

Limitations to miniaturization in CCD-technology

• *Miniaturization* • *Optics* • *CCD* • *Photography* • *Technology speed* • *Technology management*

Summary

In modern photography CCD-sensors are the dominant technology for image recording. Big progresses in miniaturization led to this success. But especially in the largest market segment for compact cameras, accounting for over 120 units in 2007, a technological dilemma surfaces. Firstly, picture quality has reached a satisfactory level, making further improvements almost obsolete. Secondly, experience shows that cameras with pixel sizes beyond 3 μm witness loss of picture quality, whereas average pixel size already in 2003 dropped beyond this threshold. New compact cameras often show inferior picture quality compared to their predecessors. This is no new finding for photographers; though this paper shows the severeness of these problems as an industry-wide issue by analyzing technical properties of over 1000 digital cameras since 1996.

Practical Relevance

Product ergonomics considers human skills and customer needs marketing products. But such marketing influence can have negative effects too, as is the case with digital cameras where expectations raised cannot be fulfilled technologically. Technological progress reached a deadlock, this finding is of importance for both the manufacturers and customers. The former ones need to shift their focus in marketing and development in order to create new potential for differentiation. The latter bases his buying criterion on long past and obsolete criteria. Cameras require new measurands substituting for megapixels declaring image quality.

Les limitations de la miniaturisation de technologie CCD

• *Miniaturisation* • *Optique* • *CCD* • *Photographie* • *Vitesse de la technologie* • *Management de la technologie*

Résumé

La technologie CCD est dominante pour l'enregistrement d'images dans la photographie actuelle. Le grand progrès de la miniaturisation a permis ce succès. Le plus grand segment du marché des cameras photographiques comptant plus que 120 millions pièce en 2007 est ce des cameras compactes. Précisément ici il y a des problèmes avec le progrès technologique. D'une part la qualité des images est arrivée à un niveau satisfaisant, rendant obsolète d'ultérieur développement. D'autre part des expériences montrent que la grandeur des pixels ne doit pas être inférieure à 3 μm , sinon des effets secondaires deviennent visibles. Pourtant la moyenne a déjà en 2003 passé cette „limite“, rendant la qualité de nouveaux modèles inférieurs à leurs prédécesseurs. Bien que ce phénomène soit connu, l'analyse de plus que 1000 camera depuis 1996 souligne, qu'il s'agit d'un problème avec des conséquences pour l'industrie entière

Importance pratique

L'ergonomie des produits cherche un compromis entre les compétences humaines, et les besoins des utilisateurs pour la commercialisation des produits. Le marketing peut influencer les besoins humains. Mais cette influence peut aussi avoir un effet négatif, comme est le cas avec les cameras digitales. Les expectatives ainsi créées ne peuvent plus être satisfaites aux causes technologiques. Le progrès technologique a atteint un sommet.

Grenzen der CCD-Miniaturisierung

• *Miniaturisierung* • *Optik* • *CCD* • *Fotographie* • *Technologiesgeschwindigkeit* • *Technologiemanagement*

Zusammenfassung

In der heutigen Fotografie ist der CCD-Sensor die dominante Technologie für die Bildaufzeichnung. Die großen Fortschritte der Miniaturisierung in der Vergangenheit führten zu diesem Erfolg. Bei den Kompaktkameras, welche mit über 120 Millionen verkauften Einheiten 2007 das größte Marktsegment bilden, zeigt sich jedoch ein technisches Dilemma. Einerseits hat die Bildqualität der aktuellen Kameras bereits ein so hohes Niveau erreicht, dass weitere Fortschritte für die Kunden praktisch keinen Vorteil mehr bringen. Andererseits zeigt die Erfahrung, dass die Pixelgröße der Kameras nicht unter $3\ \mu\text{m}$ fallen sollte, da sonst Nebeneffekte der Miniaturisierung die Bildqualität stören. Die durchschnittliche Größe der Pixel fiel jedoch bereits 2003 unter diese Grenze, was dazu führte, dass einige neue Modelle eine schlechtere Bildqualität aufweisen, als ihre Vorgänger.

