The Virtual Image Chain: A Powerful Tool for the Evaluation of the Perceived Image Quality as a Function of Imaging System Parameters

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Abstract

A generalized digital imaging system model approach, called *virtual image chain,* permits to simulate the pixel-wise propagation of images through various digital imaging system and - in a next step - to evaluate the visual perception of image details based on a spatial model for human color vision.

First, various imaging systems can be modeled by a sequence of a rather limited number of *fundamental image operations* (FIO) representing the corresponding physical and/or technological properties of the system under investigation. Furthermore, to allow for perceived image quality analysis, simple models for spatial human color vision are integrated in the virtual image chain.

Within the limitations for the models of the imaging system and the human visual system, respectively, the virtual image chain approach allows for a quantitative evaluation of perceived image quality as a function of technological image system parameters. A demonstration of such an image quality evaluation will be presented.

Introduction

In all fields of imaging for photo, graphical and medical applications analogue technologies are actually being overcome by more or less "digital" systems due to advantages in the workflow, shorter access times and the applicability of digital image enhancement methods. As a common feature these systems share the representation of image data in some digitized form in at least one intermediate stage of the imaging process, which distinguishes them from conventional analogue printing systems.

The image formation may thus be traced back to the imagewise transfer of the fundamental elements of an digitized image: a pixel. In terms of a system modeling approach the performance of digital imaging systems may therefore completely be represented by their pixel transfer characteristics, which - in terms of the definitions of the Image Quality Circle by Engeldrum[1,2] - relates their technological system parameters to physically measurable image quality attributes in the print. Once, the pixel transfer characteristics of a given imaging system has been modeled (including the interaction between printer, colorant and medium), even an image-wise simulation of the resulting print is possible, i.e. the distribution of the printed colorants on a microdensitometric scale.[3]

Furthermore, by applying appropriate models of the human visual systems on these simulated images one arrives at the visual judgement of image quality attributes, giving access to perceived image quality parameters. Models of the human visual system (HVS), that include spatial resolution and further relevant psychometric effects (e.g. adaptation and masking), have been presented rather recently or are still under development.[4-8]

Especially the combination of system models and HVS-types of models enable a complete correlation of perceived image quality attributes and technological system parameters, thus opening synergies from the view of system designing. Therefore, it might be worth to review system model building for digital imaging systems from a more generalized point of view, especially stressing fundamental similarities given by the digital nature of the image formation process. By exploiting these similarities, which finally correspond to defining a rather small set of fundamental image processing operations, a convenient platform for digital-imaging-system-model-building can be implemented, which provides a system independent tool for describing and optimizing the design of digital imaging systems in terms of the pixel transfer approach.

This paper will summarize some aspects of this generalized approach and present first results on a comparably simple example, a laser recorder for photographic applications.

A Generalized Digital-Imaging-System-Model

Pixel Transfer through the Virtual Image Chain

Figures 1a & b sketch common aspects of digital imaging systems, which thus may be regarded as building blocks of the virtual image chain approach. Starting point is an image (data-)file, which in this special context may contain typical technical test patterns such as raster lines, noisy or homogenous patches, letters, continuos wedges etc. for later physical and/or psychometric evaluation.

Prior to printing these image data typically undergo several stages of signal processing and/or image processing, involving data-operations in a pixel- and/or image-oriented way. Pixel-oriented operations refer to all mathematical operations working on the data content of one image point in space (typically a data n-tupel like RGB or CMYK), the kind of which may e.g. be realized by Look-Up-Table (LUT) techniques. These LUT's are usually found in the context of color correction and the (inverse) compensation of dot-gain or characteristic curves. It is well known, that due to limited data-widths (i.e. bit-depth / color-depth) in LUT`s digital quantization artifacts may arise, depending on the bit-depth (color-depth) of the imaging system.

Image-oriented data processing describes those operations, which involve a filter-kernel containing more than only one pixel. Such operations are typically used in the frame of image processing, such like unsharp masking. Formally, interpolation methods and raster- or screening-algorithms also belong to this group, since neighboring pixels are involved in each of these operations.

The printer model collects those aspects of the system design that characterize the spatial distribution of the image information primarily delivered by the printer hardware, e.g. a laser spot (thermal or light), an inkjet droplet. This fundamental characteristics is usually given by some sort of point-spread function (PSF) working on a regular grid according to the spatial resolution of the printer. Thus, appropriate representation of image data on a sub-pixel level ("over-sampling") is needed from this point on to include the shape of the PSF.

The PSF may be modified (e.g. by means of mathematical convolution) to account for any further spread of the primary image information, e.g. all sources of statistical pixel-misalignments (variation of inkjet trajectories or flare accompanying the laser light) motional unsharpening due to flying-spot techniques or media transport. The PSF itself may be the result of a detailed physical model of the process under question.

The paper model describes the interaction of the primary image information (e.g. light or ink droplets) with the print medium under consideration, including the additional point-spread during the writing process (e.g. light diffusion or physical diffusion) and the corresponding density-response characteristics. This determines the effective spatial distribution of colorants in the print.

