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Visual performance optimization of high-quality display-touchscreen combinations

Michael E. Becker - Display-Messtechnik & Systeme - Rottenburg am Neckar - Germany

Abstract: *In order to assure recognition of visual information provided by displays of high-performance digital devices - usually they are combined with a touch-sensitive input screen - under ambient illumination, disturbing and disabling reflections have to be controlled. Scattering anti-glare (AG) layers have been extensively used for control of reflections, but unfortunately they also may introduce an annoying visual effect named* ***sparkle*** *and they potentially effect blurring of the visual information to be transmitted to the observer. We present measurement methods and instrumental realizations for systematic optimization of the visual performance of combinations of display and touch-screen. These approaches can also be applied to evaluation of the effects of intensive use of the touch-screen on the visual appearance of state-of-the-art ICT products and thus on the related user experience and satisfaction.*

Keywords *- display performance optimization, control of reflections, scattering anti-glare layers, sparkle, image blurring, effect of wear and scuff, product appearance, user experience.*

I. INTRODUCTION

Scattering anti-glare (AG) layers are often applied to combinations of display and touch-screen for control of disturbing reflections and for haptic reasons, i.e. to make silky smooth swiping gestures possible and to avoid stick-slip-phenomena. The paths of (1) information forwarding light emerging from modulated subpixels and of (2) disturbing reflections caused by ambient light sources are sketched in Fig. 1.

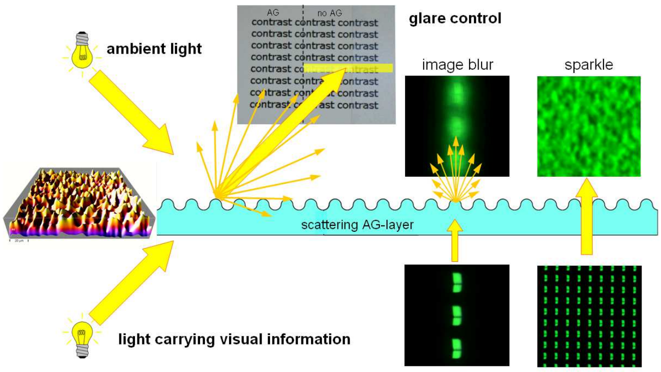

Fig. 1. Generation of sparkle by refraction of transmitted light induced by the micro-structured surface of the anti-glare layer.

The display subpixel matrix in combination with scattering AG-coatings or layers often features a disturbing visual phenomenon named sparkle, a kind of a random moiré pattern [1, 2]. Sparkle is perceived by the human observer as a random arrangement of tiny dark spots across the display area with the pattern changing its appearance rapidly with viewing direction.

The light from the display subpixels which is forwarding the intended visual information to the observer is scattered during transmission through the AG-layer and as a consequence, images and text may be blurred and details may be lost if the overall system performance has not been adjusted appropriately [3].

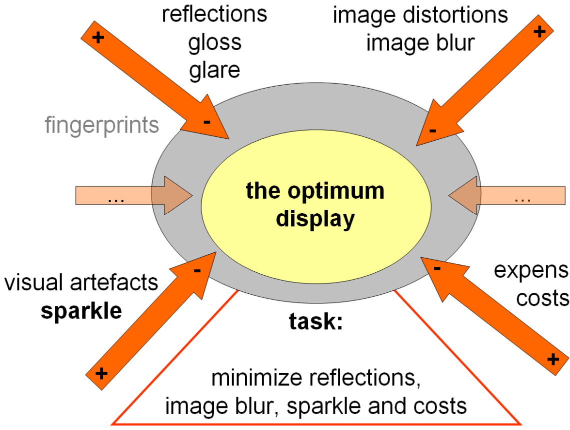

Fig. 2. In order to realize optimum display performance three quantities have to minimized simultaneously: (1) unwanted reflections; (2) disturbing sparkle and (3) blurring of image details and text. These quantities may exhibit opposing tendencies, i.e. improvement of reflection control is often accompanied by aggravation of sparkle and increased image blurring.

In order to optimize the visual performance of advanced displays with touch-screen input devices the engineers must perform the following task of simultaneous minimization as illustrated in Fig. 2:

- minimization of unwanted reflections;
- minimization of disturbing sparkle; and
- minimization of blurring of images and text.