Die Probleme der Abbildungsqualität haben zwei Hauptursachen: Die einzelnen Pixel auf den CCDs sind mittlerweile derart klein, dass zu wenig Licht auf ein einzelnes Pixelelement fällt. Die einzelnen Pixel beginnen ein digitales Verhalten zu zeigen. Entweder registrieren diese ein einfallendes Photon oder nicht, Farbnuancen werden wenig differenziert erfasst. Zusätzlich verhindern Beugungseffekte weitere Verbesserungen der Abbildungsqualität. Das durch das Objektiv eintretende Licht wird abgelenkt, anstelle eines Punktes erzeugt jeder Lichtstrahl eine Scheibe, die Airy-Disk. Je größer die verwendete Blende bei der Bildaufnahme, umso größer wird diese Airy-Disk. Die eintretenden Bildinformationen enthalten so oft bereits weniger Bilddetails, als dies die CCDs aufzeichnen könnten. Bei aktuellen Spiegelreflexkameras tritt dieser Effekt ab Blende 9 und bei Kompaktkameras bereits ab Blende 3 auf. Die CCD-Sensoren stoßen an physikalische Grenzen. Linsen mit größeren Durchmessern würden dieses Problem verbessern, jedoch lassen sich diese oft nicht in die kleinen Geräte integrieren. Diese Phänomene sind bereits seit einiger Zeit bekannt, jedoch zeigt eine Analyse der technischen Merkmale von über 1000 Digitalkameras seit 1996, dass es sich hierbei um ein industrieweites Problem handelt. Im Gegensatz zu den Kompaktkameras sind die Spiegelreflexkameras noch weniger von diesen Effekten betroffen. Einerseits, weil qualitativ hochwertigere Objektive verwendet werden und andererseits, weil die Miniaturisierung weniger weit fortgeschritten ist. Die Objektive weisen grössere Durchmesser auf und die CCD-Fläche ist um ein Vielfaches grösser, als bei den Kompaktkameras.

Die beiden Marktsegmente, Kompaktkameras für den Massenmarkt und Spiegelreflexkameras für anspruchsvolle Fotografen befinden sich in unterschiedlichen Stadien. Wäh-

rend im professionellen Umfeld die technische Entwicklung fortschreitet und die Anforderungen der Fotografen immer besser erfüllt werden, sind bei den Kompaktkameras physikalische Grenzen vermehrt leistungsbeschränkend. Zusätzlich besteht nur in wenigen Situationen ein Bedarf nach mehr Auflösung und besserer Abbildungsqualität. Zudem arbeiten die Hersteller von Mobiltelefonen daran ihre Kameramodule stetig zu verbessern und verkleinern so den Abstand zu den Kompaktkameras laufend. Das Segment für die Kompaktkameras kommt so von zwei Seiten unter Druck und wird sich in Zukunft wohl verkleinern.

Praktische Relevanz

Die Produktergonomie sucht einen Kompromiss zwischen den Fähigkeiten der Menschen und deren Bedürfnissen. Dies ist für die Vermarktung von Produkten von zentraler Bedeutung. Das Marketing kann menschliche Bedürfnisse teilweise beeinflussen, was sich auch negativ auswirken kann, wenn wie im Fall von Digitalkameras Erwartungen geweckt werden, die technisch nicht machbar sind. Der technologische Fortschritt hat seine Grenzen erreicht. Für Hersteller und Kunden ergeben sich daraus unterschiedliche Konsequenzen. Während Hersteller angewiesen sind ihren Fokus im Marketing und in der Entwicklung zu überdenken, stellt sich für die Kunden die Frage ob die Anzahl Pixel als Qualitätsmass nicht längst überholt ist.

1 Introduction

Today's photo-chemical color photography is still based on the same chemical technologies used back in the mid-1930s. But with the advent of television systems, necessity arose for electronic images. Initially, this requirement was matched by the use of ancient Vidicon-Tube-Technology. But despite some advantages over chemical image detection, their image quality was limited. In the early 1970s, charged couple device-technology (CCD-technology) was designed in the Bell Laboratories. The image quality of these CCDs was superior to Vidicon-Tubes and far better suited for color television, which at that time was about to be introduced by the public broadcasting stations. In the 1980s, CCDs were used by professional photographers for the first time; it wasn't before the 1990s that the technology became affordable for end users, though. Improvements in production processes and economies of scale resulting from a growing diffusion led to a decrease of costs. Concurrently picture quality picked up substantially, closing the gap to photo-chemical photography. Digital photography based on CCDs can be considered as the dominant design today (Smith 2006).

CCD sensors offer a big spectral sensitivity, through adaptation and optimization a range from 350 nm to 1,1 µm can be achieved (Engelhard & Seitz 1993). Accordingly, near infrared-, visible- and near UV-light can be detected. X-rays can be registered using CCDs, but only with special optics. Thus, CCD is the technology of choice for a vast set of applications. Each application has its particular requirements, which lead to adaptations and compromises. These constraints in digital cameras and especially compact cameras account for physical limits. Thus, digital compact cameras are an interesting research item assessing technological progress at its limits. According to International Data Corporation (IDC), in 2007 compact cameras accounted for 123,3 million units compared to 7,5 million units for single-lens-reflex-cameras (SLR), they are the biggest area of application for CCDs.

