is a measure of the visibility of different spatial frequencies at different orientations. It reflects the decline in human visual sensitivity at higher spatial frequencies and at very low frequencies, as well as the lower sensitivity at oblique orientations (the oblique effect). The aperture function models the decline in human-visual sensitivity with distance from the point of fixation.

Automated Measurement System Structure

Automated measurement and analysis of displays with an imaging colorimeter requires combination measurement control and analysis software. The general structure of the system that we have developed for this application is shown in Figure 1. The key components of the system are: (1) a scientific-grade imaging colorimetry system; (2) PC-based measurement control software which both controls the imaging colorimeter and test image display on the device under test; and (3) a suite of image analysis functions that allow various tests to be run, including JND analysis. The result is a system that can be easily automated for a variety of display defects and delivers quantitative results including point and line defects as well as JND analysis.

The software architecture used has as a basis a core set of measurement control modules that provide the interface with the imaging colorimeter and the display under test. A series of specific test functions is built on this base, using function calls to generate various measurements of white, red, blue, green display screens at various brightness settings for uniformity analysis, or of checkerboard patterns for contrast measurement. A consolidated user interfaces allows selection of tests to be run as well as specification of test parameters and pass / fail criteria where relevant. For production applications the user interface supports both administrator mode – with full access to test specifications – and operator mode – that only allows test execution.
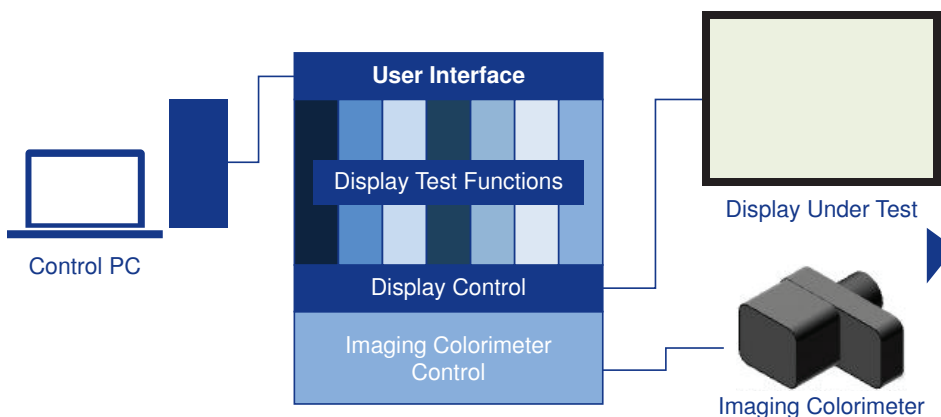

User Interface

Display Test Functions

Display Control

Imaging Colorimeter Control

Control PC

Display Under Test

Imaging Colorimeter

Figure 1 - *Structure of an automated display measurement system, which consists of an imaging colorimeter and measurement control and image analysis software. The User Interface allows the selection and management of the Display Test Functions, which, in turn drive the display and imaging colorimeter through control interfaces.*

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The Use of Imaging Colorimeters for Measuring Displays

The quality of the analysis of display mura is dependent on the quality of the data gathered by the imaging colorimeter. While such a system is conceptually simple, in practice careful attention must be paid to the design and calibration of the imaging colorimeter and to the measurement set-up in order to yield accurate results. This is especially true for mura detection, although the standard image analysis algorithms for uniformity measurement, line defect detection and point defect detection also require good input data as well as accurate data analysis to be meaningful.

Figure 2 - *The ProMetric® Imaging Colorimeter is typical of the test and measurement equipment used for display defect detection. The imaging colorimeter technology and resolution are usually selected based on the display specifications and the array of tests to be performed. Most tests are performed with the display normal to the imaging colorimeter, but the display may be rotated with respect to imaging colorimeter to obtain view angle data, including for JND analysis.*

Imaging Colorimeter System Design

The main components of an imaging colorimeter are an imaging lens, a set of color filters, a CCD detector and data acquisition and image processing hardware/software [2]. Other elements may include neutral density filters and a mechanical shutter. To perform colorimetric measurements, the system acquires an image of the device under test through each of the various color filters. When needed, neutral density filters are employed to ensure that each color measurement uses the full dynamic range of the sensor. Photometric measurements are performed using only the green (photopic) filter. The image data is then processed using previously determined calibrations to yield accurate color or luminance data for every pixel in the image. The spatial resolution of this data depends upon the imaging optics and sensor dimensions. The benefit of using an imaging colorimeter is that the luminance and color of every pixel in a display are measured simultaneously, at a given view angle. The imaging colorimeter preserves the spatial relationship of measurements across the display, which is required for measuring spatial variations.

