ARE THE CCD SENSORS GOOD ENOUGH FOR PRINT QUALITY MONITORING ?

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Abstract: The evolution of optical imaging Charge-Coupled-Devices (CCD) has been rapid in recent years. The line detectors have been developed to be used not only in facsimile applications but also for spectrometric purposes. The area sensors have become extremely wide with up to 16 million separate light sensitive elements and they are gradually replacing conventional film materials in certain high-end applications. The use of both sensor types is based on the conversion of light energy into electrons which are accumulated in the photosites during the integration period, i.e. during the exposure of image at the focal plane. The second phase of the operation cycle is the serial readout of the elementary charges which are then amplified for further processing.
The feasibility of commercial CCD sensors in print quality monitoring has been studied in the Instrument Laboratory of the Technical Research Centre of Finland. The area sensor is suitable for imaging non-moving objects, such as offset printing plates, and it can also be used to monitor whether a running web in a printing press calls for any manual maintenance. The linear devices offer a good resolution and a wide dynamic range, which might justify their use as sensors in automotive printing presses. The idea of measuring the print density and register using a CCD front-end should not be overlooked, even though the compensation for the sensor´s non-uniform sensitivity, dark drift and readout ringing requires the full capacity of modern 16-bit microprocessors to be benefitted.

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CCD principles

The concept of a Charge-Coupled-Device (CCD) was first proposed in 1970 at the Bell Research Laboratory in the U.S.A. The CCD is basically a long analog shift register, where charge packets are driven from one end to another using electrical clock pulses which generate moving potential barriers. The principle is schematically shown in Fig. 1. In an optical CCD the charges are generated in photosites by means of photoelectric injection. The

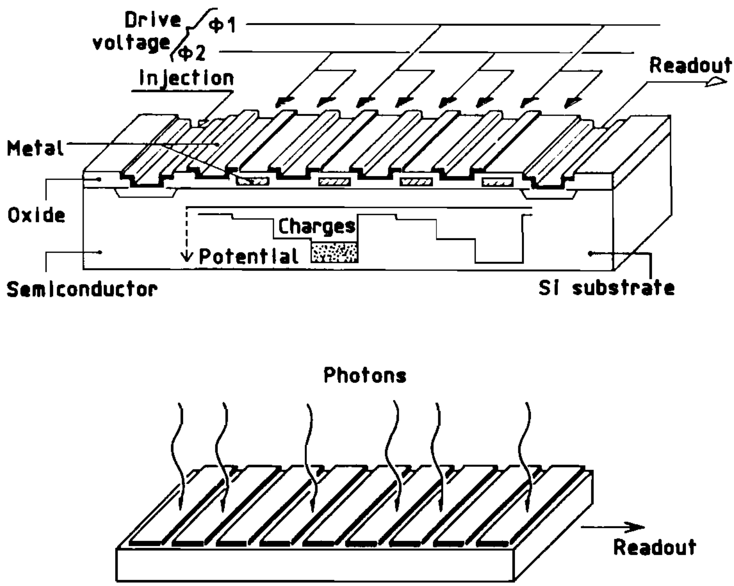

Fig. 1. The structure of a typical 2-phase CCD with a typical potential profile (Thomson-CSF).

photosensitive elements may be arranged in a line form or in a matrix form. The number of photosites in a linear device varies from 128 up to 4096 or 5000 (EG & G Reticon, Toshiba) and the largest array sensors are the one million element devices from Thomson-CSF and Videk which is a Kodak company. Tektronix has developed the largest detector of 2048 x 2048 pixels. The geometric dimensions of photosites vary from 7 x 7 μm^2 to 27 x 27 μm^2.

During operation a CCD device is usually set at the focal plane of a lens and it serves as an alternative to photographic film. The photons generate electron/hole pairs inside photosites and additional charge is integrated as long as the exposure period is active. The quantum efficiency of a CCD cell is as high as 40 % over the spectral range of 400 nm...1100 nm, whereas the quantum efficiency of photographic film is only 1 %, roughly the same as that of a human eye. In addition, the signal response of a CCD cell is linear in comparison with the logarithmic response of conventional film.

