Evaluating Digital Cameras

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ABSTRACT

The quality of digital cameras has undergone a magnificent development during the last 10 years. So have the methods to evaluate the quality of these cameras. At the time the first consumer digital cameras were released in 1996, the first ISO standards on test procedures were already on their way. At that time the quality was mainly evaluated using a visual analysis of images taken of test charts as well as natural scenes. The ISO standards lead the way to a couple of more objective and reproducible methods to measure characteristics such as dynamic ranges, speed, resolution and noise. This paper presents an overview of the camera characteristics, the existing evaluation methods and their development during the last years. It summarizes the basic requirements for reliable test methods, and answers the question of whether it is possible to test cameras without taking pictures of natural scenes under specific lighting conditions.
In addition to the evaluation methods, this paper mentions the problems of digital cameras in the past concerning power consumption, shutter lag, etc. It also states existing deficits which need to be solved in the future such as optimized exposure and gamma control, increasing sensitivity without increasing noise, and the further reduction of shutter lag etc.

Keywords: digital photography, image quality, noise, dynamic range, resolution, ISO speed, shutter lag, power consumption, SFR

INTRODUCTION

When the first digital consumer cameras, such as the Casio QV 10, were launched in 1995, it was clear that the image quality was not acceptable but that technological development would be fast. Soon afterwards cameras, such as the Kodak DC series and the first Canon PowerShot with a larger pixel count and better image quality, were launched. At that time it was already clear that digital photography would be the future and that taking pictures on film would be replaced by electronic sensors. However many people said that if the quality would ever be as good as that of film, it would take a long time. That was the problem at photokina 1996: nobody could predict when digital cameras would be good enough to replace analogue ones. But, with the launch of the Olympus Camedia cameras, it was clear to the experts that this would only take a few years. At that time, magazines such as the German "Color Foto" started thinking about an objective test procedure to test digital cameras and I was asked to develop a test stand for digital cameras.

WHY DO WE NEED TESTS FOR DIGITAL CAMERAS?

The reactivation of the photographic market caused by digital photography raised a lot of interest in the industry, as well as among the publishers of photographic magazines, and of course, among consumers. Everybody wants to participate in that market and the creativity in selling products by creating new terms and phrases for the technical specifications seems to be unlimited. Manufacturers need test procedures to ensure, and to increase, the quality of their products. In order to make sure that the creativity of the marketing people relates to the real world and to help customers to find the right cameras for their specific applications, the magazines also need standardized procedures for testing digital cameras.

TESTS BASED ON VISUAL ANALYSIS

Most of the magazines started by taking pictures from various scenes and viewing the images on a monitor or judging printed paper outputs. Since neither Photoshop nor most of the printers supported color management until version 5.0,

Digital Photography II, edited by Nitin Sampat, Jeffrey M. DiCarlo, Russel A. Martin,
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the quality of the images the testers looked at was often limited by the restrictions and the calibration quality of the output devices. Because the tester has to make sure that the output or viewing device and its calibration is not the bottle neck for determining the image quality of a camera, the tests were not easy to handle.
At the same time, the lighting conditions and surrounding temperature of the scenes used to evaluate the cameras often varied and the results were in many cases not reproducible and comparable between the different cameras. So what was urgently needed by the magazines was a standardized test scene with a constant illumination photographed under constant conditions. This constancy is required whenever numerous cameras are to be compared over a certain period of time.
Another aspect is that of creating a scene consisting of objects which allow the doubtless evaluation of a certain image quality aspect even if a tester is in a bad mood. These objects are required especially for aspects such as resolution measurements, dynamic range, white balancing and color, and they are not easy to find.
For a real measurement using a software to analyze an image instead of the human eye we have the same requirements: constant and appropriate illumination (e.g. standardized Daylight D55 or tungsten light 3050°K as specified in ISO 7589[1]), constant temperature (23 +/- 2° [2]), relative humidity between 30 and 70% [2], and suitable objects to measure the values and the right software for the analysis.
The approach of using the visual analysis of a single test scene or multiple "real images" of various scenes always conflicts with the requirement of most magazines to have a single number for the classification of a specific image quality aspect. Sometimes the magazines even want a single number to classify the complete camera. If we look at colors for example, although it is not easy, it might be possible to classify the reproduction of a single color in an image. But how can one come up with an objective number representing the complete color reproduction quality of the camera without any measurements? If we look at the same aspect for resolution, we find that this might be easier because we can define a so-called limiting resolution. Taking a picture of the ISO 12233 resolution chart we can look at it and find a frequency limit, up to which point the lines can be seen as separated lines. But if we look at Figure 1 we see that this task is often not as easy as we expect it to be.

