Modelling the Modulation Transfer Function of Various Imaging Devices

Samira Bouzit and Lindsay MacDonald
Colour & Imaging Institute, University of Derby
Derby, United Kingdom

Abstract

The Modulation Transfer Function (MTF) describes the resolution capabilities of an optical system, and hence of an image capture or display device. Various methods have been derived for evaluation of MTF, but in many cases they are applicable only to a specific class of device. In this study, we used a single method to characterise the spatial performance of a range of input and output devices for typical desk-top imaging systems, including digital cameras, scanners, displays and printers. Monochrome spatial frequency response (SFR) was evaluated for horizontal and vertical orientations by using the slanted-edge technique. On the basis of the measured data, we suggest that a normalised second-order polynomial function provides a good fit to the MTF data for most devices.

1. Introduction

The modulation transfer function is a measure of how well an imaging device or system can reproduce a scene. In practice most real devices are not perfect reproducers of spatial detail, because they contain imperfect optical components and also sample the image in a discontinuous manner. This means that no imaging device is capable of perfectly representing the spatial information of the original scene. To quantify these losses it is necessary to characterise the modulation transfer function of each imaging device to determine its spatial performance, as this has a major influence on image quality.[1]

In this study, we characterised the spatial performance of a range of input and output devices for typical desk-top imaging systems. The devices included one high-end and one low-end example of digital still cameras, scanners, displays and printers. A simple test target was created for the experimental measurements. Monochrome MTFs were evaluated for both horizontal and vertical orientations by using the slanted-edge technique, which has been proposed as a standard for the determination of MTF in digital imaging devices.[2]

The measured MTF will generally be for a system containing a chain of processes, each of which has its own MTF. Provided that all the processes and the links between them are linear, the cascading property states that these multiply together to produce the system MTF[3]. The effect of an individual process may be removed from overall system measurement by dividing by the individual process MTF at each frequency.

2. MTF Measurement Methods

Several methods have been described in the literature. for different imaging systems[4,5,6,7]. The three most significant are as follows:

2.1 Sine Wave Method

This method involves the measurement of one-dimensional sine wave charts comprising a number of patches with different frequencies of known modulation[5]. One of the disadvantages of using a sine wave target is that it can be very time consuming. A previous study showed that at least 20 samples must be taken over the period and orientation of the target to get a good estimate of the MTF[6]. Also a noise problem is often encountered in a pattern-reading micro-densitometer, particularly at high frequencies. The accuracy of computing MTF decreases because determining the maximum and minimum intensity values is made more difficult by the scattering problem.

2.2 Noise Method

The input and output noise power spectra of linear systems can be used to estimate their transfer characteristics. This method was introduced by Gouch et al. and applied to determine the MTF of a scanner.[7] Van Metter used the same procedure for measuring the MTF of an Inkjet printer.[8] A particular advantage of this method is that the generation of the noise test stimuli is not critical, provided that they have a pseudorandom phase spectrum and contain sufficient high spatial-frequency information. One limitation is that it is difficult to get the correct balance between grain noise of the target and photon noise in the system.[7] In other words, the amplitude of grain noise must significantly exceed the amplitude of the electrical noise of the system, otherwise the electrical noise will give an offset to the resulting MTF. This offset is a function of frequency response of the electronics and can be very difficult to compensate in the measurements without a detailed knowledge of the electronics.

2.3 Slanted Edge Method

The slanted edge Spatial Frequency Response (SFR) method can be used for the creation of one-dimensional uniformly super-sampled edge profiles and the calculation of the frequency response of a digital device.[9] This method involves scanning the image of the edge to produce the Edge Spread Function (ESF). This is differentiated to obtain the system Line Spread Function (LSF). The modulus of the Fourier transform of the LSF, normalized to unity at zero frequency, is the required MTF. This method is widely used to evaluate the performance of an optical system. One of its advantages is that no special target calibration is required to determine the Modulation Transfer Function. This method has been evaluated as simple, accurate, and robust.[2] It should be noted that noise will influence the highest frequencies the most, because of the differentiation stage. Even if the edge spread function is smoothed prior to differenttiation, some uncertainty in the resulting MTF still remains[3].