For simplicity, all interactions of light, colorant and print medium during the process of reading the image may also be incorporated into the paper model. These comprise multiple reflections and scattering, giving rise to all kind of dot gain effects in the case of halftone images or non-linear density transfer effects in the case of contone systems. If necessary for the evaluation later on, apertures of illuminating and detecting system have to be considered in this context. Furthermore, information on the spectral absorption of the colorants has to be provided to allow for status (A) weighting as well as for visual judgement in the evaluation stage.

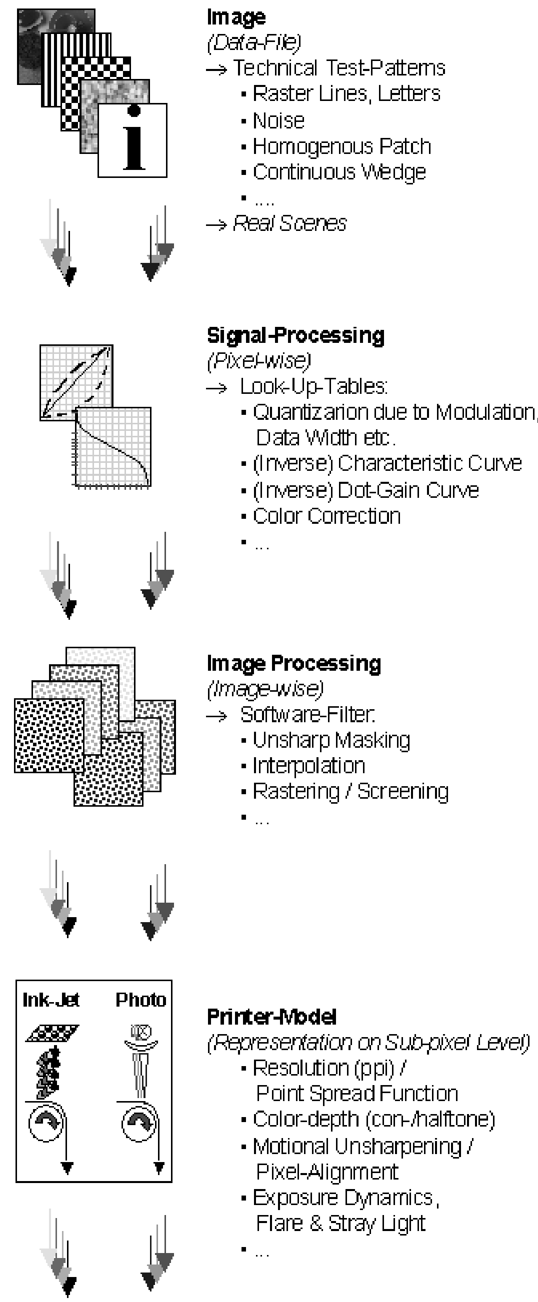

Figure 1a. Model of Pixel-Transfer (Part a), continued in Figure 1b.

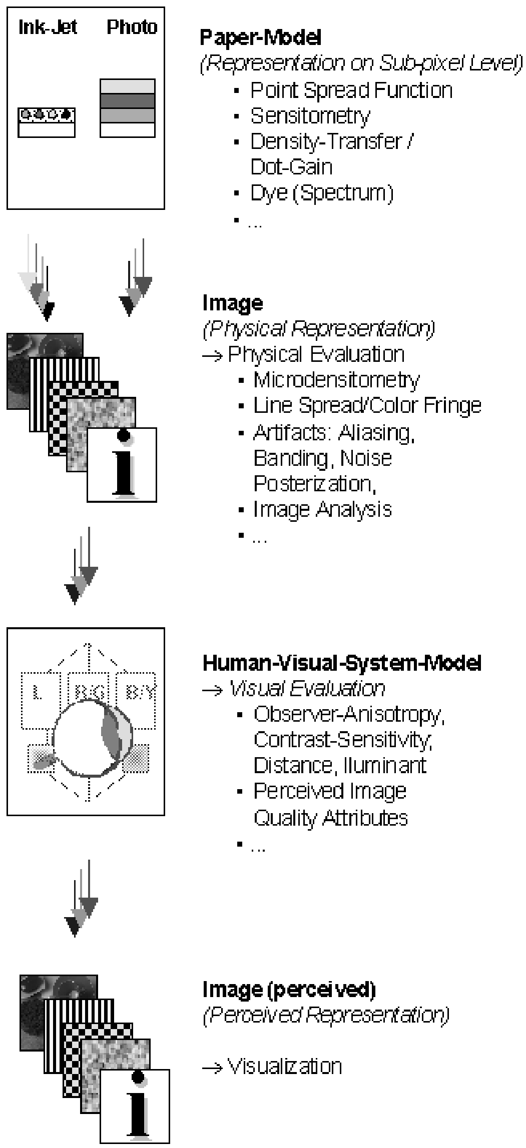

Figure 1b. Model of Pixel-Transfer (Part b), continued from Figure 1a.