Compact cameras are designed to offer users a handy tool to record their pho-

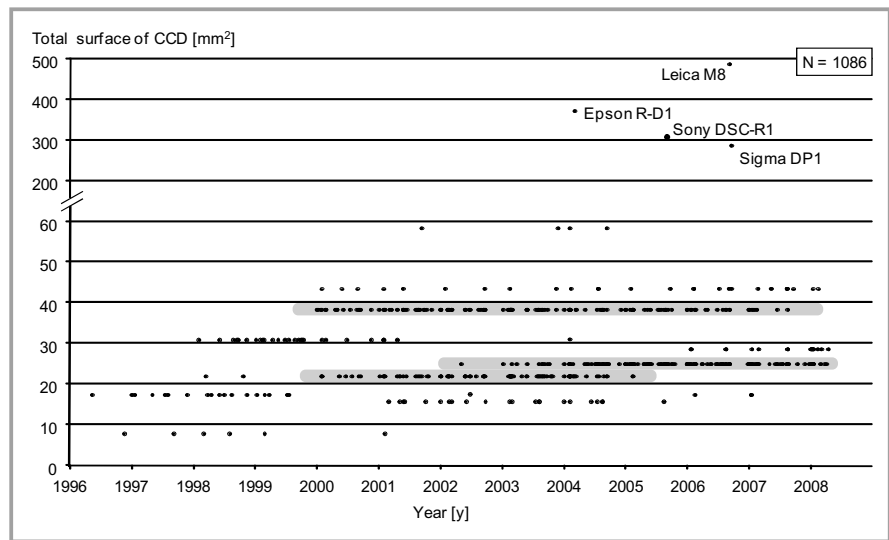


Figure 1: CCD surface: Evolution of the CCD-chip size over the past 12 years – depicted in grey the dominant formats

Bild 1: CCD Oberfläche: Entwicklung der CCD-Chip Grössen während der vergangenen 12 Jahren – grau hinterlegt die dominanten Grössen

Illustration 1: CCD surface: Évolution de la dimension du CCD durant les dernier 12 ans – figuré en gris les formats dominants

tos. Their big advantage is small size and weight. They are now even used as modules in cell phones. Old photo-chemical technology could never have achieved this. Compared to SLR, physical camera size is limited leading to tradeoffs in all camera modules: Power consumption is reduced and light-weight lithium accumulator packs are used, memory modules are in compact scale, CCD-sizes are reduced to make the optical system much smaller and electronics is highly integrated. These achievements were mainly driven by miniaturization. Miniaturization allows for reduced CCD-sizes and increased resolution (Hotta & Matsuura 2006). But CCD-formats did not change much during the past 10 years for compact cameras: 25 mm² or 38 mm² and for about 5 years also 21 mm² CCDs were used frequently (figure 1). These platforms allowed for reuse of lenses across several product families, reducing production costs. This allowed a fast diffusion of the digital imaging technology, substituting incumbent photo-chemical photography to a large extent. The data depicted throughout figure 1-4 and 6 is compiled using the freely accessible directory of www.dpreview.com.

2 Technology speed and customer needs

Initial application of CCDs in photo cameras did not achieve image quality customers were used to from traditional photography. Resolution was too low even for standard 9 x 13cm photographs. Therefore, research and development focused preliminary on increasing image quality. This effort was successful, cameras increased average resolution by a factor of 10 during the past 10 years since 1998 (figure 2).

Digital cameras are high-tech products, customers decisions are driven by product performance. At the beginning the ability to send pictures to distant users and the ease to store and process the picture was very attractive for some professionals like journalists. But conventional users always compared with incumbent technology. Acceptance of improvements in performance resulted from unmet demands. Marketing departments responded by promoting their products mainly through technical specifications. Like CPUs in computing are advertised with their clock rates, digital cameras use megapixels