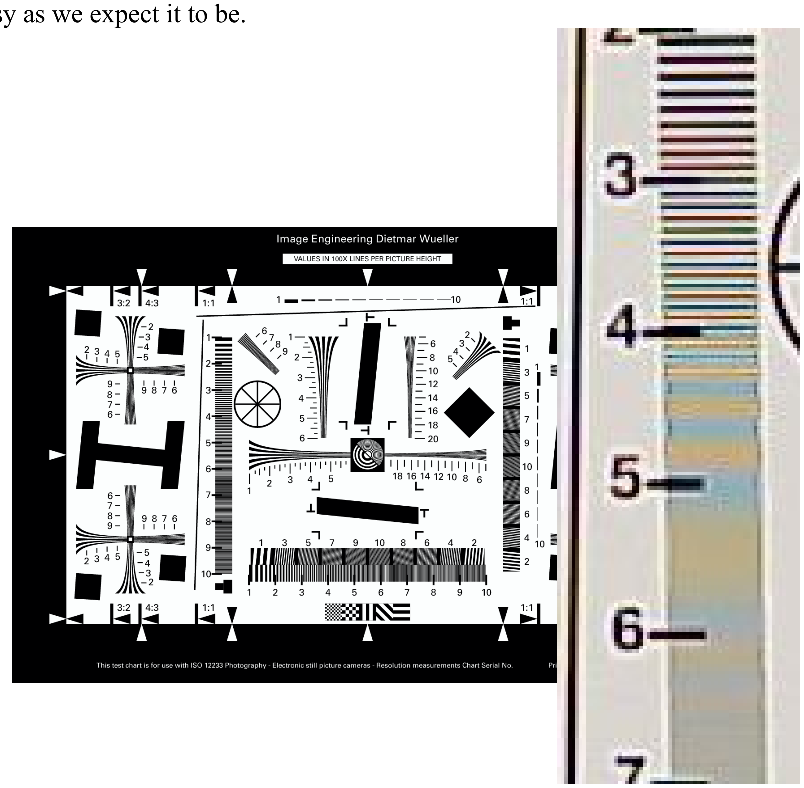

Figure 1: The visual analysis of limiting resolution is often not as easy as we expect it to be.

Another problem using the visual approach is that we usually do not know the characteristics of the camera because that's what we want to test. The testers may know the limitation of the output device but they need to be very experienced to judge at the borderline whether they still see the camera characteristics or if the results are limited by the device.

MEASURING THE CHARACTERISTICS

In order to anticipate a major aspect: measuring specific image quality aspects helps a lot to characterize a camera but these measurements always have to be related to the real world images and there are numerous aspects which we will never be able to measure. This is why it is impossible to completely test a camera without taking pictures of natural scenes.

We at Image Engineering based our measurement procedures on the ISO standards [1, 2, 3, 4, 5, 6] which were already on their way at the time we built the first test stand in 1997, and which served as a good starting point.

In order to get a sufficient characterization of a digital camera, a couple of characteristic values seem to be mandatory and others may be recommended or optional. The two characteristics which seem to be most important are to measure the OECF [2] (opto electronic conversion function) and the resolution [5], but a few others belong to this group as well.

The following aspects are mandatory: • Resolution • Sharpness • OECF • White balancing • Dynamic range (related scene contrast) • Used digital values • Noise, signal to noise ratio Recommended values are: • Distortion • Shading / Vignetting • Chromatic aberration • Color reproduction • Unsharp masking • Shutter lag • Power consumption • Aliasing artifacts • Detailed noise analysis • Compression rates • Exposure and exposure time accuracy and constancy • ISO speed	Optional values may be: • Color resolution • Battery life • Detailed macro mode testing (shortest shooting distance, max. scale, distortion) • Flash capabilities (uniformity, guiding number etc.) • Auto focus accuracy and constancy • Startup time • Image frequency • Video capabilities (pixel count, resolution, frame rate, low light behavior) • View angle, zoom range (at infinity and shorter distances) • Hot pixels • Display (refresh rates, geometric accuracy, color accuracy, gamut, contrast, brightness, visibility in sunlight) • Metadata (Exif, IPTC) • Watermarking • Spectral sensitivities • Bit depth of raw data • MMS capabilities for mobile phone cameras (resolution, frame rate, compression etc.) • Optical stabilization

