A New Instrument for Distinctness of Image (DOI) Measurements

Ming-Kai Tse and John C. Briggs
Quality Engineering Associates, Inc.
755 Middlesex Turnpike, Unit 3, Billerica MA 01821
Tel: 978-528-2034 · Fax: 978-528-2033
e-mail: info@qea.com
URL: www.qea.com

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Ming-Kai Tse* and John C. Briggs*

* Quality Engineering Associates (QEA), Inc., USA

As digital printing becomes more and more mainstream in the consumer as well as professional photography markets, the appearance attribute called Distinctness of Image (DOI) is receiving increasing attention as very important in the customer's perception of "photo-like" quality. In this paper, a new measurement technique for DOI is introduced. The underlying principle and design of a new instrument based on this technique are described. DOI results, for both printed and unprinted samples, are correlated with subjective reflected image clarity. Example applications of the technique to the study of ink-media interaction in inkjet printing are presented. Correlations of this new technique with several commercially available instruments are also reported.

Appearance and Distinctness of Image (DOI)

The overall appearance of any object such as a digital photograph is a combination of its chromatic (color) and achromatic attributes (such as gloss, haze, and texture). The combination of these attributes contributes to the total quality of what we perceive. Hence, both types of attributes should be measured and accounted for when making visual or instrumental assessments of appearance.

The subject matter of color and color measurement is well known. Similarly, gloss is generally well understood in terms of its physics and measurement. However, as customer demands and market forces continue to push the envelope of appearance quality in the growing digital photography market, we begin to recognize that the attribute of gloss may not be as simple as we once thought. Often we find that traditional gloss values simply do not correlate with customer's preference. An emerging belief is that there are different gloss-like elements that may influence a customer's perception; and one such element is called Distinctness of Image, or DOI.

While the term DOI may be less familiar to the digital imaging community, it is a term well known to the automotive industry. It has long been recognized as an attribute that characterizes coatings and painted surfaces. In fact, several commercial instruments are available for both visual and instrumental DOI assessments [1-5], primarily targeted for automotive applications.

Conceptually, DOI is the sharpness or clarity of the image produced by reflection of an object on a surface. If the reflection of an object on a surface appears sharp and clear, the surface has high DOI and conversely, if the reflection is blurry and of low contrast, it has low DOI. A related phenomenon called "orange peel" describes the appearance of a high gloss surface with a wavy pattern of light and dark areas. In the automotive industry, absence of orange peel is of utmost importance, and routine DOI assessment is key to assure suitable paint and coating appearance.

Gloss, DOI and Surface Structure

Among several types of gloss identified [6], the most relevant ones to this discussion are: specular gloss, DOI, and haze. Specular gloss is the classic phenomenon of reflection of an object on a "perfectly" smooth surface such as a mirror in which the reflection is very sharp and clear. The angle of reflection equals the angle of incidence in specular gloss. What happens if the surface is not "perfectly" smooth but has some structure or texture? Basically, the presence of the surface structure perturbs the reflected image, leading to the different types of gloss observed.

DOI is a measure of the "spread" in the specular gloss due to scattering by fine structure close to human eye resolution. In digital imaging applications where most observations are made at "normal" viewing distance, the human eye resolution is significantly better than 1mm, say, in the range of 100 to 500 μm.

Haze refers to a cloudy or milky appearance, also due to scattering of light. Light may be scattered, for example, by pigment particles, an "imperfect" surface caused by dirt or oil contamination, or a fine structure.

The main point here is that if a surface deviates from "perfect" smoothness, it scatters the reflection of an incident light beam or an image and broadens the specular gloss, decreasing the DOI, and adding the appearance of haze. In other words, surface structure is basic to the observed deviation from specular gloss and is a key controlling factor of an object's appearance. Hence, to engineer high quality substrates for digital printing and digital photography in particular, the effects of surface structure have to be understood, controlled, and measured.