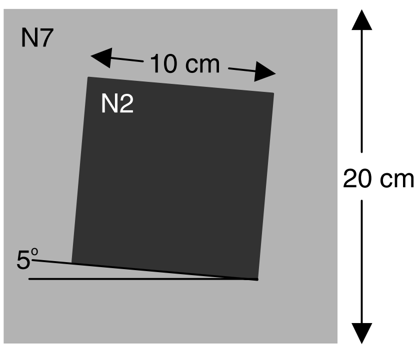

Figure 1. Edge target used for measurement

3. Experimental Measurement

3.1 Digital Camera

In this study we used two digital still cameras: the Canon *PowerShot Pro70* and Sanyo *VPCG200.* A simple physical test target was produced using N7 and N2 Munsell Gray Scale patches, with the central patch slanted by 5 degrees. Its size was 20×20 cm for the outer and 10×10 cm for the inner part, as shown in Figure 1. The test target was placed inside a VeriVide *DigiEye* cabinet illuminated with D65. This cabinet was fully enclosed, with only a small opening at the top where the camera was positioned. The diffuse illumination was sufficient to provide an acceptable camera output signal. The camera was rigidly mounted with its optical axis perpendicular to the plane of the target. The lens of the Canon was 36 cm and of the Sanyo 42 cm from the target. For both cameras the lens aperture was set automatically while the exposure time was set as default. Sanyo camera’s autofocus system was used to focus. The focal length for the Canon camera was adjusted via the zoom setting to 10 mm, and the focus adjusted manually. The captured images were downloaded to a compatible PC via the Adobe *PhotoShop* software plug-in, as 24-bit data (8 bits for each channel).

3.2 Desktop Scanner

Two desktop scanners, Agfa *Duoscan* and HP *ScanJet 6300*, were used to capture the same test target as for the digital cameras. Scanning was performed with *gamma* set to 1.0 and with all other scanner settings set to default (i.e. automatic exposure, no transfer curve modification, no brightness or contrast or sharpness modifications). One way to dedicate a number of pixels per unit area on the original target would be to scan the object using different scanner resolutions. This solution was not very appealing, due to the limited optical resolution of the device. Also, scanning at different resolutions would introduce quality variation from scan to scan, due to different scales of interpolation. Both scanners were used in their RGB mode with resolution set to 600dpi. Scanning was performed by placing the target in the centre of the frame.

3.3 Display Monitor

A 15” *iMac* CRT monitor and a 15” flat panel *Apple* studio display were tested, set to their recommended resolution of 1280×768 addressable pixels. We calibrated the displays to D65 white point and set gamma to its default value of 1.8. The studio display was driven by a PowerMac G4. Maximum luminance levels measured in a dark room were 84.86 cd/m^2 and 130.4 cd/m^2 for CRT and LCD monitors respectively.

The MTF measurement of the display system was determined by employing the *Canon PowerShot Pro70* digital camera for the acquisition of the displayed test target, at a fixed distance of 30 cm from the display faceplate. A digital target with the same features as the physical camera target was generated and displayed at the centre of the monitor screen. To avoid any ‘jaggies’ arising from the pixellation of the display that might confuse our measurements, the middle square of the target was not slanted. Instead the camera was slanted at 5 degrees from vertical to give a slanted image.

3.4 Printer

An HP *DeskJet 895cxi* inkjet printer and an HP *LaserJet 5000GN* printer were tested. A simple non-slanted edge stimulus was generated using Adobe *PhotoShop*, with 20% and 70% reflectance factor for the 100 mm centre and 200 mm surround respectively. For both printers the target was printed on a heavy-weight coated paper. Density measurements were made along the length of the edge to ensure a consistent density. The print was placed inside a VeriVide illumination box, slanted at 5 degrees to the cabinet walls. At a distance of 52cm above the target, the Canon camera was rigidly mounted so that its optical axis was perpendicular to the plane of the target. The camera aperture was set automatically, the exposure time was set as default, while the focal length (zoom) was adjusted to 10 mm (same conditions as for camera characterisation, except for the height). Captured images were downloaded to a PC via Adobe *PhotoShop* plug-in, as 24-bit data.