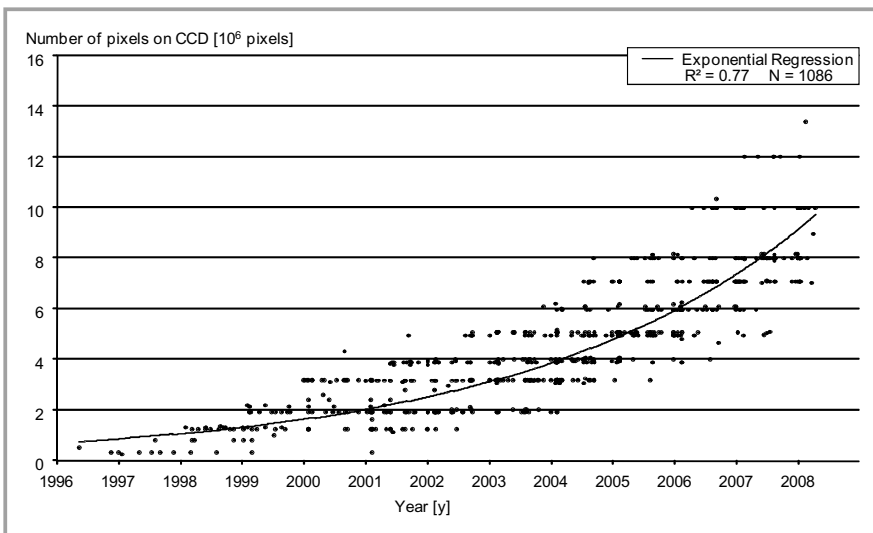


Figure 2: Resolution of digital cameras: Increase of resolution by a factor of 10 within 10 years

Bild 2: Auflösung von Digitalkameras: Steigerung um den Faktor 10 während 10 Jahren

Illustration 2: Résolution des camera digitales: Augmentation d'un facteur 10 durant 10 années

displaying their overall performance in a single number.

But today's resolution of 10 megapixels and above, also in the segment of compact cameras, deliver a satisfactory performance level and diminishing marginal utility of further increasing resolutions is assumed. Photo processing companies suggest a density of image information of 300dpi, compared to 96dpi used for newspaper printing as a quality comparison. A short calculation shows, that a resolution of 10 megapixels allows for printing A4 images above 300dpi. Thus, additional resolution does not pay for most users. Only specific scenarios rely on higher resolving images such as enlarging images or digital zooming. Hence, technological progress needs to be observed in the context of users' preferences.

Professional photographers in many cases ask for as much resolution as they may afford. Taking photos under difficult circumstances, for instance of sport events, makes it sometimes difficult to capture the right moment of a situation. Higher resolution offers the possibility to crop images to achieve the desired cutting. Reserves in image information allow compensations of shortcomings in the actual picture. Thus, the perception of technological

development for professional photographers, the so called "technology speed", is assumed as follows:

$$\text{Technology speed} = \frac{\Delta \text{ pixel/US\$}}{\Delta \text{ year}}$$

Technology speed is defined by the increase of the number of pixels available for a fixed budget per year. Technolo-

gical improvements and decreasing prices let this figure constantly rise during the past years: Technology speed increased exponentially (figure 3). The data show big variance, SLR cameras witnessed specialization for different market segments. This is consistent with market fragmentation in later phases, in this case after 2004.

For hobby photographers the situation looks somewhat different. Today, photos are looked at on computers or printed out in the traditional format of 9 x 13cm. As A4 printing devices are the most common sold printer category in Europe, 10 megapixels comply with the demand for image granularity in these reproductions. Also reproduction on computer or television screens do not require higher resolving images: The standard resolution of computers offers 1024 x 768 pixels, resulting in 0,8 megapixels, the upcoming high definition television standard 1080p features 1920 x 1080 pixels, resulting in 2 megapixels. Hence, technology reached a satisfactory performance level. New attributes, such as product design, pricing or time to picture, substitute resolution as a buying criterion. Therefore, in the market segment of hobby photographers compact cameras are sold, delivering a handy photo-tool with an appealing design at low price. As average prices for compact cameras

