State of the Art of Professional Digital Cameras

Reimar K. Lenz
Technical University of Munich, Munich, Germany

Abstract

Professional Digital Cameras

This paper is concerned solely with cameras which use area solid state imagers and that are capable of producing colour images with six million pixels and more. Also, only cameras with a permanent link to a host computer, i.e. in a more or less stationary environment are considered, such that there are no severe limitations with respect to storage capacity and power consumption. This implies that the primary design goal can be image quality. The basic characteristics of the sensors most commonly used in such cameras are described, together with methods to improve their performance in terms of resolution, field of view, alias suppression and live imaging speed.

Introduction

Since the Photokina in 1998, the Full-Frame-Transfer CCD (charge coupled device) sensor FTF3020[6] with 3072x2048 ≈ 6.3Megapixels has taken over in the field of digital cameras for photo studios (Imacon "FlexFrame 3020", Jenoptik "Eyelike MF", Heidelberg "ColorCam", MegaVision "T32", Mosaic Imaging "Luma", PhaseOne "Lightphase", Rollei "Gamma C6", Scitex "Leaf Cantare", Sinar "SinarBack 23"). This 36 x 24mm sensor with 12 µm square pixels by Philips almost completely replaced the previously used 2k x 2k sensors from Thomson and Loral, probably due to its larger pixel count, the low dark current, the built-in anti-blooming circuitry, the reset capability and a comparatively low price of about US$ 1500 when purchased in quantities.

It was until the beginning of 2001, that a seriously competing device came along: The KAF16801[7] from Kodak, also a Frame-Transfer CCD sensor, however with 4080 x 4080 ≈ 16.6Megapixels on a 9 µm square pitch, yielding an image size of 36 x 36 mm. Due to its high pixel count, this sensor has been rather successful (Imacon "FlexFrame 4040", Kodak "ProBack", MegaVision "T44", PhaseOne "Lightphase H20", Sinar "SinarBack 44"), even though its price is twice as high as the FTF3020´s. Also, it lacks the reset feature, which makes it quite power consuming to keep the sensor in a "clean" state, especially because the capacitances of gates needed to be clocked are extremely high. Furthermore, due to the high pixel count, the readout of the sensor takes about two seconds, in contrast to 0.8sec for the FTF3020 (assuming 10MHz pixel clock for both sensors).

Philips is currently launching a counter attack with the FXA1001, again a Frame-Transfer CCD sensor with 4008 x 2762 ≈ 11.1Megapixels @ 9µm square pitch. It will probably quickly replace the FTF3020, because most customers primarily seem to be looking at the mere pixel count, even though 6Megapixels on a rectangular image format - about the quality of 35mm slides or negative film - are sufficient for most applications.

A camera manufacturer, who does not design his own image sensors (as Scitex "C-MOST" or Foveon, both with CMOS (complementary metal oxide semiconductor) technology), is dependent upon the two initially described sensors available on the market. Therefore, the fundamental characteristics of most e.g. 6Megapixel cameras are quite similar, because they are all using the same CCD sensor.

An exception to this are high-resolution microscanning cameras, used primarily in the field of digital microscopy. As early as 1989, long before high-resolution Interline-Transfer CCD sensors became available, a digital camera with almost 7Megapixels came on the market: The ProgRes 3012 by Kontron.[3] It is still available today (by Jenoptik), probably due to its extremely good colour fidelity, resulting from the unique colorimetric filter characteristics of the 0.3Megapixel sensor ICX021. This colour fidelity has not been reached by its 12Megapixel successors (Jenoptik "ProgRes c14", Leica "DC500", Nikon "DXM1200" and Zeiss "AxioCam HR"), even though all these cameras use the more modern 1.34 Megapixel sensor ICX085,[8] which has been developed by Sony more than ten years after the ICX021. By using narrower spectral response curves, colour accuracy has been sacrificed in favour of raw-data colour saturation.

Sensor Characteristics

Frame-Transfer CCD Sensors

Because both, the Philips 6M-sensor FTF3020 and the Kodak 16M-sensor KAF16801, are CCDs of the full-frame transfer type, i.e. without charge storage capability, a number of properties are similar:[1,2]

- optical/mechanical shutter is necessary
- nearly 100% fill factor (monochrome versions)
- poor spectral response for the blue channel
- full well capacity about 1ke- per square µm.