Measurement of DOI

Several methods for measuring DOI have been reported in the literature. They can be categorized as:

a. *Goniometric Method* (Goniophotometry). This is the basis of Method A in ASTM Standard D5767 [7]. In this method, a device with a narrow aperture for the light source and the detector is used to make measurements at specular and slightly off specular angles (±0.3°). Several commercial devices, which we believe to be based on this method, are or have been available [1-3]

b. *Variations of Method A.* These include Method B & C in ASTM Standard D5767. In Method B, light

* Quality Engineering Associates (QEA), Inc.
99 South Bedford Street, #4, Burlington, MA 01803 USA
Email: mingkaitse@att.net

through a narrow slit is projected onto a specimen and the reflected image intensity is measured through a sliding combed filter to provide a value of image clarity. In Method C, a pattern is projected onto the specimen and the reflected image intensity is measured to provide a value of image clarity. We are not aware of any commercial device that implements these methods.

c. *Optical Profilometer*. In this method, an instrument with a narrow-beam light source (such as a solid state laser diode) is scanned over the sample and an optical profile of the surface structure is obtained. From this profile, various DOI measures at different structure size scales are obtained using bandpass filtering. In one implementation [4], the surface structure is broken into several bands: du (dullness, <0.1mm), W_a (0.1 to 0.3mm), W_b (0.3 to 1.0mm), W_c (1.0 to 3.0 mm), W_d (3.0 to 10.0mm), and W_e (10 to 30 mm).

d. *Visual Inspection Method*. In this method, a pattern of features of decreasing size (such as circles, or letter Es or Cs) is projected onto the sample surface and the user subjectively determines the smallest resolvable feature in the reflected image. Equipment based on this method is commercially available [5]. This is basically a qualitative method.

While these methods are available and commercial instruments exist, the applications of such instruments to the digital imaging field is new and the literature on the subject is quite limited [8]. Further, it appears that most of the instruments available today are designed for automotive paint and coating analysis and their applicability to digital print media analysis is not clear. The objective in this paper is to introduce a new DOI measurement method and to demonstrate its efficacy by applying a prototype instrument based on this method to analyze DOI in inkjet printing. The instrument is compact, portable, and does not require any scanning motion. To simplify the following discussions, the instrument will be referred to as the DIAS (**D**istinctness of **I**mage **A**nalysis **S**ystem, patent pending).

The DIAS Method

The basic principle behind the DIAS involves projecting a sharp edge onto a surface, and capturing the reflected image using a solid state area or line sensor, e.g. CCD or CMOS. From the digitized image (Fig. 1a), a reflectance profile is obtained (Fig. 1b) and analyzed to obtain a measure of the DOI of the sample-under-test.

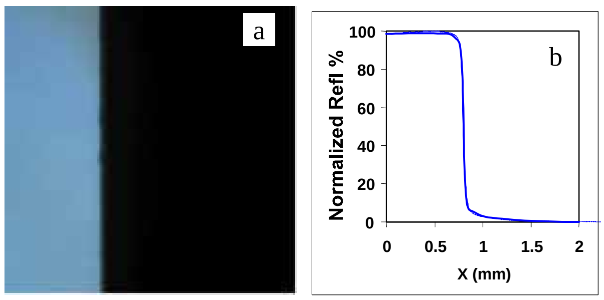

Figure 1: The reflected image of a sharp edge (a) and the corresponding edge spread function (b).

The main idea in this method is similar to the idea of obtaining the MTF (Modulation Transfer Function) of an imaging system from the ESF (Edge Spread Function). MTF, is a property of an imaging system that describes the effect that the system has on the sharpness of an object. In this method, an ESF is computed from the image. Figure 1 shows an image for a high DOI sample and its corresponding profile. From the ESF, we can obtain the Line Spread Function (LSF) by its derivative (Fig. 2a). Mathematically, the LSF is the probability density function for the location of a reflected edge. Ideally, if the surface were perfectly smooth, the ESF would be a step function and the LSF would be a delta function with zero width.

The MTF is the LSF in the frequency domain. Mathematically, the MTF can be obtained by performing an FFT (Fast Fourier Transform) of the LSF. Surface quality information such as the DOI, image clarity, or sharpness can be obtained by characteristics in the LSF or the MTF. In the LSF the important features are peak height and half width. In the MTF, the important features are half bandwidth and rolloff. In this paper, we use the halfwidth of the LSF and the inverse of the halfwidth as the DOI measures. The halfwidth is reported as blurriness (B) in mm and the inverse of the halfwidth as sharpness (S) in mm^{-1}. The lower the blurriness or the higher the sharpness, the higher is the DOI (Distinctness of Image) of a surface.

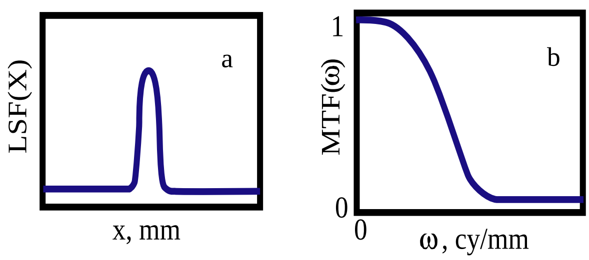

Figure 2: LSF obtained as the derivative of the ESF and MTF as the LSF in the frequency domain.