At this point of calculation the over-sampled representation of the printed image is available. Thence, the image content may physically be evaluated by means of "virtual" measuring devices, which resemble the function of a microdensitometer. Subsequently, artifacts like aliasing, noise, banding and posterization, as well as line spread and fringing may quantitatively be measured corresponding to the technical test pattern under investigation. A mathematical convolution or a kernel-oriented operation may describe the measuring process.

In addition to the evaluation of physical image parameters one may also directly apply a human visual system model on the calculated image to obtain the corresponding perceived image quality attributes. Such an observer model should at least include color vision, the contrast sensitivity of the human visual system and its anisotropy. Masking effects and local adaptation is of further interest. Last but not least a simple straight-forward "visualization" of the perceived image is possible with this kind of HVS filter.

Aspects of Implementation

Obviously, images represent the fundamental object within this calculation scheme, especially since all types of PSF and kernel functions for image-oriented operations may be represented in terms of images. Therefore, the following fundamental image operations (FIO) already cover most of the functions needed for building digital imaging system models.

Table 1. Fundamental Image Operations (FIO)

Filter-Function	writes any 2-dim. function, e.g. Gauss- or Lorentz-Profile, into image
Grid-& Sampling Function	writes 2-dim. on/off pattern according to the over-sampling needed into image
Noise-Function	writes 2-dim. white-noise into image
Matrix-Function	applies $n \times n$ matrix on image (pixel-wise on "RGB")
Look-Up-Table	applies n-dim. LUT on image (pixel-wise on "RGB")
(Inverse) Fourier-Transformation	converts spatial domain image into frequency domain image and vice versa
Image-Multiplication (pixel-wise)	multiplies images pixel-wise (corresponds to convolution in the Fourier-domain)
Linear-Combination of Images (pixel-wise)	normalizes and combines images (esp. filters)
Interface to external functions	applies external functions on images (e.g. screening or interpolation algorithms)

Based on these FIO's and the virtual image chain approach various printer models may set up with a comparably limited effort for implementation using a commercial image processing software. These packages include image processing libraries, that already provide most of the FIO's needed, offer a scripting and graphical user interface building capability (e.g. Visual Basic) and contain an interface to external programming libraries, which allows to introduce external functions as special image operations, e.g. proprietary interpolation- and screening-algorithms.

The authors have chosen the commercial software package ImageProPlus[11] (IPP) as programming platform in combination with TIFF (Tagged Image File Format) as data container. In addition, IPP directly supports a lot of useful, special tags of the TIFF definition, e.g. different horizontal and vertical spatial resolution, expressed as dots per inch, and last but not least allows to read/write additional information into its header section.

A Photographic Laser Recorder

Using the basic elements of the virtual image chain, a laser recorder for photographic prints on conventional silver-halide material may serve as an example.

The printer is characterized by its 2-dim. PSF for the laser spot, assuming a Gaussian, which is convoluted with a Lorentzian to account for additional flare. The width of the Gaussian corresponds to the pitch given by the resolution. Furthermore, two LUT's are considered during signal processing: one resembling the characteristics of the light modulator and the other to provide visual neutrality corresponding to a calibration.

The photo paper is described by its optical spread in terms of the modulation transfer function (MTF), which has been determined experimentally. Furthermore, the practical characteristic curves of the photo material are used, which have been determined after appropriate laser exposure (130 ns per pixel) and standard processing (RA4). The simulated exposure is given in log H units relative to this characteristic curve and controls the maximum density in the print.

Based on this model, the interaction between system parameters of printer and paper and its tradeoff can be investigated quantitatively, especially in combination with the sCIELAB-model for visual evaluation. A point of interest in this context is e.g. the trade off between high maximum density (> 2.3) and the occurrence of line spread and colored fringes at image contents of high contrast, especially e.g. white letters on black background.[12]

For the evaluation of line spreads and color fringes black and white chessboard patterns and white letters on black background are used. The simulated images are filtered with the sCIELAB-model to obtain the perceived values of spreading and fringing. Roughly speaking, in the case of the chessboard pattern fringing leads to an overall color cast, which can be quantified by the sCIELAB-transformation for quantitative tradeoff considerations.

Conclusion & Outlook

The availability of human visual system models fertilizes the building of meaningful imaging system models. In this combination of model system parameters and perceived image quality may be directly correlate with each other, which increases the significance and applicability of such models dramatically. Furthermore, since there are only few fundamental image operations needed as prototypical building blocks in such a *virtual image chain,* system model building for digital imaging systems may become feasible using commercial image processing software packages, for which libraries with human visual system filters become highly desirable.

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Biography

J. Jung (35): received his diploma in physics at the Technical University of Braunschweig in 1991 and his Ph.D. at the University of Mainz in 1995; he joins the R&D department of Agfa-Gevaert (Photo) in Leverkusen since 1996; his work is focused on color-reproduction and image quality in conventional and digital photo-printing.