After integration the charges are clocked out and they are converted into signal voltages, i.e. a video signal is generated. The readout time is strictly dependent upon the clocking frequency: a 2048-element linear detector may be read in 100 microseconds, if a clock of 20 MHz is used, provided that odd and even pixels are clocked out separately (Fairchild). Faster readout times have been introduced recently by EG & G Reticon which offers tapped CCD outputs, thus obtaining line scan times of 8 µs for a 1024-element device. The repetition rate of successive scans must not be confused with the exposure times which may be as short as 1 µs if fast flashes or electronic shuttering are used. A new image can, however, be obtained only after reading out the old one.

The image sensors of array-form are necessarily slower. What was said about flashed images earlier, is valid also here, and usually the images are not obtained faster than at a normal video speed. The large sensors are even slower, the maximum frame rate of a Videk imager is 10 samples per second for the shortest exposure time.

The readout time of the large Tektronix imager is more than one minute. Its applications are in scientific work, astronomy, medical imaging, spectrographic analysis etc.

The dynamic operating range of CCD sensors is usually defined as a relation between the saturation output and dark end noise. The latter one increases strongly as integration periods become longer. The dark current doubles for every 7 ^{o}C increase of temperature. Therefore it may also be easily reduced by cooling the device. In case of short exposure times the dark current is no problem, but the electronic system must be designed carefully in order to avoid noise spikes related to clock pulses resetting the transfer gates in the CCD sensor.

The spectral sensitivity of silicon-based CCD imagers covers the visual spectral range, but in principle a good quantum response may be obtained through the wavelength range from 1 Å to 10^4 Å, thus permitting, for example, the direct detection of soft X-rays.

The use of CCD sensors for detecting light waves is the most important application field, however. The linear and areal devices have been used in machine control for robot guidance and in pattern recognition systems which require the utilization of the full capacity available in modern 16/32-bit microcomputers. The use of image sensors in quality monitoring, for instance in density or register evaluation at printing presses, has been less common. The reports have been rather few, but at least Mitsubishi and Toko have pioneered in applying CCD detectors and video frame memories for print quality monitoring.

Light sources

The use of CCD sensors as monitoring devices generally implies that the print under study is evenly illuminated. The narrow dynamic range of the detector should not be wasted to the compensation for a varying intensity response. The lamps of conventional bulb-type do not provide even illumination unless positioned far away from the surface studied. A long tube lamp is more suitable, such as the familiar fluorescent lamp.

Incandescent halogen lamps are also available in tube form, but their drawback is the large amount of infrared radiation which makes them very hot and power consuming. The near-infrared radiation from the lamp has to be rejected in the range of 700...1100 nm, because it does not carry any useful information concerning the print. Lowpressure pulsed Xenon lamps are also available in tubular form. They are manufactured with arc lengths up to more than one meter. Xenon lamps also radiate strongly at infrared, some 40 % of the energy is radiated outside the visual response range, but the blue output is good, i.e. the use of a Xenon lamp compensates for the poor blue response of silicon detectors. A Xenon flash lamp can be used to "freeze" the movement of the object observed. The length of a light pulse can be on the order of 10 microseconds, which is essentially shorter than the shortest feasible integration period of a CCD device. This should be kept in mind, as blurred images are not accepted from array sensors. The maximum repetition rate for a typical lamp unit is some 15 flashes per second if the long life of 100 million pulses is desired.

Print density measurements

The print density is the logarithmic value of quotient I_o/I, where I is the light intensity reflected from the printed surface and I_o is the light reflected from unprinted paper in similar geometrical and spectral conditions. The logarithmic function has been introduced for vision-compatibility. The highest sensitivity for small ink thickness variations will be achieved when the highest spectral sensitivity of the optical system coincides with the wavelength of the ink's lowest transmission. Consequently, if a printed spot reflects only one percent of light from the amount of light reflected from an unprinted paper under the same conditions, the print density is D = 2. In order to get the inaccuracy of one percent in the dark end densities, the total signal dynamics should exceed 1 to 5000 which is usually the upper limit of linear CCD devices. The operation range of areal image sensors is from the thermal noise level of some 100 electrons per pixel to the maximum charge packet of 400 000 electrons. These figures should be regarded as examples of operation in optimal conditions: the practical signal range is often reduced because of dark current due to increased ambient temperature, or because of reset noise spikes introduced earlier.