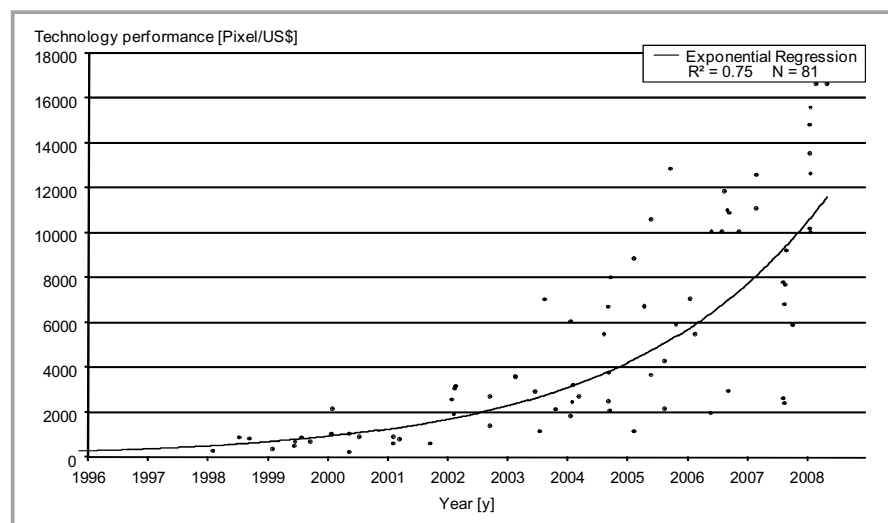


Figure 3: Technology speed for professionals: Ever increasing image quality

Bild 3: Technologiegeschwindigkeit für professionelle Fotografen: stetig steigende Bildqualität

Illustration 3: Vitesse de technologie pour les professionnelles: Qualité de l'image augment continuellement

have been dropping for some years, pricing is an important decision criteria and perception of technology speed would be defined as follows:

$$\text{Technology speed} = \frac{\Delta \text{ US\$/pixel}}{\Delta \text{ year}}$$

Technology speed is thus defined by the price per pixel over time. Technology speed is decreasing, approaching its limit in an asymptotic manner.

But compact cameras not only exist for cost optimizing customers; of special interest are for instance Epson R-D1, Leica M8, Sigma DP1 and Sony DSC-R1. These cameras utilize SLR-sized CCDs with 300-500 mm² in order to achieve top image quality compared to the dominant design of 25-38 mm² (figure 1). Pricing for these cameras approaches professionals rather than hobby photographers (figure 4). But, accounting for the largest market segment, compact cameras witness over-engineering, customers do not use and are not willing to pay. But besides the lack of customer acceptance of these over-designed products, technological problems arise as well. (Boutellier & Rohner 2006)

3 Technological limits

As the size of CCDs converged to a standard over the last decade and concurrently the amount of pixels squeezed into this area constantly rose, technological problems emerged with compact cameras. Miniaturization leads to side effects which are difficult to handle (Burt 1991):

- Photosensitivity
- Reproduction of details
- Noise
- Diffraction pattern
- Chromatic aberrations

It is questionable whether further increase in image resolution is offset by these side effects – in this case, overall perceived picture quality would actually decrease. Compared to com-

compact cameras, SLR cameras use larger CCDs and far more expensive optics making them less sensible to these side effects.

3.1 Photosensitivity

Cramming more and more pixels on the same sensor area reduces the size of each pixel. Though, the amount of light arriving on the CCD is still the same, but distributed across more and smaller pixels. This reduces the so called dynamic perimeter per pixel. Pixels present a digital behavior: either a photon is converted into a charge or it is not. Therefore, either a white or a black spot is stored in memory. Bigger or more sensitive pixels with better quantum efficiency when registering arriving photons allow for increased hue ranges. With bigger pixels, as featured in most compact cameras with 6 megapixels, black is reproduced with much more variability. But photosensitivity is more difficult to achieve, as with small pixels the difference between one or two arriving photons implies a larger difference in luminance. This effect is most noticeable on very dark and very light areas on photos by elapsing of entire sections.

Very bright sections of images witness another side effect: “blooming”. Eve-

ry single pixel can register photons only up to a specific level of electric charge. If a pixel is overexposed to photons, the electrical charge starts to flux into neighboring pixels energizing them as well, resulting in overexposed sections.

3.2 Reproduction of details

Camera resolution in advertisements is usually given by the number of pixels that are located on a CCD, but photographers are interested in how many pixels are distinguishable on the stored image. This can then be considered as the true resolution, the capability to reproduce details. Detail reproduction depends not only on the CCD, quality of the lens, shutter systems, focus, optical filters and vibration have a big impact as well. The weakest component defines overall system performance as once lost details can’t be recovered in a later step. Till recently, CCD resolution was the restricting factor, hiding shortcomings of other components. Today bottlenecks of the optical system become visible. Reproduction problems at the image corners for instance become more and more a nuisance, making higher-resolving CCDs useless. This is a limiting factor for the lenses since the Raleigh Crite-