Also similar are:

- low dark current (30sec exposure time possible)
- dynamic range above 4000:1 (12 f-stops)
- Bayer-pattern colour filter array (colour versions)
- built-in anti-blooming circuitry

Their major differences are shown in the following table:

Major differences between KAF16801 and FTF3020

Kodak "KAF16801"	Philips "FTF3020"
4080x4080pixels @ 9µm	3072x2048pixels @ 12µm
36x36mm square image	36x24mm rectang. image
Lateral anti-blooming	Vertical anti-blooming
No reset capability	Reset capability
1182nF total vertical CCD clock capacitance	240nF total vertical CCD clock phase capacitance
Up to 10MHz pixel clock	Up to 36MHz pixel clock
One output	Up to four outputs
Tight cluster defect specifications	Relaxed cluster defect specifications

The lateral anti-blooming circuitry of the Kodak chip reduces the fill factor and the full well capacity of the sensor. However, due to the gaps necessary for a colour filter array and the higher charge-to-voltage conversion factor of the Kodak chip, its dynamic range is not affected adversely. Actually, the dark current of the Kodak chip seems to be somewhat lower than that of the Philips chip, which is helpful when considering the long readout time.
The major advantage of vertical anti-blooming is the capability to instantaneously reset the complete sensor. This is useful when the camera is to be kept in a mode ready for image acquisition without any delay. Sensors without reset capability need to get cleaned from dark current induced charges by permanent operation of the vertical CCD clock phases. This heats up the camera and thus causes higher dark current.

With up to four outputs operating at up to 36MHz each, the Philips sensor could in principle be read out more than fifteen times faster than the Kodak chip. However, none of the cameras listed above use these features – for good reasons:

a) The optimal dynamic range of the two sensors is achieved at an A/D-conversion rate (or pixel clock) of about 10MHz. Higher signal bandwidths increase the thermal amplifier noise, lower frequencies lead to larger dark current noise due to longer readout times.
b) Using more than one output implies the use of more than one (power consuming and expensive) analogue/digital converter. Also, the precise matching of multiple channels under all operating conditions is quite difficult.

Thus, these nice features are not used in practice.

Finally, the relaxed cluster defect specifications make the Philips sensor more expensive for the camera manufacturer than indicated by its nominal price, because a significant percentage of these sensors cannot be used for high quality photography due to too large cluster defects.

CMOS Sensors

Not much is publicly known about the custom-designed CMOS sensors of Scitex (6.6MPix) and Foveon (16.8MPix). However, it is known, that their dark current is about one order of magnitude larger than that of the above mentioned CCD sensors, reducing the maximum exposure time also by an order of magnitude. Besides this "technical" difficulty, there is also a principle drawback of CMOS sensors: The dominant noise source of a solid state imager, i.e. the reset-noise of the capacitors which perform the charge-to-voltage conversion, cannot be eliminated by "correlated double sampling" in the same way as for CCD chips. This significantly reduces the dynamic range of a CMOS sensor, typically by about one or two f-stops. Therefore, CMOS sensors have not had a real breakthrough in professional still photography.

For cinematographic applications, the author is currently having an 8Megapixel CMOS sensor designed and manufactured, with enough bandwidth (1440 Megapixels per second) to allow for true (digital) correlated double sampling in conjunction with a speed of up to 90 images per second.

Interline-Transfer CCD Sensor

To the author's knowledge, the 2/3 inch Interline-Transfer CCD sensor ICX085 from Sony is used in all micro-scanning cameras that create images with more than 10Megapixels. From the cameras listed above, only the DXM1200 is not a "real" digital camera, because the A/D-conversion (8bits wide) takes place on a PCI-Bus frame grabber board, not within the camera head, i.e. the transmission of the image information is based on analogue signals.

The main features of the ICX085 are:

- 1300 x 1030pixels @ 6.7 µm pitch
- interline-transfer architecture (no shutter required)
- progressive scan architecture (non-interlaced)
- Bayer-pattern colour filter array (colour version)
- built-in anti-blooming circuitry, with reset capability
- built-in micro-lenses
- about 20,000 electrons full well capacity
- dynamic range about 2000:1 (11 f-stops)
- dark current: <1electron/pixel/sec at 25°C

Nothing is really fascinating about these figures, except for the extremely low dark current, which is several orders of magnitudes lower than that of the KAF16801, FTF3020 or the ICX021. A typical figure used for comparing long time exposure capabilities of sensors is the "time to fill", i.e. the full well capacity divided by the dark current of a pixel. For the ICX085, this is 20,000 seconds (more than five hours!). Acceptable image quality can be expected until up to about 10% fill-up or about 30min exposure time. This makes this sensor well suited for low light level applications such as fluorescence microscopy. In fact, in situations where even a well dark adapted human eye sees practically nothing, this sensor is capable of delivering brilliant colour images via long time exposure, at nearly its full dynamic range and without cooling.