4. Data Analysis

To determine MTF from the captured images, we used the Spatial Frequency Response plug-in (SFR) software.[10] For each individual imaging device in this study, we measured pixel values corresponding to individual steps of a greyscale. A polynomial fitting procedure was used to fit the measured data to produce a 256-step lookup table, which served as the Opto-Electronic Conversion Function (OECF). This function is necessary for the linearisation of the device signals. For each image of the slanted edge, a region of interest (ROI) covering 300×100 pixels was selected, over which the SFR plug-in was performed. It was important to keep the vertical to horizontal aspect ratio of the *region-of-interest* as high as possible to increase the signal-to-noise ratio of the SFR estimates.[11] The software plug-in returns the spatial frequency axis normalised to the range 0–1 cycles/pixel, for which the Nyquist limit falls at 0.5. The SFR data was related to the device's native spatial frequency scale (cycles/mm or cycles/degree) by calibrating the 0.5 position to the calculated Nyquist limit of the device.

4.1 Camera Spatial Characterisation

The Canon *PowerShot Pro*70 camera had a 1/2-inch CCD of dimensions 10.57 × 7.04 mm and resolution 1536 × 1024 pixels (3:2 aspect ratio and pixel size of 6.9 µm). With the focal length of the zoom lens set to 10 mm at an object distance of 36 cm, the test target of width 20 cm subtended an angle of 31° and had a width of 1330 pixels in the image, corresponding to 43 pixels/degree. The Nyquist limit of the lens plus CCD array was therefore 21.5 cycles/deg.

The Sanyo *VPCG200* camera had a 1/3-inch CCD of dimensions 6.79 × 5.08 mm and resolution 640 × 480 pixels (4:3 aspect ratio and pixel size of 10.6 µm). With an object distance of 42 cm, the test target of width 20 cm subtended an angle of 26.8° and had width of 320 pixels in the image, corresponding to 12 pixels/degree. The Nyquist limit of the lens plus CCD array was therefore 6 cycles/deg.

The overall camera MTF was a combination of the MTF of the CCD array, the lens and the electronic components. We determined SFRs for the upper, lower, right and left edges of the target for both cameras using the plug-in software. The average SFRs in both directions are shown in Figure 2, from which it can be seen that both cameras show similar behaviour in the vertical and horizontal directions. The peak in the curves for the *Sanyo* camera at a spatial frequency of approximately 2.5 c/deg, suggests that a sharpening filter is applied by image processing circuitry within the camera. The maximum spatial frequency that can be resolved by the camera is approximately 6 c/deg, in good agreement with the Nyquist limit calculated for the CCD array. The SFR curves for the Canon camera, with the zoom lens set to the mid focal length of 10 mm, decrease smoothly to 50% of maximum value at about 7.5 c/deg in the horizontal direction (vertical edge) and at 6 c/deg in the vertical direction (horizontal edge). For both directions the SFR drops to 10% of maximum value at 13 c/deg. It seems that the lens optics are the overall limiting factor on MTF for the camera, but that there is some horizontal enhancement.

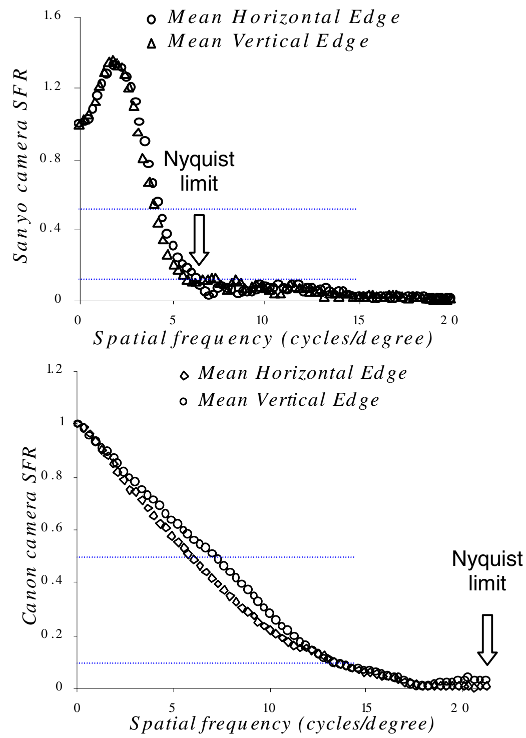

Figure 2. Average MTF of the Sanyo (top) and Canon (bottom) cameras for vertical and horizontal orientations.