Because an imaging colorimeter acquires multiple data points in a single measurement, it is inherently much faster than an approach based on spot measurements. In addition, simultaneously measuring the entire surface of the device under test makes it useful for gauging color and luminance uniformity, and for identifying very small defects. The imaging colorimeter can even be used for assessing characteristics of projection systems such as distortion and focus quality. Likewise, the ability to render a processed image of the display can help to reveal subtle features (mura) for quantitative analysis.

Application to Display Performance Analysis

The selection of an imaging colorimeter for specific display measurements will depend on display specifications, including pixel resolution and pitch, and measurement objectives, including whether uniformity only or pixel level defects are to be measured. Imaging colorimeter attributes that can be selected include CCD type (full frame or interline transfer), CCD resolution (greater resolution is usually required to identify pixel or sub-pixel defects), dynamic range, field of view (which will be a function of CCD and lens choice), and measurement speed (where faster measurement speed usually means lower measurement accuracy).

In our application of JND analysis for display defect detection, a ProMetric G3 Imaging Colorimeter was used with measurement control and test management functions performed by TrueTest software. This software manages a full range of the visual and quantitative tests for qualifying display performance.

TrueTest includes tests for brightness and gamma correction, color correction, identification of general mura and pixel defects, brightness and color uniformity, contrast ratio, image quality, image size and location, convergence, and many other tests. For the study discussed in this paper, we incorporated a JND analysis test function into TrueTest.

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Test Set-Up
Display testing must generally take place in a darkened environment. Either a dark room or a test tent must be used to provide the level of darkness necessary for accurate measurements. If a screen is being used (i.e. front projector system), then the environment must also have dark walls, ceilings and floors to prevent stray light from reflecting off these surfaces onto the screen. This is particularly important during the illuminance calibration process. Dark curtains and floor coverings that have a textured surface work best for dampening the reflected light.

In addition, some mechanism for positioning the display at the appropriate working distance from the imaging colorimeter must be implemented. This can either be done manually or with a mechanical system.

Implementation of JND Algorithms for Automated Display Testing

The implemented JND analysis function processes a captured image of a display to generate a JND mapping of the image. The algorithm also outputs three JND metrics that may be used to grade the visual quality of the display. This has immediate value for production line applications, for example both in LCD fabrication facilities and final display assembly lines. The generated metrics are:

(1) Aperture: The aperture function represents the fovea vision of the eye. Aperture is a localized metric that indicates the visibility of artifacts at each point in the image. The aperture JND metric, at each pixel, reflects the visibility of artifacts in a region in the neighborhood of that pixel, when the observer is fixated on that pixel. The output of the Aperture metric is thus an image (JND image). The Aperture metric is best suited to small local artifacts, such as typical spot mura. The **Max JND** metric is the maximum value found in the JND image.

(2) Total JND is the result of a nonlinear pooling across the JND image. It gives an overall measure of the visibility of artifacts in the image. It is most useful when the image contains several artifacts at different locations in the image.

(3) Single JND is a metric that works best with large extended artifacts that extend over a large region of the image. It is the result of a summation over the contrast image filter by the CSF (contrast sensitivity function) raised to a certain power. The aperture function is not applied in this metric - so it does not assume the observer is fixated on a small area. It produces only a single value, rather than an image.

The JND analysis was implemented with a number of input options that are detailed in Table 1. The input options increase testing flexibility, allowing the JND analysis to be applied to a broad range of measurement situations.

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Table 1. User selectable options implemented for JND analysis.