Unfortunately, a local minimum of one quantity (e.g. reflection) may be resulting in a local maximum of another quantity (e.g. sparkle or image blur).

A prerequisite for such a demanding optimization is the availability of reproducible and robust measurement methods and reliable instruments for the above listed optical characteristics.

II. LINEAR SYSTEMS APPROACH

The effect of physical processes like light scattering and image formation by optical components and systems can be characterized by the transfer of spatial frequencies as specified by the optical transfer function, OTF, which generally is a complex valued function of a spatial frequency, f, [4, 5].

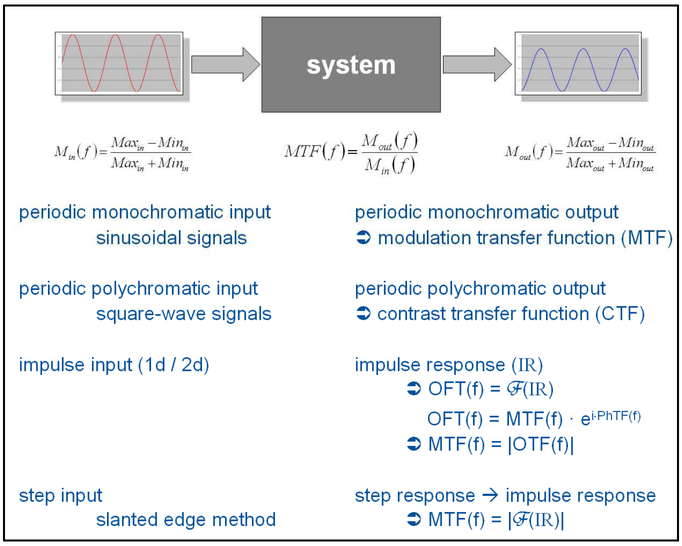

Fig. 3. Specification of the effect of an optical system by the modulation transfer function, MTF, and the contrast transfer function, CTF, and approaches for their evaluation.

The optical transfer function, OTF, is defined as the Fourier transform of the impulse response of the system (point- or line-spread function), the MTF is the magnitude of the complex OTF.

A first way to evaluate the MTF applies periodic sinusoidal modulation of the lateral intensity distribution of light as it can be realized by photographically patterned test-charts. Such test-patterns are quite expensive and their application is cumbersome without specially tailored software. The modulation must be determined individually for each frequency provided by the test-pattern.

A second way replaces the sinusoidal grating by a variable frequency target with periodic square-wave profiles where the transmittance is either minimum or maximum. Such targets however do not produce monochromatic signals, i.e. a range of harmonics of the fundamental frequency is included in the spectrum of the input signal. The modulation must be determined individually for each fundamental frequency provided by the test-pattern. Evaluation of the system response then yields the contrast transfer function, CTF.

The response of the system may also be evaluated by application of a pair of transitions instead of periodic signals, e.g. by impulses in 1 or 2 dimensions (line- or needle-shaped, respectively). The response is called line- or point-spread function, respectively. The Fourier transform of the point-spread function is the 2-dimensional optical transfer function, OTF.

The response of the optical system to a step-function as input can be processed (i.e. numerical calculation of derivatives) to obtain the impulse response from which, basically, the OTF/MTF can be derived [6].

When the system response is determined by electronic imaging, the MTF of the imaging LMD itself must be evaluated and taken into account as described in a series of papers by Masaoka [7, 8].

A. MTF of light measurement devices

A simple approach for estimation of the MTF of an imaging LMD at certain settings (i.e. working distance and aperture, f/#, of the lens) is based on the fact that a transition between dark and light (i.e. edge-spread function, ESF) as produced by a super-sampled slightly rotated knife-edge target can be neatly approximated by a cumulative normal distribution function, CND - or by a superposition of several CNDs - via numerical fitting.