Resolution

The optical resolution of sensors with a two-dimensional array of light sensitive sensor elements can be increased by so-called micro-scanning, a multi-exposure image acquisition technique, where the sensor is shifted two-dimensionally by fractions of the pixel pitch between successive exposures. Even for monochrome frame-transfer CCD sensors with a fill factor of practically 100%, where there are no gaps between adjacent light sensitive sensor elements (aperture width $l \approx$ pixel pitch s), the optical resolution can be doubled in both the x- and y-axis. This is due to the fact, that the modulation transfer function (MTF; here, for simplification, one axis only) of a square sensor element aperture is:

$$MTF(f) = \sin(\pi \cdot f \cdot l)/(\pi \cdot f \cdot l) \quad (1)$$

which is greater zero for spatial frequencies $f<1/l$, whereas the Nyquist limit due to sampling at a pitch s is already given by $f_{Nyq}=1/(2s)$.

Due to optical shielding between the different colours of the colour filter array, colour sensors typically have smaller light sensitive apertures than their monochrome counterparts: The FTF3020C e.g. has $l \approx 10\mu m$, yielding a maximum optical resolution of $f=100[line\ pairs]/mm$; the Nyquist limit is $f_{Nyq}=1/(2 \cdot 12\mu m) \approx 42/mm$. Typically, for this type of colour sensor and also for modern interline-transfer sensors with almost gapless adjacent micro-lenses (as the ICX085), a effective resolution gain factor of about 2.5 can be achieved by micro-scanning. The effective maximum optical resolution of the FTF3020C is about 7400x4900 pixels, and about 3400x2700pixels for the ICX085 (monochrome and colour version).

Due to the large number of exposures needed for 3x-resolution micro-scanning, only those cameras, that use an interline-transfer sensor, which does not need a shutter, currently fully exploit the resolution capability of the sensor. The photo-studio cameras with frame-transfer sensors are limited by software to 2x-resolution enhancement.

Of course, multi-exposure micro-scanning cannot be used for capturing moving objects.

Image Size

Another method to increase the pixel count is to enlarge the sensing area in the focal plane, a technique called macro-scanning. To the author's knowledge, Sinar supplies the only commercially available motorized product: a macro-scan adapter module, which nearly doubles the image size vertically and horizontally.

In the course of the European EspritIII project "MARC" (Methodology for Art Reproduction in Colour), the author has built a few samples of combined micro-/macro-scanning cameras with a resolution of about 20,000 x 20,000 = 400 Megapixels, based on the 290 Kilopixel sensor ICX021. More than 12000 interleaved and tiled TV-resolution images needed to be captured for one full-resolution image[4] with a file size of 2.5Gigabytes.

The software task to join the overlapping regions of adjacent image tiles seamlessly with sub-pixel accuracy is quite challenging.

Colour Aliasing

Sensors with a colour filter array (CFA) suffer from colour aliasing.

After the expiration of Dr. Bayer's patent (Kodak), which was issued about 20 years ago, most sensor manufacturers adopted this arrangement of colours for still photography applications. In the author's opinion, the Bayer CFA, which consists of repeated unit cells of 2x2 pixels with two primarily luminance carrying filters in opposing corners, is optimal: for purely vertical or horizontal spatial frequencies, the checkerboard pattern of the green (luminance) pixels yields the same Nyquist sampling limit as a monochrome sensor. For diagonal "green" spatial frequencies the Nyquist limit is halved, but also for all "red" and "blue" spatial frequencies.

Due to the spatial shift (or 180° phase shift in spatial frequency domain) between luminance and chrominance carrying channels, severe colour aliasing occurs in the vicinity of diagonal spatial frequencies $f_{diag}=1/(\sqrt{2}s)$, e.g. 59/mm for the FTF3020C or 79/mm for the KAF16801CE. Colour aliasing resulting from this spatial frequency can neither be detected nor corrected by software.