The ESF contains more information than DOI alone, e.g., the magnitude of the leading edge and the trailing edge reflectance. The leading edge reflectance is related to specular gloss and the trailing edge reflectance is related to the deviation from the specular gloss at moderate to large deviation from the specular angle, hence related to the haze characteristics of the surface.

Experiments, Results, and Discussion

To demonstrate the efficacy of the DIAS method, a study of DOI in inkjet printing was conducted. The results from this study are summarized in Figures 3-5. In using the DIAS, the instrument is placed on the sample-under-test. The region of interest (ROI) of the measurement is 2.5×2.5mm. A DOI measurement is made using the control software in the Pocket PC built-into the instrument.

Figure 3 consists of: (a) the reflected image of a window blind and a potted plant on an inkjet printed substrate captured by a 35mm digital camera; (b) the image captured by the DIAS (2.5x2.5mm); and c) the corresponding ESF profile. Results from several media type are shown: E, a very smooth glossy film, D, a “premium” glossy paper, and A, another glossy paper. All images were printed on the same printer. Ink type was the OEM dye based black ink for this printer. DOI is quantified by the sharpness (S) & the blurriness (B) values as described earlier. The difference in DOI between the different media types is evident in both the large area 35mm images and the DIAS images & profiles. The data also show the correlation between visual ranking (35 mm images) and instrument (DIAS) assessments. The visual ranking is E > D > A and the corresponding DIAS readings are, for sharpness, 20.2, 4.7 and 1.5 mm^{-1} and for blurriness, 0.050, 0.211 and 0.655 mm, respectively.