4.2 Scanner Spatial Characterisation

The Agfa *Duoscan* and HP *ScanJet 6300* are capable of scanning reflective originals of size up to 203×355 mm and 216×356 mm respectively. In both cases we set the scanning resolution to 600 dpi or 23.6 dpmm in both directions. The Nyquist frequency of both scanners was therefore 11.8 c/mm. Figure 3 shows the SFR curves determined for both scanners, corresponding to the horizontal and vertical scanning directions respectively (also called fast and slow directions). For vertical edges (slow scan direction) the SFR responses had similar shape, with the Agfa dropping to 50% and 10% at spatial frequencies of 4.5 and 14 c/mm, compared to 2 and 11 c/mm respectively for the HP. For horizontal edges (fast scan direction), however, the behaviour was rather different, with the HP having higher MTF for spatial frequencies less than 4 c/mm, and the Agfa having higher MTF for frequencies greater than 4 c/mm. The effective resolving limit was approximately 450 dpi for the HP scanner, which also showed some noise at higher spatial frequencies. This suggests that the HP scanner has an intrinsically lower MTF from its CCD array, but applies a one-dimensional sharpening filter to the pixel signals as they are read out from the array (fast scan direction).

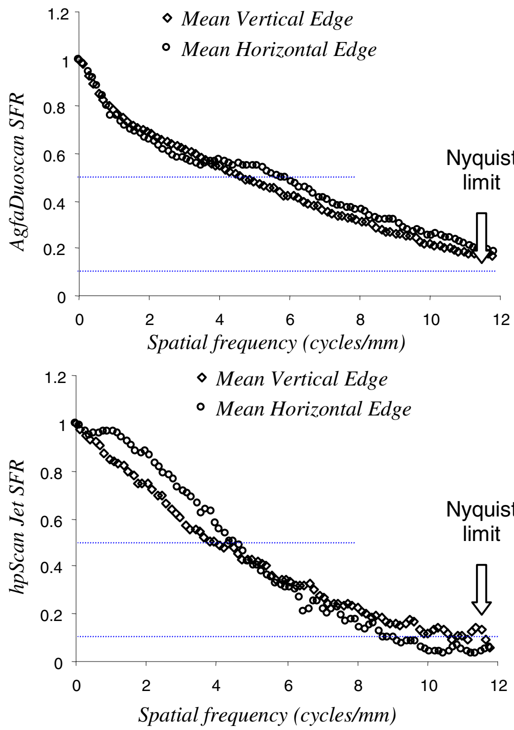

Figure 3 Average MTF of the Agfa (top) and HP (bottom) scanners for vertical and horizontal orientations.

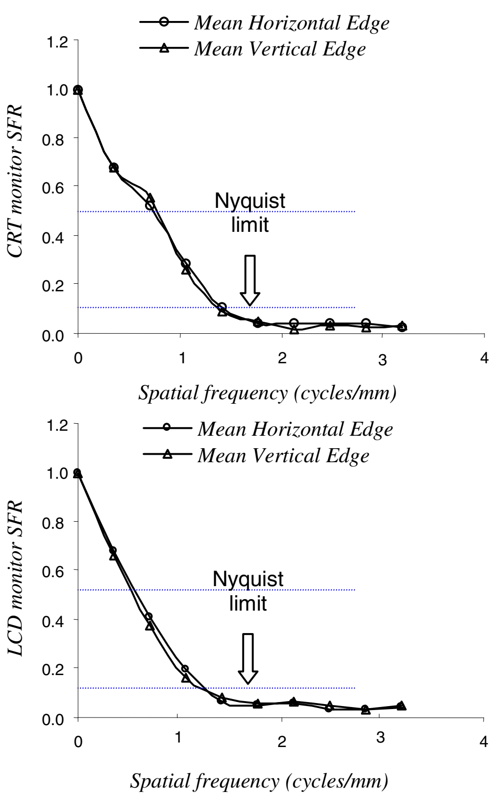

Figure 4. Average MTF of the CRT (top) and LCD (bottom) displays for vertical and horizontal orientations.

4.3 Display Spatial Characterisation

The MTF of the display was determined by employing the Canon *PowerShot Pro 70* camera for acquisition of the displayed test target. Thus, the measured system MTF was the cascaded combination of the individual MTFs of the camera and display. Phosphor dot pitch of the CRT was 0.28 mm. Both displays were of size 15” diagonal, using the full display area of 304×230 mm. The addressable resolution was set to 1024×768 pixels, so that the physical dimensions of one pixel were of size 0.30 mm square, corresponding to an angular subtense from the camera’s viewing position of 0.143 degree. This corresponds approximately to 14 c/deg, i.e. a Nyquist limit of 7 c/deg or 1.67 c/mm on screen surface.