Irrespective of these cautions concerning the insufficient signal dynamics, some commercial linear CCD sensors with 2048 picture elements were tried in our laboratory for density measurements. The experimental system is shown in Fig. 2. A white fluorescent tube-lamp was used to provide an even illumination onto the print under study and the linear CCD sensor was located behind a focused wide-angle lens, f = 28 mm. Depending upon the sensor, the angular observation cone of the optical system was either 2×15^o or 2×25^o. A red-absorbing glass filter was used for near-infrared rejection and gelatine color filters were used to obtain various spectral sensitivities for the camera system. The distance from the lens to the print studied was about 80 cm and the total width of projection line was about 70 cm. The integration period was chosen to utilize the available signal dynamics for each filter.

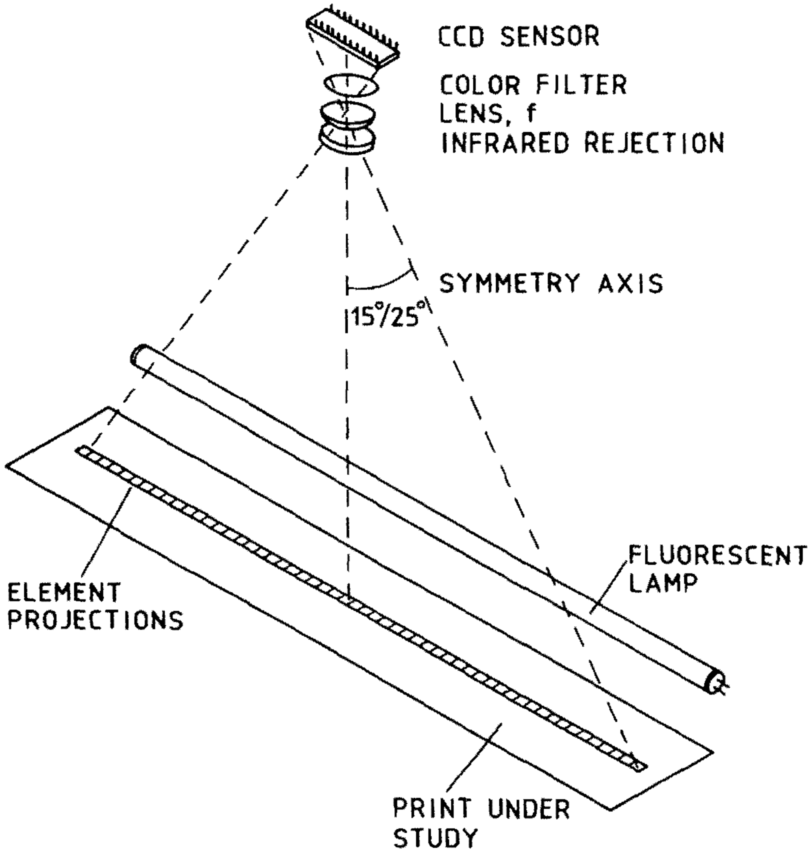

Fig. 2. Test assembly for density measurements.

The various sensitivity properties of the system with a fixed integration time of 50 ms are shown in Fig. 3. The highest sensitivity was obtained with the green filter (Kodak Wratten 58) and the lowest with the blue filter (Wr. 48). The red sensitivity (Wr. 23 A) was slightly below the green one because of the red-absorbing infrared filter (Schott BG 38). The intensity response curves show a strong dependence on the observation angle, i.e. the position of each projected picture element. This phenomenon is due to two factors: firstly the distance variation causes the intensity attenuation according to