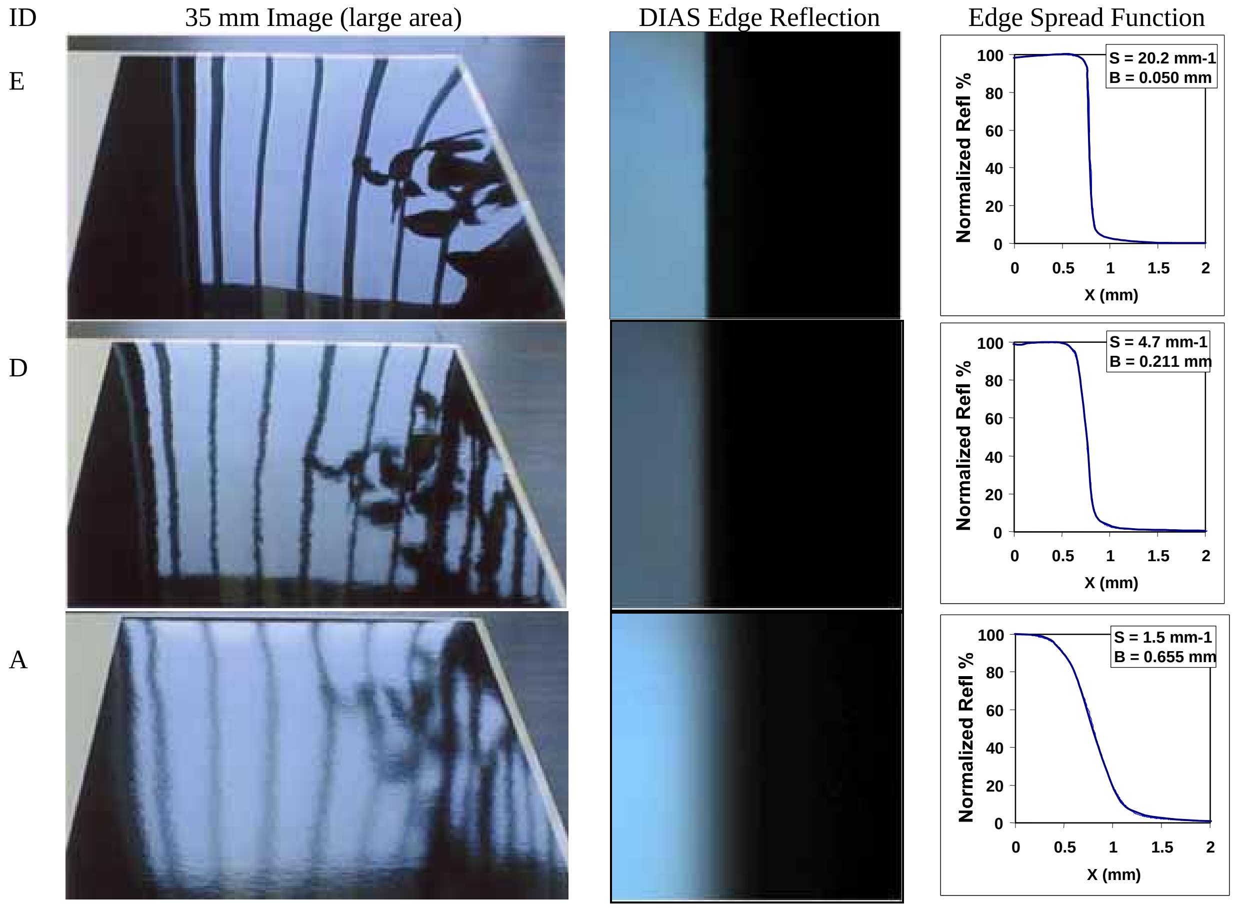

Figure 3. Correlating visual ranking (35 mm images) with instrumental DOI assessments (DIAS).

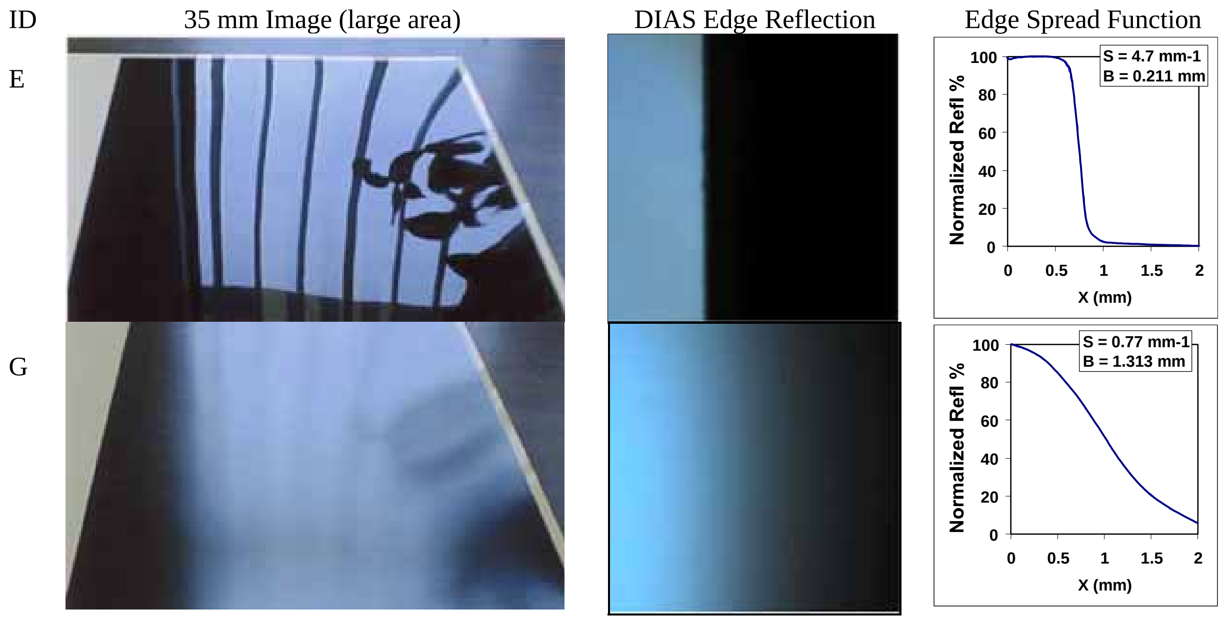

Figure 4. Comparing the DOI characteristics from two different printers (and different ink type) on the same media. Note that the print media is identical in Samples E & G.

Figure 4 compares the same images on the same paper, but printed on two different printers with different ink types (dye and pigment). The difference in DOI between the two printers (and ink types) is very significant. However, one should not jump to the conclusion, from this set of data, that dye based inks always produce higher DOI than pigment based ink. High DOI prints can also be obtained with pigment based ink.

Figures 5 to 8 demonstrate the correlation between the DIAS readings and various commercially available instruments:

Figure 5: The DIAS sharpness (DOI) reading is compared with the visual inspection method implemented in the "Glow Box" by I^{2}R [5]. There is considerable scatter in the data, possibly due to the subjectivity involved in using the "Glow Box" and the coarseness in resolving distinctness differences by this visual inspection method.