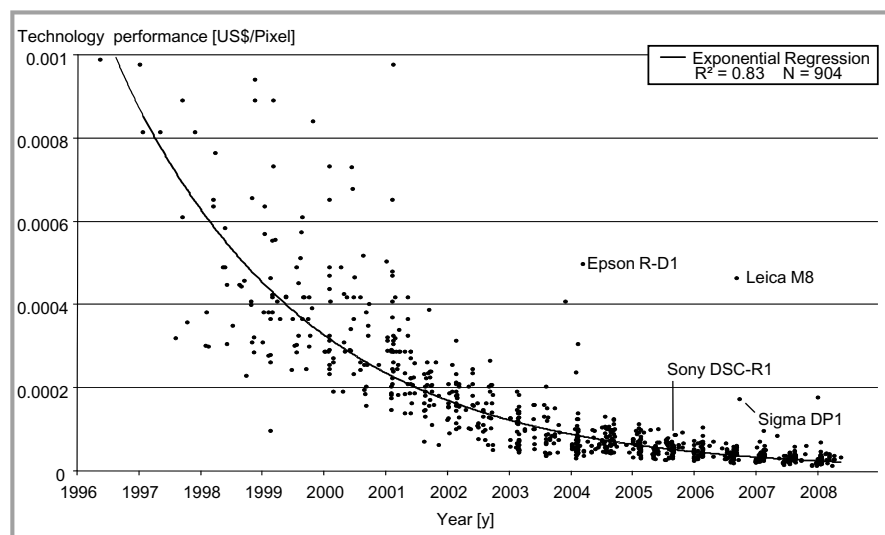


Figure 4: Technology speed for consumers: Technological progress reached a deadlock
Bild 4: Technologiegeschwindigkeit für den Massenmarkt: Der Fortschritt kommt zum Stillstand
Illustration 4: Vitesse de technologie pour le grand public: progrès technologique en stagnation

tion tells us, that there is an absolute limit to miniaturization.

3.3 Noise

Image quality suffers from soaring noise caused by miniaturization of pixel sizes. Noise is a reproduction error caused by errors in registering arriving photons and processing signals during the read out phase of the CCD. Sensitivity of each pixel differs over time and among pixels. The same amount of photons is not always transformed into the same amount of electrical charge among different pixels and does not remain constant with the same pixel over time, statistical variations occur. Even with no photons arriving, a noise is present. This so called background noise varies with temperature. Different sources of noise are known, most of them can be handled by noise reducing software algorithms, on average only. But with the shrinking of pixels, noise reducing becomes more and more difficult. With smaller pixels the amount of photons arriving onto one pixel decreases such as the “energized” state of a pixel contains a smaller energy difference than with bigger pixels, making it more and more difficult to distinguish signal

from noise. In low light, image noise is getting more and more severe, as signal with respect to noise is lower. Amplification of weak signals causes noisy pictures. More miniaturization leads to more noise causing waste heat on the same chip area.

3.4 Diffraction

Below a certain size of applied optics, quantum effects start to reduce the signal quality. Diffraction occurs when a wave passes nearby an obstacle leading to a deflection of the light. Instead of a suggested linear dispersion, photons spread out around the geometrical image of the emitting source. Thus, detail quality gets blurred. CCDs cannot be made smaller and smaller without deterioration of image resolution. In the optical system the Raleigh Criterion defines the limits of the resolution power, as the light going through a lens is spread out through the well known Airy-disc. This is of relevance for compact cameras, as big apertures may limit detail resolution (figure 5):

Whereas r is the radius of the Airy-disc f is the focal length of the lens:

$$r = \sin \theta \times f$$

Substituting $\sin \theta$ by $1,22\lambda/d^{\text{lens}}$ leads to:

$$r = \frac{1,22\lambda}{d^{\text{lens}}} \times f$$

The aperture N is defined as f/d^{lens} resulting in:

$$r = 1,22\lambda \times N$$

The human eye is most receptive for light with a wavelength λ of 550 nm:

$$r = 0,67\mu\text{m} \times N$$

Bigger apertures decrease detail resolution. As soon as more than one pixel of a CCD is covered by the Airy-disc from a “one-point-object” the image is blurred. For SLR cameras featuring an average pixel size of 6 μm , apertures above 9 and for compact cameras with an average pixel size of 2 μm , apertures above 3 lead to a loss in detail reproduction. Although CCD sensors would be able to record more detailed information. Thus there is an upper limit for the aperture of the lens; together with the lower limit of the pixel size this sets an absolute limit to the miniaturization of the total system. Low camera apertures can be achieved with expensive lenses only, but engineers have to compromise.