Since this paper can not cover all of the procedures in detail, I would like to refer to our white paper which can be downloaded from http://digitalkamera.image-engineering.de/index.php/Downloads .

TEST CONDITIONS

The test conditions should be set up in such a way that they represent the typical conditions present in the real-world use of the camera. If the camera is tested in a mode unusual for the specific application, or under unusual conditions, the result may not represent the real image quality achievable for this application.

The setup should fulfill the following requirements:

- Check the factory or standard settings of the camera for plausibility (sharpening, contrast, speed, saturation, white balancing) with specific care for reproducibility.
- Uniform illumination of the test chart: the use of an Ulbricht integrating sphere (app. 98% uniformity) is recommended for all measurements which require uniformity. If a light box is used the non uniformity has to be compensated by a calibration image.
- For photographic applications, color temperature and spectral distribution has to fit the requirements of ISO 7589[1].
- For photographic applications, the exposure value[4] for the OECF and color measurements should be EV7 or higher.
- Test charts for resolution, distortion, and chromatic aberration measurements should be at least 40 x 60 cm or bigger. For test charts the integrating sphere may be replaced by a typical reprographic daylight illumination.
- Temperature should be 23°C +/- 2°C and relative humidity should be 50% +/- 20%.
- For visual inspection and comparison, a calibrated and profiled monitor is required.
- If results are required for different lighting conditions, these conditions should be typical and the lighting conditions have to be specified.

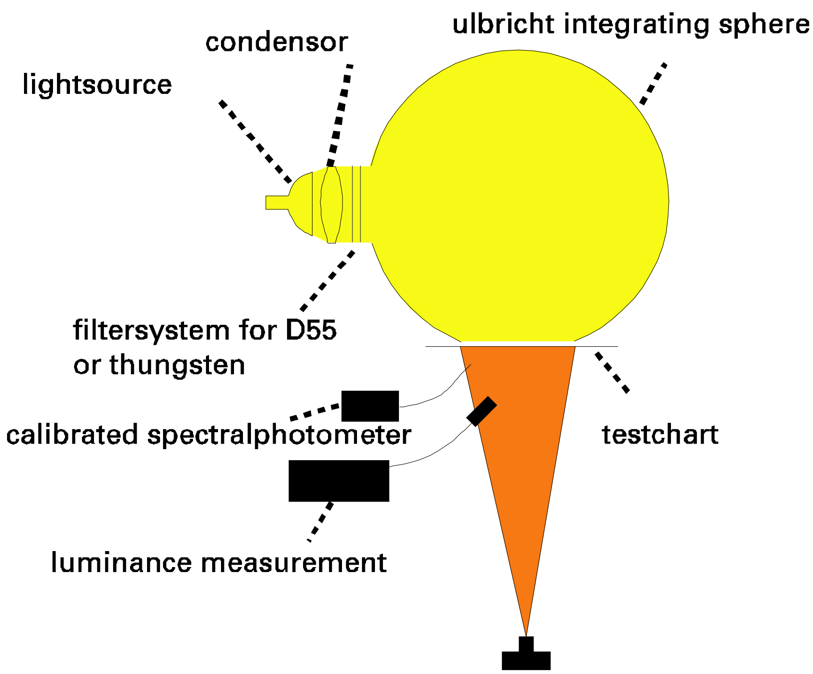

Figure 2: a sample set up for a uniform illuminated transparent test chart.

THE IMPORTANCE OF OECF MEASUREMENTS

The OECF describes how the camera transfers the illumination on the sensor into digital values in the image. This information or at least the images of the test chart are necessary to answer the following questions:

- What is the maximum contrast in a scene that can be captured by the camera in all its tonal details (dynamic range)?
- Is the white balancing o.k.?
- Does the camera use all possible digital values in the image?
- Is there a gamma or tonal correction applied to the captured linear image?
- What is the signal to noise value for different grey levels?
- What is the ISO speed of the camera?