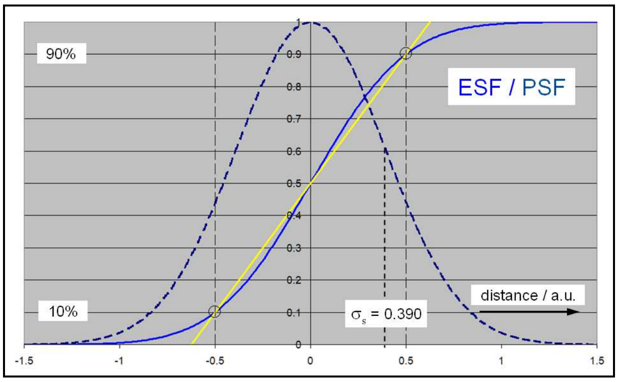

Fig. 4. Edge-spread function approximated by a cumulative Gaussian function (blue) and a linear slope. The edge-width (90% - 10%) is normalized to one spatial distance unit. The standard deviation of the corresponding Gauss distribution function, i.e. the point-spread function, PSF, is 0.390.

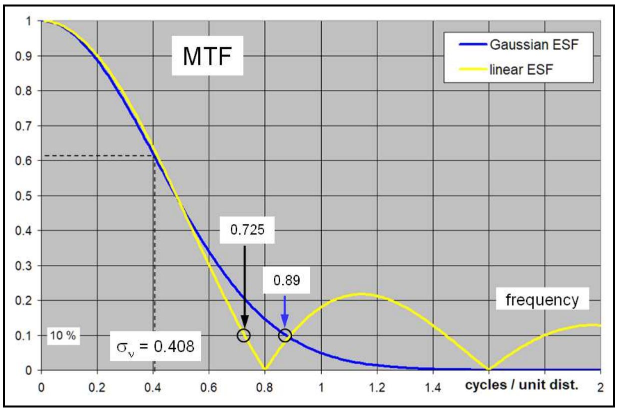

Fig. 5. Modulation transfer function for the linear slope (yellow) and for the cumulative Gaussian function (blue) with a standard deviation of $\sigma_v = \pi/2\ \sigma_S$. The 10% limit is reached at 0.725 c/u (linear ESF) and at 0.890 c/u for the Gaussian ESF (blue curve).

With these standard deviations the derivatives of the edge-spread function, i.e. the normal or Gauss distribution function which represent the point-spread function, PSF, are known and thus also the modulation transfer function, MTF, is readily available since the Fourier transform of the Gauss function is a Gauss function. When the Gaussian ESF is normalized to one spatial distance unit, the drop of the MTF to 10% is reached for a spatial frequency (in terms of cycles / distance unit, c/u) of 0.890.

The original idea for that approach is sketched in the book of Smith [9] where the author approximates the step-response of electronic circuits by several sigmoid functions, i.e. a linear slope, a cumulative normal distribution and an exponential function. Transfer of that idea to the field of optical metrology turns out to be beneficial at low instrumental and computational costs. The results thus obtained are transparent and comprehensible first order estimates. If, for example, the ESF of an imaging LMD is 10 LMD detector pixels, p_{LMD}, wide, the Gaussian MTF drops to 10% at 0.89 cycles / 10 LMD detector pixels = 0.089 c/p_{LMD} which corresponds to one cycle per 11.24 LMD-pixels.

III. MEASUREMENT OF REFLECTED LIGHT

The most comprehensive characterization of reflectance of opaque surfaces is given by the BRDF (bidirectional reflectance distribution function) [10]. The BRDF is a function of the direction of incident and received light, of wavelength and polarization state of the light. Measurement of the BRDF requires either bulky motorized directional scanning mechanisms, complex lens and/or mirror systems, or, alternatively, they can be based on the analysis of the lateral distribution of scattered light, i.e. the spread-function of a point or line light source [11]. The latter approach is well suited for industrial use and well established for characterization of the scattering characteristics of anti-glare (AG) layers for display devices. The method does not require motorized scanning and is robust since it always includes the light source in each measurement as a reference. In addition it provides a high directional resolution, typically in the range of 0.1° and higher [5, 6].

IV. MEASUREMENT OF TRANSMITTED LIGHT

The most comprehensive characterization of the scattering properties of transmissive layers is given by the BTDF (bidirectional transmittance distribution function). Analogous to the BRDF, the BTDF is a function of the direction of incident and received light, of wavelength and polarization state of the light. Measurement of the BTDF requires either bulky motorized directional scanning mechanisms, complex lens and/or mirror systems, or, alternatively, they can be based on the analysis of the lateral distribution of scattered light, i.e. the spread-function of a point or line light source [12]. The latter approach is well suited for industrial use and well established for characterization of the scattering characteristics of anti-glare (AG) layers for display devices. The method does not require motorized scanning and is robust since it always includes the light source in each measurement as a reference. In addition it provides a high directional resolution, typically in the range of 0.1° and higher.