3.5 Chromatic Aberration

Chromatic aberrations are caused by lens materials having different refraction indexes for different wavelengths of light. Objects appear surrounded by fringes of colors, because each wavelength can't be focused at a single common point. This effect gets increasingly visible with smaller pixels.

3.6 Relevance

All these side effects have in common that they aggravate with miniaturization. Camera manufacturers try to eliminate these effects through optimization algorithms. Image correction and applied signal processing strategies work well on average, but to some extent always eliminate details of images. Details are difficult to be differentiated from noise.

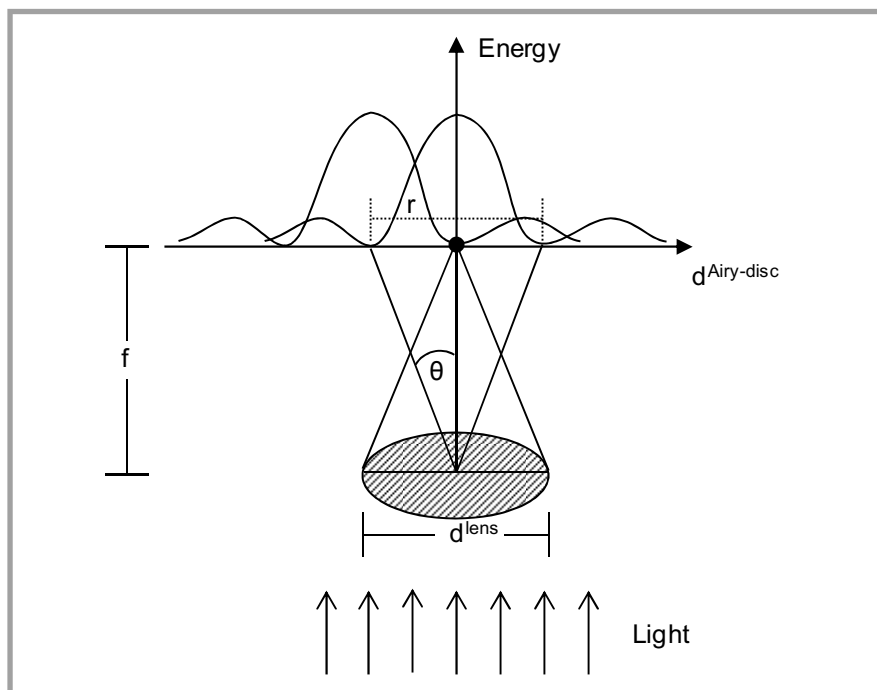


Figure 5: The radius of the Airy-disc limits the resolution of the optical system
Bild 5: Der Radius der Airy-Disk limitiert die Auflösungskapazität des optischen Systems
Illustration 5: Le radius de l'Airy-disque limite la résolution du système optique

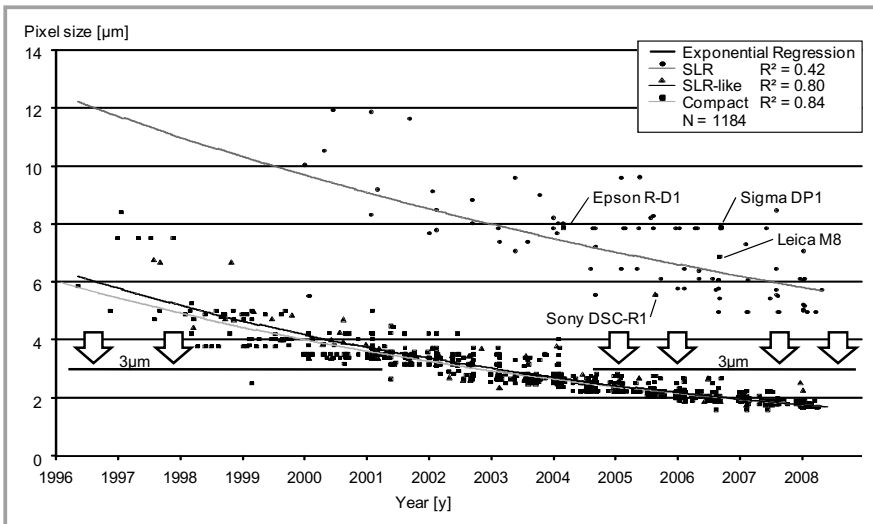


Figure 6: Miniaturization of pixels on CCDs: Physical limits prevent further progress
Bild 6: Miniaturisierung der Pixel auf den CCDs: Physikalische Limiten verhindern Fortschritte
Illustration 6: Miniaturisation des pixels sur CCDs : Limite physique empêche le progrès technologique