A picture of a single chart answers all these questions.

The camera OECF (opto electronic conversion function), as specified in ISO 14524 [2], is measured using a test chart with patches of different grey levels aligned in a circle around the center.

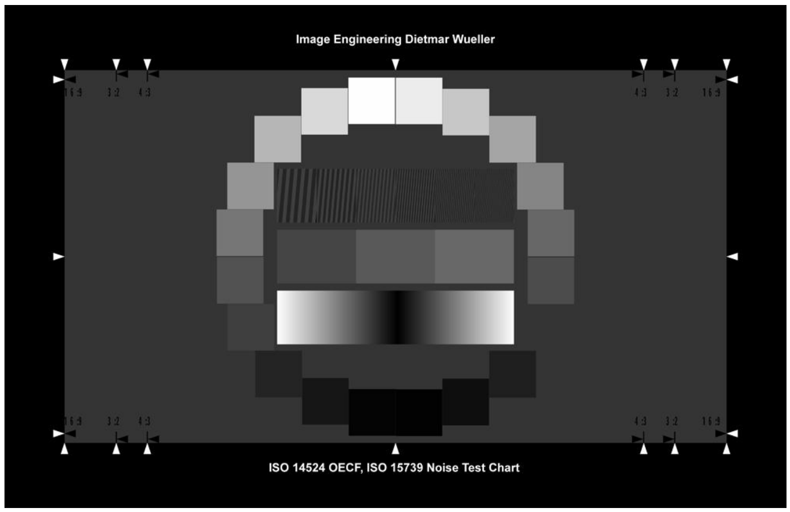

Figure 3: The OECF chart of ISO 14524 combined with the noise patches of ISO 15739. This is a special version with 20 grey levels.

The OECF comparison of the digital SLR cameras (Figure 4) shows that the cameras use different level corrections to transform the scene luminances into digital values. Since the images are exposed in a way that the highest luminance patch reaches the saturation level, the differences in the curves are the starting point in the darkest patches and the shape of the curve. An early starting point together with a highlight compression (Fujifilm S3 Pro) shows a high dynamic range of a camera. This was a result we expected when Fujifilm came up with the SR-Sensor type of the Super CCD. The other digital SLRs are about 1 f-stop behind. An internal test showed that the dynamic range of the S3 Pro also exceeds that of the processing chain negative film printed on paper by more than 2 f-stops. So the dynamic range of a professional digital camera is higher than that of film/paper.

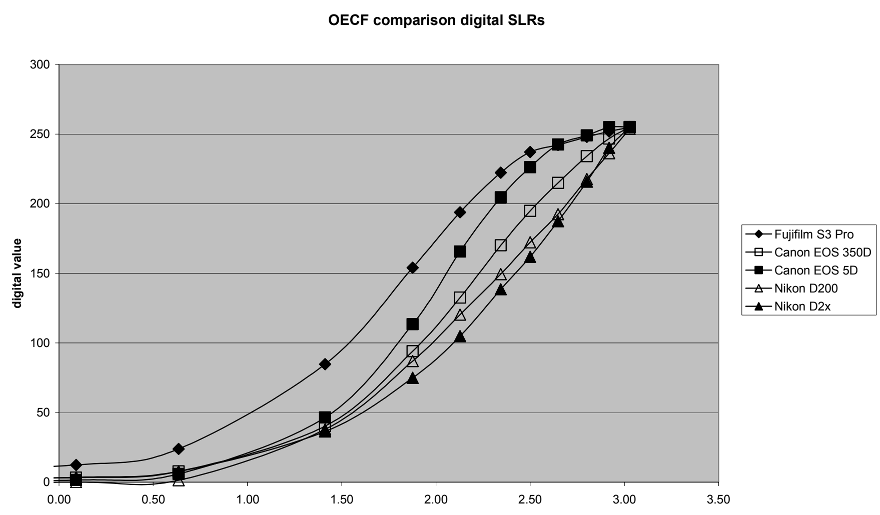

Figure 4: The OECF comparison of the digital SLR cameras indicates that the Fujifilm S3 Pro has a higher dynamic range because the curve starts at lower log luminance values. To keep the highlights we find highlight compression expressed by a shoulder in the curve. The Canon EOS 5D tries to do the same in the highlights but fails to start earlier in the low lights.