Option or Parameter	Description
Down-Sample	The image may be down-sampled to decrease the processing time. Down-sampling normally has small to negligible effect on the resulting JND values, unless the down-sampling is excessive. Typical values are 2x2. For example, 2x2 down-sampling will select every other row and column for processing. No averaging is done; the skipped rows and columns are simply ignored.
Save to Database	When *SaveToDatabase=True*, the resulting JND image will automatically be save to the current measurement database at the conclusion of the processing. In addition, a difference image will also be saved showing the contrast *difference* between the test image and a calculated reference image. In any case, the final JND image can be manually saved to the database by executing separately the "SaveToDatabase" image process.
Viewing Distance	The viewing distance parameter is the approximate distance which a human observer would evaluate the display. It is not the camera distance. The viewing distance value is specified in units of the display height. For example, a value of 2 indicates the viewing distance is equal to 2 times the height of display. Changing the viewing distance has the effect of making artifacts more or less visible. A small point defect may be visible at close viewing distance but less visible or not visible when viewed from further away.
Region of Interest	A region-of-interest (ROI) inside the measurement may be defined for mura analysis by dragging a rectangular region with the left mouse button on the bitmap image. The region-of-interest will appear as a solid white rectangle. It is not necessary to crop the measurement to this region-of-interest. The image process will utilize the image area defined by the white rectangle. If no region-of-interest is supplied by the user, the image process will automatically find the active-display-area in the measurement image, removing the dark border surrounding the image, if there is one. If there is not a well-defined edge defining the active-display-area, then the user should provide a region-of-interest.
TristimType	If a single tristimulus image (*TrisX, TrisY or TrisZ*) is selected in the parameter table, then the image process will operate only on that tristimulus image. The other two tristimulus images will be dropped. If the TristimType selected is *All*, the image process will be applied to all three tristimulus images in the case of a color measurement; or to the TrisY image in the case of a monochromatic image.

Measurement Examples

The JND analysis algorithm defined above has been applied to many different display image samples to test its usefulness. In general, the technique has been demonstrated to work well in identifying mura; more importantly the computed JND value provides a numerical assessment of the JND that can be used to grade different mura or displays.

In Figures 3, 4, and 5, the application of the algorithm to a LCD FPD is shown. In this case a white screen image is processed. Two JND maps of the screen are shown: raw JND image, and a JND map with a color scale to distinguish between various levels.

In Figures 6 and 7 the JND algorithm is applied to an LCD projector screen image. In this case a very obvious mura at the upper center of the image is readily identified. In both cases we show the results of measuring an all white display. The analysis can also be applied to any other uniform screen image, including black screens.

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Figure 3 - LCD FPD screen measurement with gradients near the edges of the display and two mura near the center of the display. The mura at the center of the screen are faint and barely noticeable in the original image (indeed, it helps to know that they are there!).
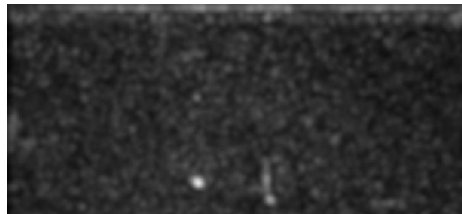

Figure 4 - The raw JND analysis of the screen image (lighter for higher values of JND and darker for lower values) clearly shows the mura at the center of the screen. In addition, some artifacts – light leakage and dark spots – at the edge of the screen are also visible. This analysis highlights mura that were barely visible in the original image.
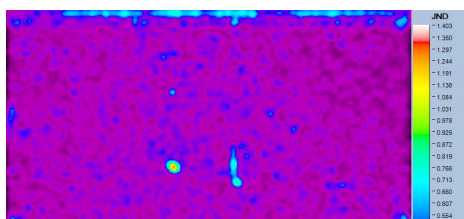

Figure 5 - In a false color representation of the JND map, it can be seen that the two spots in the center of the display and some areas along the bottom of the display have JND values of greater than 1 (the threshold value for being "just noticeable"). The dark spot in the bottom right corner of the display has the largest computed JND value. The mottled area across most of the display apart from the mura at the center and along the edge represents JND values of about 0.7 or lower and could be smooth by setting a threshold value.
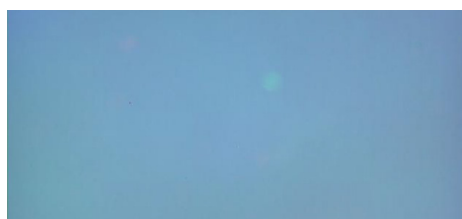

Figure 6 - An image taken of a white display from an LCD projector - a mura in the upper center of the screen image is readily visible.

Figure 7 - The JND image computed from the LCD projector white screen measurement. The Max JND, Total JND, and Single JND values allow grading of various attributes of display performance.