Display SFRs for vertical and horizontal directions are shown in Figure 4. Comparing the graphs, it can be seen that the two displays showed similar behaviour in both directions. For the *iMac* CRT monitor the curves drop to 50% of maximum value at 0.75 c/deg, and to 10% at 1.4 c/deg. For the flat panel *Apple Studio* monitor, both curves drop to 50% of maximum value at 0.5 c/deg, and to 10% of maximum value at 1.25 c/deg. It can therefore be inferred that the CRT display has a performance similar to the LCD, with slightly better rendering of spatial frequencies in the range 0.5-1 c/deg.

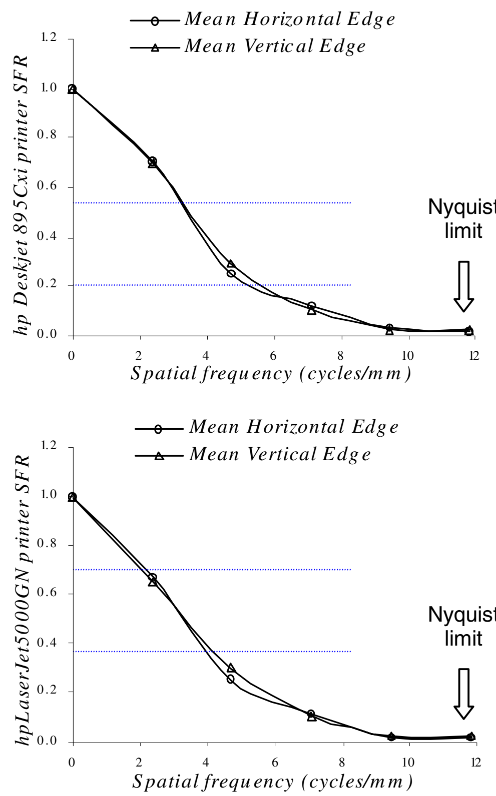

Figure 5 Average MTF of the inkjet (top) and laser (bottom) printers for vertical and horizontal orientations.

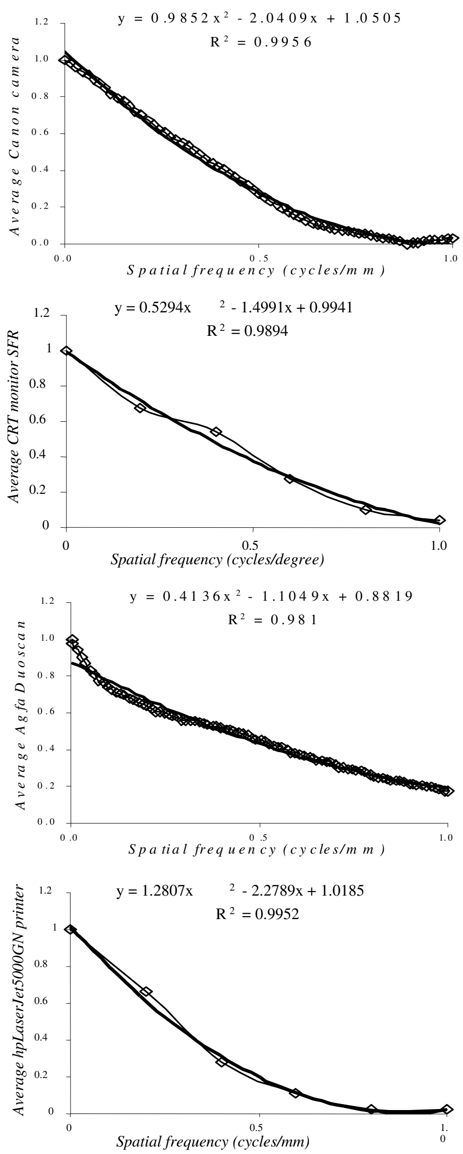

Figure 6. Fitting of second-order polynomial functions to measured MTF data for four imaging devices.