Since these methods for measurement of transmitted light require a point or line light source to be present behind the layer to be characterized, they are not applicable to inseparable combinations of display and touch-screen.

A simple and reliable method for characterization of the blurring effect of scattering layers is based on direct evaluation of the contrast transfer function (CTF) with the display itself forming the test and reference pattern (individual subpixel □ "pixel crosstalk", subpixel-line, subpixel-grille in horizontal and vertical direction) as discussed in [13].

The modulation transfer function (MTF) of scattering surfaces can be obtained directly by Fourier transformation from the respective directional distribution functions, BRDF and BTDF, which represent the response of the surface as a linear, shift-invariant system to an impulse-shaped input function.

V. REALIZATIONS

We have realized an instrument for measurement of the directional distribution of transmitted and reflected light (TDF, RDF), the distinctness of transmitted images (DOI) and the level of disturbing sparkle based on an imaging light measurement device, LMD [14].

A. *Measurement of unwanted reflections*

Based on the method of transforming the point or line-spread function under reflective illumination into the reflection distribution function (RDF, [12]), we have realized an instrument with a linear light source for evaluation of the RDF within a range of ±10° about the specular direction. From that RDF a range of characteristics can be calculated such as the full width at half maximum (FWHM) or the generalized haze (amount of light scattered out of the specular direction into user-definable directional intervals). The most important characteristic is directly characterizing the reduction of the reflected intensity in the specular direction as caused by the scattering of the AG-layer (here: to 8% of the 4.2% reflectance of the black glass mirror).

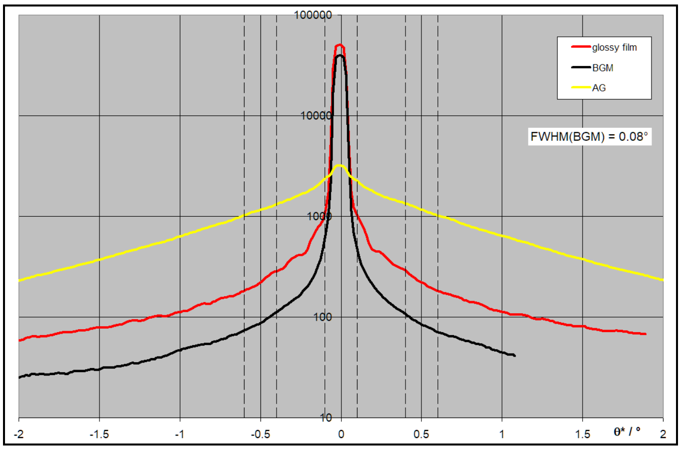

Fig. 6. Reflectance distribution function, i.e. reflected intensity (a.u.) as a function of the angular distance to the specular direction (4.6° from the DUT normal), θ*, for an LCD monitor with a low-scattering AG-layer (AG), for a glossy clear adhesive film added for neutralizing the scattering of the AG-layer (glossy film) and for a polished black-glass mirror (BGM) with a specular reflectance of 4.2% .

The haze as given by the average intensity reflected in the off-specular directions (here: into two windows of 0.1° width and centered about ±0.5° as shown in Fig. 4) related to the intensity reflected in the specular direction (window width 0.1°) are listed in table 1.

	black-glass mirror	**glossy film**	**AG-layer**
haze	0.0061	0.0119	0.4285

It is obvious from the reflectance distribution functions shown in Fig. 4 that the glossy clear adhesive film effectively suppresses scattering from the surface of the AG-layer and re-establishes a specular reflection component. Comparison with the RDF of the black glass mirror (BGM) shows some degree of scattering from the internal structures of the LCD (color filters, black matrix, etc.).

B. Measurement of sparkle

While sparkle is perceived by the human observer from a distance where the pixel-matrix of the display is not visible (i.e. below the visual thresholds given by the contrast sensitivity function of the human visual system), periodic intensity modulations caused by the display pixel matrix are contained in the electronic images from which the sparkle contrast is to be determined. These modulations have to be suppressed in the recorded images by filtering in the spatial or in the frequency domain as described and compared in [2].