Conclusions

We have been able to demonstrate the application of the SSO algorithm for describing mura on a JND scale as a component of an automated system for display defect detection. As a standalone test, the algorithm has been applied to a variety of display technologies and has been demonstrated to be able to identify display mura.

Continuing application of the algorithm in analyzing real world displays is required to understand its full potential. In addition, display mura do not generally exist in isolation. In a real-world testing environment, the measurement system must be able to identify physical defects such as a scratch or other display image defects such as bad or stuck pixels and line defects. The coordinated combination of various tests, including one based on the SSO algorithm, provides the most promising approach to fully identifying and characterizing display defects. In addition, various mura identified by the algorithm may have different physical causes, so their remediation or implication for quality improvement is different; therefore the use of this analysis to not only identify and grade mura, but to extend it to classify the causes of the mura is an area for further investigation.

While the SSO algorithm was developed to describe display mura on a JND scale, we have also been able to apply it to other applications where noticeable changes in spatial contrast are meaningful, for example to characterize the uniformity of paper or paint finishes.

Further exploration of application to material characterization has broad interest for quality control.

References

[1] Watson, A.B., "The Standard Spatial Observer: A new tool for display metrology," Information Display 23(1), (2007).

[2] Rykowski, R. and Kostal, H., "Imaging Colorimetry: Accuracy in Display and Light Source Metrology," Photonics Handbook (2008).
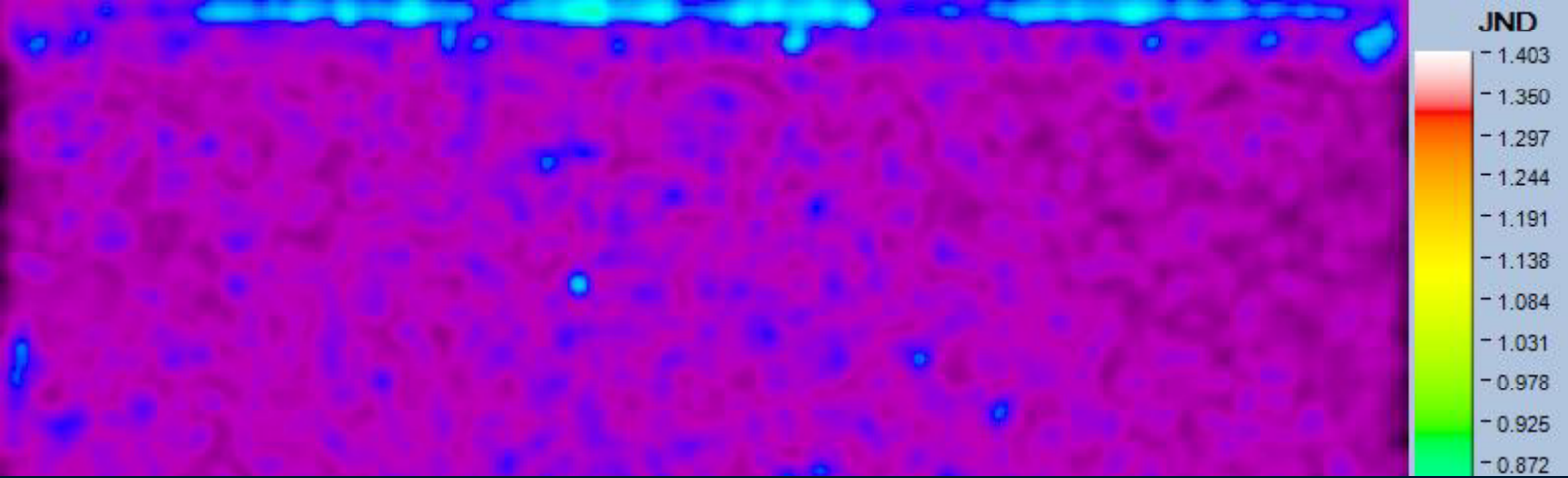
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JND
1.403
1.350
1.297
1.244
1.191
1.138
1.084
1.031
0.978
0.925
0.872

Accurately correlating human perceptions of defects with the information that can be gathered using imaging colorimeters offers an opportunity for objective and repeatable detection and quantification of such defects. By applying algorithms for JND image analysis, a means of automated, repeatable, display analysis directly correlated with human perception can be realized.

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