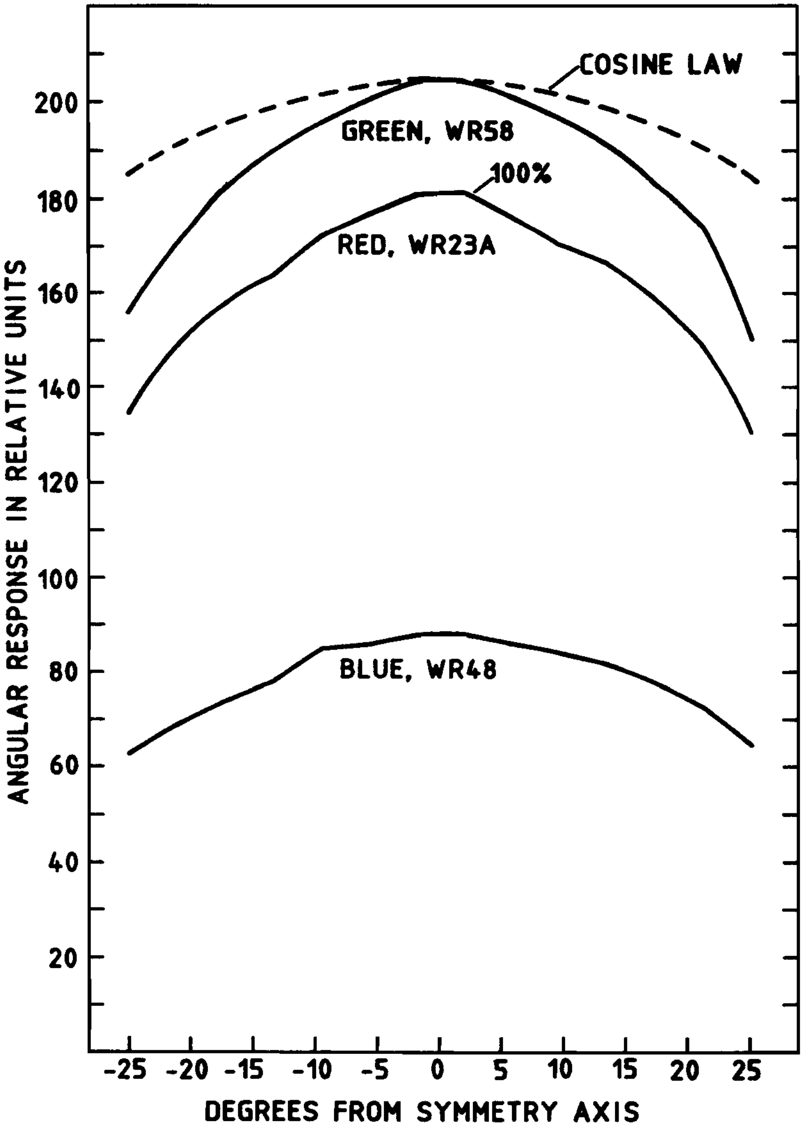

Fig. 3. Intensity profiles from unprinted paper with angular aperture of 50 degrees.

the inverse square law and secondly the cosine law is introduced in reflection and in detection. If the maximum intensity along the symmetry axis is set at 100 percent level, the edgemost intensity values hardly exceed 70 percent levels. Such a rapid attenuation suggests that the observation cone should be narrow in order to utilize the best dynamic range of a CCD sensor.

The measured density profiles across light magenta and cyan samples are shown in Fig. 4. The signal levels of white reflection and print reflection were read from the picture elements corresponding to 30 mm displacements on print plane. The lens was focused properly and the variation of density values from point to point indicate that the pixel information was gathered from limited area only. The size of a picture element on the focus plane

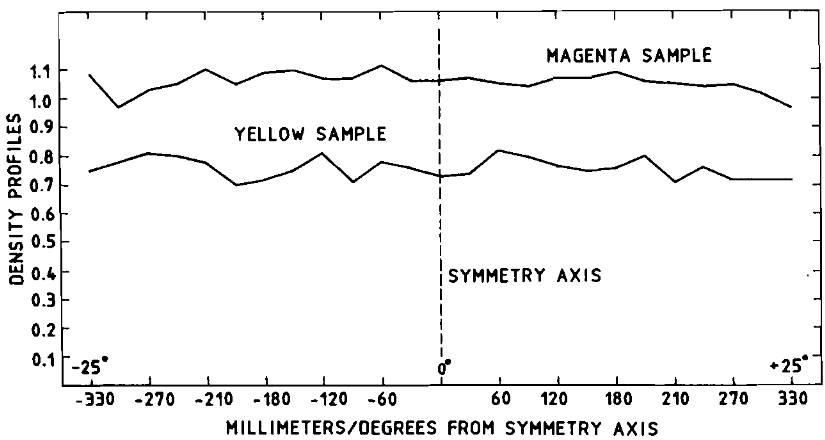

Fig. 4. Density profiles as measured using a 2048-element CCD sensor.