The clear adhesive layer with polished surface for canceling surface scattering of the AG-layer is effecting a reduction of sparkle contrast from 1.5% (with original scattering AG-layer) to 1.0% when surface scattering is suppressed by the added polished optical layer.

C. Measurement of blurring of text and image details

Methods for measurement of image blurring as caused e.g. by scattering AG-layers have been introduced and compared in [13]. The optical input may range from point-sources (e.g. a single illuminated subpixel), subpixel lines up to periodic grille patterns. When the AG-layer can be separated from the display, the light source is accessible and available as a reference during the measurement. When inseparable combinations of display and AG-layer have to be measured, for example in order to assess the effect of thousands or even millions of swiping finger movements, the light source is not accessible and changes of image clarity can be evaluated with reference to unstressed areas of the object of measurement or unstressed samples.

For the case of inseparable combinations of touch-screen and display, we have implemented a method based on a grille pattern of activated green subpixels. This pattern is providing the periodic intensity modulation with the highest possible frequency in the horizontal direction. In order to reduce the effect of image sampling by the LMD detector array (i.e. sampling rate and phase) and to consider the width of the subpixel intensity we filter the profiles (or the images) with a window of width $p_o/2$ where p_o is the display pixel pitch in terms of LMD pixels. $1/p_o = f_0$ is the fundamental frequency of the images (in terms of cycles / LMD pixel) and then we evaluate the modulation, m, of the filtered profiles. This filtering process suppresses the 2nd harmonic component of the system response including all other even harmonics and reduces the amplitudes of the odd harmonics. As a consequence the remaining modulation is mainly given by intensity variations at the fundamental frequency, f_0.

VI. MONITORING OF VISUAL APPERANCE

The visual appearance of technical devices like, for example, smart-phones, is an important aspect of the general domain of user experience and satisfaction.

Repeated use of devices that are equipped with combinations of an electronic visual display and a touch-screen may introduce wear by abrasion and thus modify the surface and induce changes of the visual appearance of the product. Display screens with an initially glossy surface may turn matte and dull at certain locations by repeated touches and swipes while initially matte surfaces may loose their scattering anti-glare properties at certain locations and thus produce an unfavorable spotted and stained visual appearance.

An important aspect for characterizing product durability and expected period of acceptance by the user is thus the visual appearance of the combination of display and touch-screen and the variations and changes it undergoes with thousands or millions of finger touches and swipes as caused by repeated use (see e.g. VDE SPEC 90017 V1, [15]).

The effect of localized mechanical stress on the visual appearance of the combination of electronic visual display and touch-screen should be evaluated considering two main aspects:

1 the appearance of the surface of the combination of display and touch-screen as perceived by reflection of light sources. Since the process of reflection and the resulting directional distribution of reflected light is very sensitive to slightest modifications of the surface properties, reflection measurements are a suitable probe for surface properties and their modifications.

2 the quality and appearance of the visual information intended to be presented to the observer. All optical components that are in between the subpixels that produce visual information by modulated transmission or emission of light and the observer should have an unnoticeable effect on both the lateral definition of the visual information and on its directional distribution. That lateral resolution is often called *image sharpness* or *distinctness of image* (e.g. ASTM D5767, [16]).

The optical measurements applied for assessment of the final product must be designed in such a way that they can be carried out without the need for disassembling the electronic device under test. The measurements must be selected according to the required significance, their applicability in industrial environments, to their robustness and repeatability.

A similar procedure for determination of the luminance modulation (i.e. contrast) of displays with non-standard subpixel layout is described in section 7.2 Grille luminance and contrast of the IDMS [17]. The draft standard IEC 62977-3-6:

"Electronic displays – Part 3-6 - Evaluation of optical performances – Spatial resolution" covers similar subjects [18].

VII. SUMMARY AND CONCLUSIONS

We have introduced a procedural and instrumental solution to the problem of simultaneous minimization of three unwanted effects occurring in the case of visual displays with scattering AG-layers, comprising:

- minimization of unwanted reflections;
- minimization of disturbing sparkle; and
- minimization of blurring of images and text.

The featured approaches can also be applied to evaluation of the effects of intensive use of the touch-screen on the visual appearance of state-of-the-art ICT products and thus on the related user experience and satisfaction.

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7.2 Grille luminance and contrast
7.7 Effective resolution - deprecated
7.8 Resolution from luminance modulation

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