4.4 Printer Spatial Characterisation

In this study the printer MTF was cascaded from the combined (camera-printer) system MTF. Ideally one should also evaluate the MTF of the paper used for characterising the printer.[12] However, it is assumed that the MTF of the paper is much superior to that of the imaging devices (printer and camera), so its contribution is ignored. The test target was printed at a resolution of 600 dpi, which corresponds for both printers to a Nyquist frequency of 11.8 cycles/mm. Figure 5 shows a close similarity in the SFRs for the two printers. In each case the horizontal curve drops to 50% of maximum value at about 3.5 c/deg, and to 10% of maximum value at 7 c/deg. This suggests that the achieved resolution of the printers is actually nearer to 400 dpi, possibly because of the effect of spreading of the printed ink dots on the paper.

5. Modelling the MTF Data

The results above demonstrate that the SFR plug-in combined with a simple slanted-edge target can produce good results for the spatial characterisation of four classes of imaging device: digital cameras, scanners, displays and printers. It would be very convenient if a generalised parametric function could be applied to each device class, obviating the need to characterise each device individually.

Observation of the curves in Figures 2-5 indicates that they all follow a similar form, especially when they are normalised to 1.0 along both axes (i.e. modulation amplitude and spatial frequency relative to the Nyquist limit). The only notable exception occurs for the Sanyo camera, in which the peak indicates an enhancement process. We therefore tested various functions containing both polynomial and hyperbolic terms to determine how well the device MTF data could be fitted. We finally decided that a simple second-order polynomial, with only three coefficients, gave a good fit in all normal (non-enhanced) cases. Figure 6 shows the results of fitting the data to the average (vertical and horizontal) for four of the devices tested, with correlation R^2>0.98 in all cases. Further measurement and analysis will be necessary to discover whether the coefficients can be predicted for each device or device class from known spatial parameters.

References

1. Jacobson R.E, An Evaluation of Image Quality Metrics, *The Journal of Photographic Science*, **43**, 7-16, 1995.
2. Burns, P.D., Slanted Edge MTF for Digital Camera and Scanner Analysis, *Proc. IS&T PICS Conf.*, 135-138, 2000.
3. Jacobson R.E, Ray S.F., Attridge G.G. and Axford N.R, *The Manual of Photography - Photographic and Digital Imaging*, 9th Ed., 393-412, Focal Press, 2000.
4. Triantaphillidou S., *Aspects of Image Quality in the Digitisation of Photographic Collections*, Ph.D. Thesis, University of Westminster, UK, 2001.
5. Dainty J.C. and Shaw R., *Image Science*, Academic Press, London, UK, 1974.
6. Granger E. M., Image Quality of Digital Cameras, *Proc. IS&T PICS Conf.*, 188-191, 1998.
7. Gouch M. and Roe M., Image MTF analysis using grain noise, *Proc. SPIE*, **1987**, 96-102, 1993.
8. Van Metter R., Measurement of the MTF by noise Power Analysis of one dimensional white noise patterns, *Journal of Photographic Science*, **38**, 144-147, 1990.
9. Williams, D. Benchmarking of the ISO 12233 Slanted-edge Spatial Frequency Response (SFR) Plug-in, *Proc. IS&T PICS Conf.*, 133-136, 1998.
10. Slanted Edge MTF – Software utilities, Image Analyser SFR plug-in User Guide, Matlab sfrmat 1.1 www.pima.net/standards/iso/tc42/wg18_sfr_matlab_page.hm, (2000).

11. Burns P.D and Williams D., Image Resolution and MTF for Digital Cameras and Scanners, *IS&T PICS Conf.* T*utorial Notes*, 2001.
12. Koopipat C., Fujino M., Miyata K., Haneishi H, and Miyake Y., Image Evaluation and Analysis of Ink Jet Printing System, *Proc. IS&T PICS Conf.*, 149-154, 2000.

Biography

Samira Bouzit received her B.Sc. in Electrical Engineering from the University of Science & Tech-nology of Algiers in 1997 and M.Sc. in Mechatronics of Robotic Systems from the University of Versailles, France in 1998. She obtained a Postgraduate Diploma in Colour Imaging at the University of Derby in 1999. Since then she has been carrying on her PhD research at the Colour & Imaging Institute, concerning image sharpness perception and reproduction in different media. She is a Member of IS&T.