is about 14 micrometers in square form which means that the element projections are roughly 0.5 mm squares when the resolving power of the lens is taken into account. The normal requirement of signal integration across a nominal 3 mm observation spot is thus not satisfied, and the eventual "cloudiness" of paper and print are the cause of profile variations. The integration could be achieved by summing up the signals from picture elements in the neighbourhood and/or letting the print sample move during the integration period.

An interesting feature occurs if a blue-enhanced sensor is used. Owing to the interference properties of the thin non-reflection layers on these devices, the absorption of blue photons coming from the side is decreased when compared with red or green photons entering from the same direction, i.e. from the same test spot. This effect can be seen in blue densities measured from yellow spots. As white paper is measured, the blue photons are,or should be, responsible for the most information, but the sensitivity of a blue-enhanced photodiode is reduced for them coming from the side. A yellow sample does not reflect blue photons and the density data are mainly based on blue-green photons which enter the detector more easily than the blue ones. This phenomen is shown in Fig. 5. where the density of yellow ink drops already at the inclination angle of 15^{o}, when a blue-enhanced detector is used. The designers of photodiode-based densitometers are already familiar with this problem;

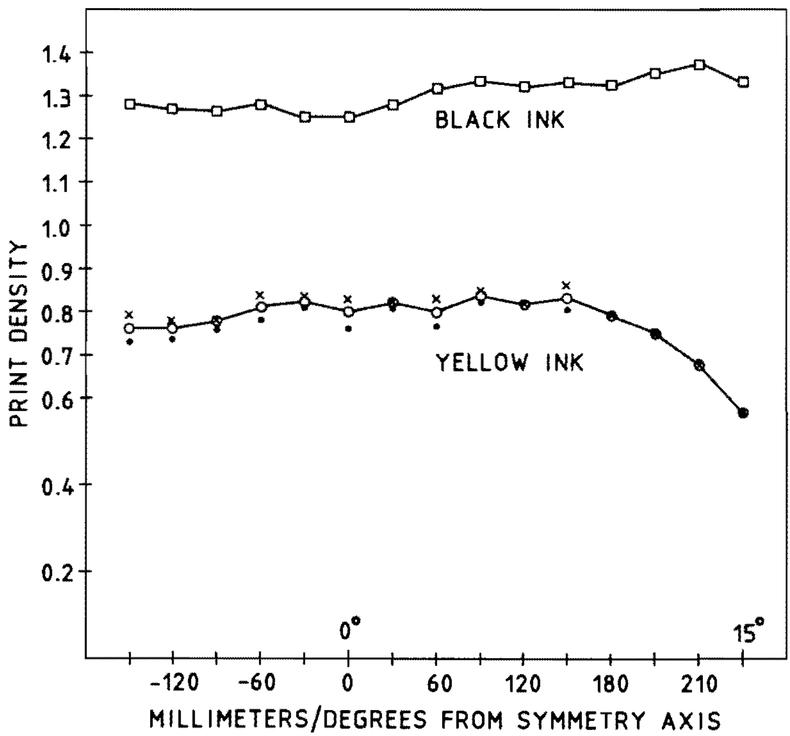

Fig. 5. The effect of blue-enhancement on blue density measured from black and yellow inks.

if they have tried to collect much light with the help of wide detector apertures: then the blue densities tend to keep low.

Possibility of register measurements

The register is often regarded more important than the density level quality. Minor density variations mean that the print is not good, but the register errors make the print unacceptable. That is why the optical register sensors have found their way to the printing houses, whereas the on-press density sensors are still rarities. The register error is simply the displacement of a marker ink spot from its original position related to some base marker, for instance black.

The observation of printed markers is not very convenient with a linear CCD: a single image contains only one intensity profile across eventual registration markers. Only the crosswise or longitudinal register error can be determined at a time. The problem of filter matching is also actual; either the yellow or the cyan marker is badly recognized depending on the color filter choice.