Miniaturization allows for more pixels on the same CCD area. But side effects deteriorate image quality. Below a limiting size of the lens system higher resolving CCDs are neutralized by miniaturization issues. Professional journals such as “c’t” and “Color Foto” publicize the quality of digital cameras on a regularly base. Their tests are conducted by “Image Engineering”. Hundreds of cameras have been tested since. Empirical evidence shows that with pixel diameters above 3 µm bothersome side effects are generally controllable in a way that overall image quality does not suffer too much. But below 3 µm the situation changes, overall image quality drastically worsens even though such cameras often offer more megapixels than their predecessors: A Sony DSC-T100 with 8 megapixels delivered better image quality and detail resolution than the next year’s model DSC-T300 with 10 megapixels. 3 µm are of course not a bottleneck carved in stone but show the ability of manufacturers to deal with side effects caused by miniaturization. Some manufacturers obviously have more advanced capabilities and can also master smaller pixel diameters, offering high quality 10 megapixels cameras, in most cases with more sophisticated and thus more expensive lenses. But with a dominant sensor size of 38 mm², 4,2 megapixels

represents the current optimum. Thus, instead of stating bare megapixels as a performance measure, pixel size needs to be displayed as well, in order to allow for a more holistic performance estimation.

Analyzing 1184 cameras introduced to the market since 1996, resolution and pixel size show that already in 2003 average pixel size for compact cameras dropped below 3 µm (figure 6). With the empirically assessed quality problems below 3 µm, overall image quality of compact cameras is ever decreasing since. SLR cameras apply much bigger CCD sensors and are not prone to these problems yet. As SLR cameras are used mainly by professional photographers asking for high image quality instead of high megapixel figures. This pinpoints the difference in marketing and engineering camera producers make for different market segments. For compact cameras though, further miniaturization is no longer able to deliver superior product quality, it reached a deadlock. The main attribute of differentiation has vanished.

Technological limits are also indicated by emerging quality problems in manufacturing, affecting high-end cameras, as well. In mid-2005, problems with Sony cameras accumulated, urging

the company to extend their warranty, afterwards other manufacturers stated similar problems. CCDs in cameras showed distorted pictures, after having been in use for years without problems. These were not individual cases but affected large populations of cameras. Even high-end products such as Leica’s Digilux 2 were affected at the end of 2006. Technical details about the causes were not disclosed. Possibly, the problems were due to another optimization in production processes further decreasing production costs. Meanwhile, this particular problem has been solved, but operating at physical limits will surface other problems from time to time.

4 Conclusion

The two market segments, compact cameras for the mass-market and SLR cameras for professionals, are in discrete stages. Whereas for the professionals the need for ever higher resolving cameras is present and is being met by technological advancements, the situation for compact cameras is different. Firstly a need for additional picture granularity can’t be derived from the average users’ requirements in this segment. Secondly, advancements lead to a dead end, or are even leading to setbacks in overall image quality. Thus, technology speed for image quality is not only declining but actually negative: Some cameras show lower image quality than their predecessors.

Compact cameras are in between SLR cameras which offer superior image quality on one side and cellular phones on the other side. Preferring the use of a compact camera over a mobile phone’s capability is founded on the expected higher image quality and higher functionality. Nevertheless whereas improvement of compact cameras stagnates, mobile phones offer better and better image quality, more and more overcoming the comparative advantages of compact cameras.

Integration of camera functionality into mobile phones evidently requires further downsizing, thus problems with miniaturization as discovered with compact cameras are expected to

arise here as well. But end-users expect quality of mobile phone cameras and compact cameras to further converge in the future. Instead of CCDs, mobile phones often rely on CMOS technology holding some advantages for low power consumption devices. This may help to overcome some limits of miniaturization.

The growth of sales in the compact cameras by 23 million units in 2007 thus, might be caused by the decrease of prices rather than by the demand for substitution of cameras already in use. End-users do not compare resolutions given by the number of pixels as decisive: It is good enough for presentations on TV screens or PC monitors.

Some manufacturers of compact cameras thus shift focus in marketing and development. "Time-to-picture" needs to be further reduced; ruggedness, autofocus capability and finally design could be the important potentials in the future. Cooperation with mobile phone manufacturers could give access to the benefits in this new market. Certainly paradigms in this market shifted un-

noticed some time ago. Some system designers seem to be aware of the fact that their CCD modules run the risk to become over-engineered and that customers are paying more attention to other attributes: The typical signs of a disruptive innovation that could entail some problems for successful module suppliers.

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