For stationary objects, one can obtain co-site colour sampling again by micro-scanning: The sensor is exposed four times and shifted by exactly one pixel pitch in x- and y-direction between each exposure, such that at each original pixel location, all colours of e.g. the Bayer CFA are captured. This method to obtain 3-chip performance free of colour alias from a single-chip colour camera is patented by the author[5]. Nikon's "DXM1200" and Scitex' "Cantare XY" are employing rather clever techniques to circumvent this patent, with only little degradation of image quality…

For moving objects, requiring just one exposure, one can

a) accept colour aliasing,
b) use an optical low-pass filter, which suppresses annoying spatial frequencies (Kodak option),
c) defocus slightly (low-pass effect),
d) use the micro-scanning actuators to create motion-blur during the exposure time (MTF synthesis)

The latter technique is used by Sinar and Jenoptik, even for flash illumination with a duration of only a few milliseconds. The piezo-ceramic actuators are fast and powerful enough, to quickly move the sensor in a diamond shaped trajectory. The size of this diamond is calculated such that the annoying spatial frequencies are suppressed.

Mathematically spoken, the sensor element aperture is convolved with the motion trajectory. Thus, nearly arbitrary modulation transfer functions can be synthesized.

Live Image

It is difficult to get live imagery for focussing purposes from large full-frame-transfer sensors such as the FTF3020 or KAF16801: Their nominal readout time is in the order of seconds and they need a shutter for normal operation. For comfortable focussing or image adjustment, at least three frames per second are needed and the shutter in e.g. middle-format camera bodies cannot be used for such permanent repeated action.

However, image quality is not very important in this operating mode. Given the use of only one sensor output and a fixed horizontal pixel frequency, there remain two methods to obtain a higher frame rate:

a) readout of a small region of interest (ROI)
b) vertical binning (addition of lines)

In contrast to CMOS sensor, CCD sensors are not randomly addressable. Therefore, the gain in speed is not as high as one could expect from the ratio between the full sensor size and the size of the ROI. Typically, the rate to flush lines, needed to proceed to the ROI, is 10 to 20 times higher than the normal line rate, so the maximum increase in speed will be no more than this factor, even for very small ROIs and short exposure times. Only when the sensor can be reset (as the FTF3020) and only few lines need to be skipped, i.e. with an ROI close to the top of the image, further speed improvements are possible.

By means of binning, the readout time is reduced by the bin factor, i.e. the number of lines which are accumulated in the horizontal CCD register before it is being read out. Because charge packets from pixels with different colour filters are added, the colour information is usually considered to be lost. However, this is only true if the bin factor is an even number. For odd bin factors, well defined residual colour information is still present and can be processed to yield a colour image – with a reduced signal-to-noise ratio (S/N), of course.

Finally, preview images with acceptable quality may be obtained from full-frame-transfer CCD sensors even without the use of a shutter: The smeared contribution of the raw image data, caused by reading out the sensor during continuing exposure, can be precisely modelled and thus eliminated by software, as long as no parts of the image are overexposed – again at the cost of reduced S/N. In conjunction with 7x-binning, Sinar has managed to increase the frame rate for a complete colour image from one frame every two seconds to about three frames per second (KAF16801 on middle-format cameras, i.e. without shutter).

Conclusion

More than 95% percent of the stationary cameras with more than 6Megapixels sold in the last few years use a very limited set of CCD sensors: the KAF16801 from Kodak and the FTF3020 from Philips for studio photography and the ICX085 from Sony for digital microscopy. CMOS sensors have not made the breakthrough in high-quality, high-resolution imaging yet.

As long as the cameras are well designed and enough bits are used for A/D-conversion (12bits are sufficient, 14bits are a good sales argument), the sensor is the limiting factor for dynamic range, sensitivity and colour fidelity. Therefore, all cameras that use the same sensor, should be similar with respect to the quality of the raw image data.

Their major difference with respect to their hardware are other features, such as micro- or macro-scanning, live image capability and speed, colour alias suppression techniques, power consumption and the computer interface (FireWire, fibre optics, analogue etc.).

The differences in application software are too large to be compared easily or fairly.

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Biography

Reimar Lenz received his Diplom, Ph.D. and Venia Legendi in electrical engineering from the Technical University of Munich in 1980, ’86 and ’90 respectively. During a post-doc assignment at the IBM research labs in Yorktown Heights in 1986, he became interested in CCD cameras. Besides teaching Digital Photography and Videometry at the TUM, he is developing and producing digital cameras.