PIXEL COUNT

Unfortunately people think that resolution is the same as pixel count and, in fact, the pixel count as the sample rate is a limiting factor for resolution. With increasing pixel count, the other parts of the imaging system are more and more the bottle neck for the resolution, i.e. the ability of a camera to capture fine detail, especially because the manufacturers try to keep the sensor size as small as possible.

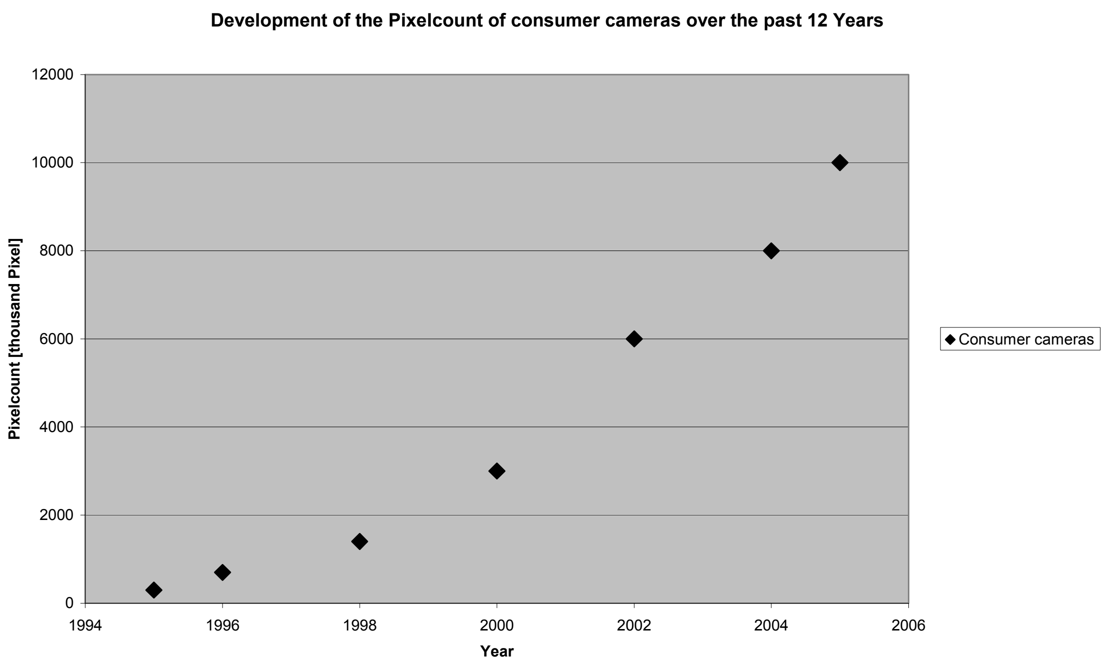

Figure 5: the rise of pixel count for consumer cameras over the last 12 years

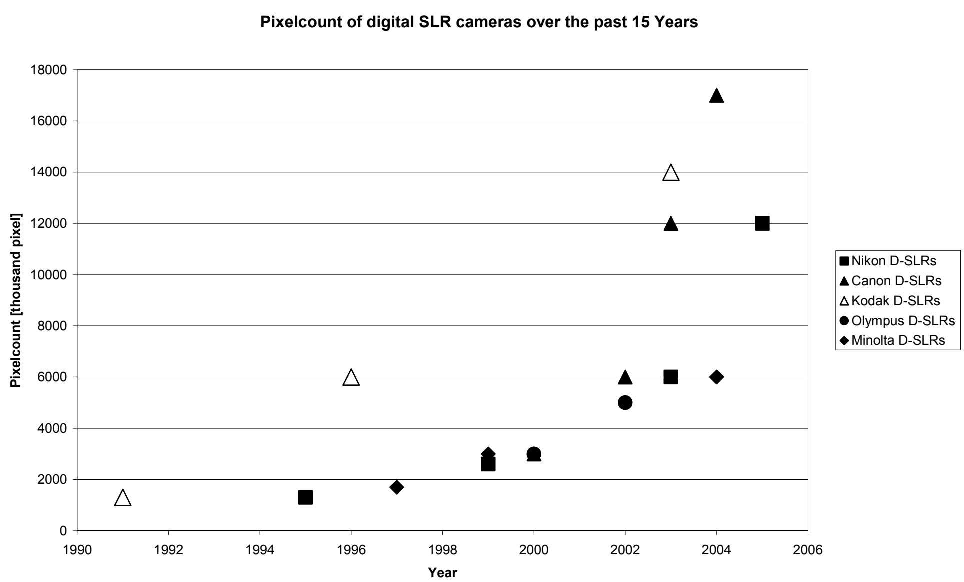