The use of an array-type image sensor might solve the problem. The group of four register markers, i.e. black, yellow, cyan and magenta spots, could be imaged onto the focal plane of a semiconductor camera as is shown in Fig. 6. In our example the size of each spot is 2mm x 2mm and their nominal edge positions are 2 mm from each other. The total width of the observation area is 10 mm which means that each marker spot is free to move one millimeter in any direction without interfering with other spots. In our case the magnenta spot has been misprinted, and the register error equals 1 mm in both directions.

Let us further imagine that the area of marker spots is controlled using an image sensor of 400 x 400 picture elements which is well below the current state of art. The spatial resolution due to a single pixel would thus be 25 µm on the object plane. In operation the image of register spots should be captured in less than 2 microseconds, because an unblurred image is required. The displacement of a web moving at 10 m/s would be 20 µm during the said exposure period. Such a short integration time can be obtained using two alternative methods: the conventional flash lamp or the electronic shutter. The use of a Xenon flash seems simple, especially for the reason that the light energy has not to cover a very wide area. The short flash period, however, can only be

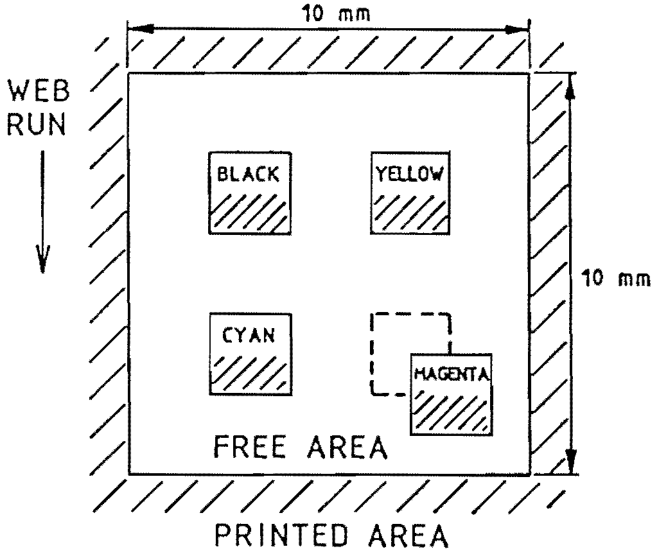

Fig. 6. Proposal for a CCD-based register measurement system. The size of test spots is 2mm x 2mm.

achieved at low energy levels. We may therefore end up being short of light. Then the second of alternative methods comes into consideration : the camera can be equipped with a gated microchannel plate light intensifier which enables the use of exposure periods of one microsecond; gating can be synchronized with the flash lamp. The register measurement camera would be equipped with two separate flashes, one with an integral blue filter and the other with a red filter. The consecutive images would be captured using the flash lamps in an alternating mode. The method of two separate lamps would guarantee a good contrast for the recognition of all register mark spots.

The correct operation of the camera system would call for flash synchronization at the accuracy of at least one millimeter, but this requirement should not pose any unreasonable task. The camera should be first located correctly in the crosswise direction and after this initial procedure the proper window of flashing should be determined using a cylinder-bound tachogenerator together with a trigger.

As soon as a new image is flashed onto the CCD sensor, the frame would be read into an imageprocessing computer which qualifies the spots and then determines their relative positions. The use of a color sensor might look promising, but the color information is obtained at the cost of spatial resolution: the consecutive picture elements are covered with various filters and so they do not provide comparable information for determining marker edges. In the case of an electronic intensifier camera the color information is already lost in the microchannel plate.

The feasibility of CCD sensors in print monitoring

When compared with discrete photo detectors, the CCD sensors suffer from rather low signal dynamics, poor noise figures and even low speed due to a serial readout mechanism. On the other hand, a CCD contains a huge amount of sensing points in a small package and even fast phenomena are easily captured in analog photosite memories by means of proper flashing. One drawback is also the immediate need for heavy data processing capacity, if a semiconductor camera is installed. But as soon as that computing capacity has been employed, the wide-looking CCD sensor can be regarded as an obedient servant; several control tasks can be performed using various algorithms. Furthermore, a semiconductor camera needs not be located very near the running web, which means less harm due to dirt accumulation. The 90´s will be the decate of artificial vision!