Figures 6 & 7: The DIAS DOI sharpness (DOI) is compared with two parameters obtained from the BYK-Gardner micro-wave-scan[4] instrument. This instrument provided many more parameters; but the best correlation with our data is shown in these figures. Generally, we found that the wave-scan instrument often reports no data ("surface too dull" error) in measuring inkjet paper samples, whereas the DIAS reports DOI readings without fail. It is our belief that the DIAS has a much wider dynamic range in DOI reading than the BYK-Gardner instrument. Further testing is needed to confirm this point.

Figure 8: This figure shows good correlation between the DIAS leading edge reflectance (reported in this figure as gloss value) with the BYK-Gardner micro-TRI-gloss[4] 60° gloss reading. The micro-TRI-gloss is a popular instrument in the paper industry.

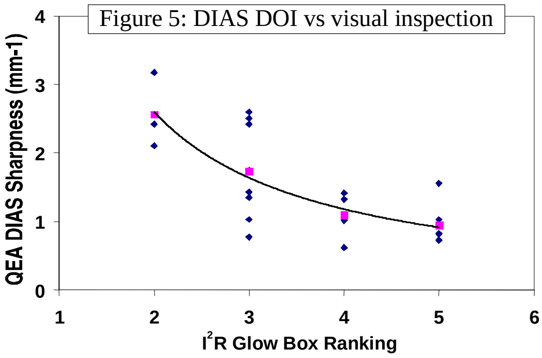

Figure 5: DIAS DOI vs visual inspection

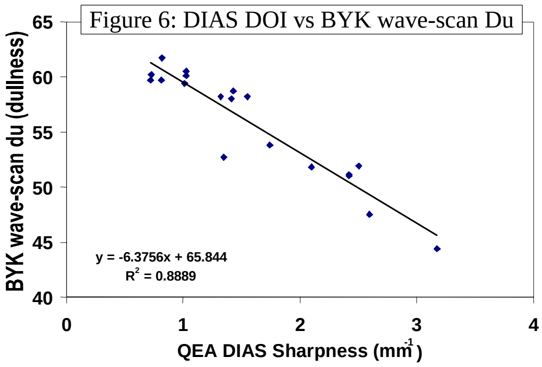

Figure 6: DIAS DOI vs BYK wave-scan Du

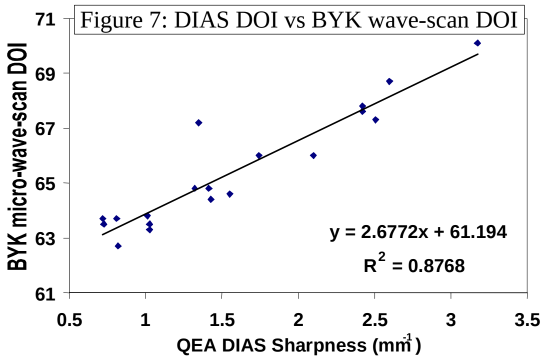

Figure 7: DIAS DOI vs BYK wave-scan DOI

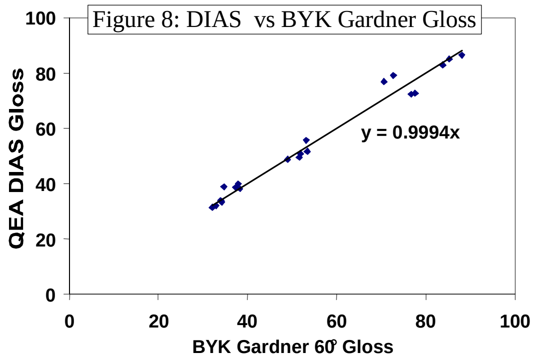

Figure 8: DIAS vs BYK Gardner Gloss

Summary

1. Gloss measurement is more complicated than the traditional view of specular gloss. Distinctness of Image (DOI) in particular is gaining more recognition as an important appearance attribute in digital imaging.
2. This paper describes a new method of measuring DOI and a prototype instrument (DIAS, the Distinctness of Image Analysis System). The basic principle is to project a sharp edge, capture the reflected image digitally using an area or line sensor, obtain the edge spread function, derive the line spread function (LSF), and obtain the DOI information in the LSF or the MTF (i.e. the LSF in the frequency domain).
3. The efficacy of this new method is demonstrated using inkjet printed images on various paper type, printer and ink combination.
4. The results correlate well with subjective visual assessment and ranking.
5. The results also correlate favorably with several commercially available instruments designed for the automotive industry lending credence to this new method and instrument.
6. The DIAS is portable, stationary, easy to use, has a broad dynamic range for measuring DOI on a wide range of digital print media, and is opening up a new opportunity in total appearance quality assessment.

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