Figure 6: Pixel count for digital SLR cameras

LIMITING RESOLUTION

When we started in 1997, the 640 x 480 pixel cameras used a 1/3” sensor. The related pixel size calculated from these dimensions is 7 µm. Current entry-level consumer cameras use sensors of about the same size but instead of 300,000 pixels the sensors have 6,000,000 pixels. This of course decreases the pixel pitch to 2.1 µm leading to a lower sensitivity, a higher noise level and requires lenses with a much higher resolution [11].

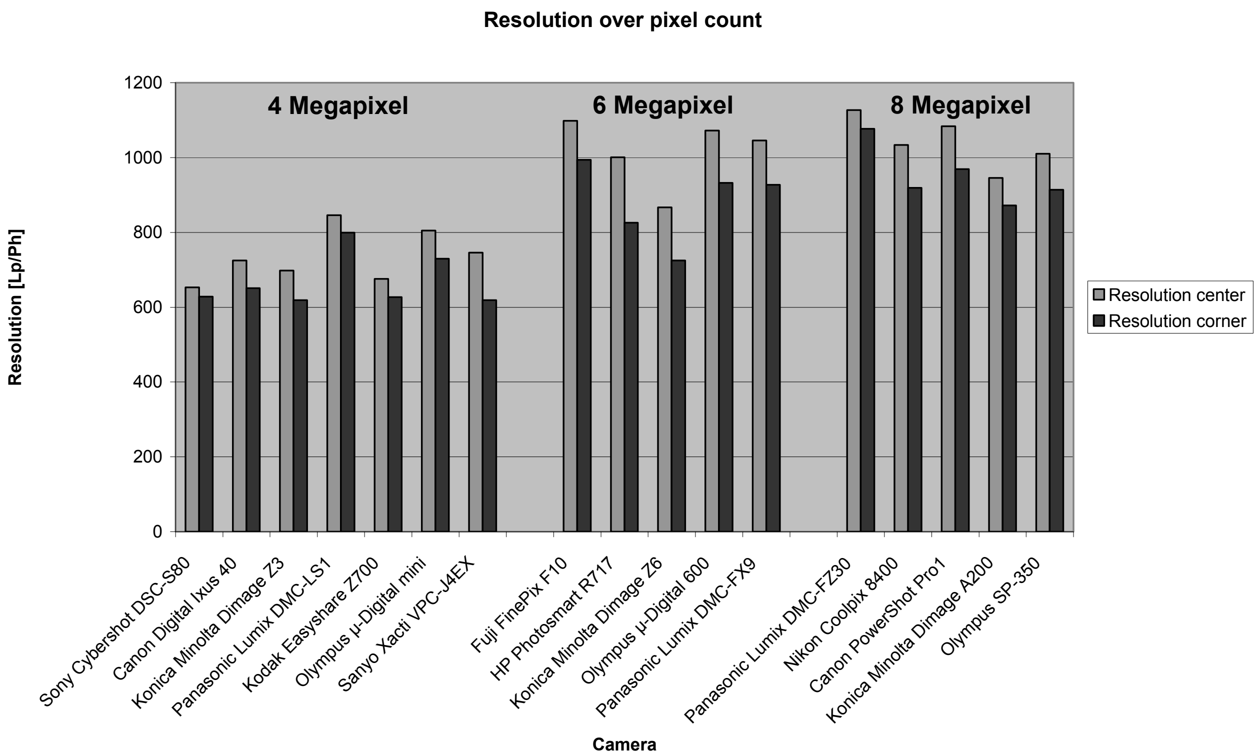

Figure 7: Limiting resolution for center and corner of cameras sorted by pixel count

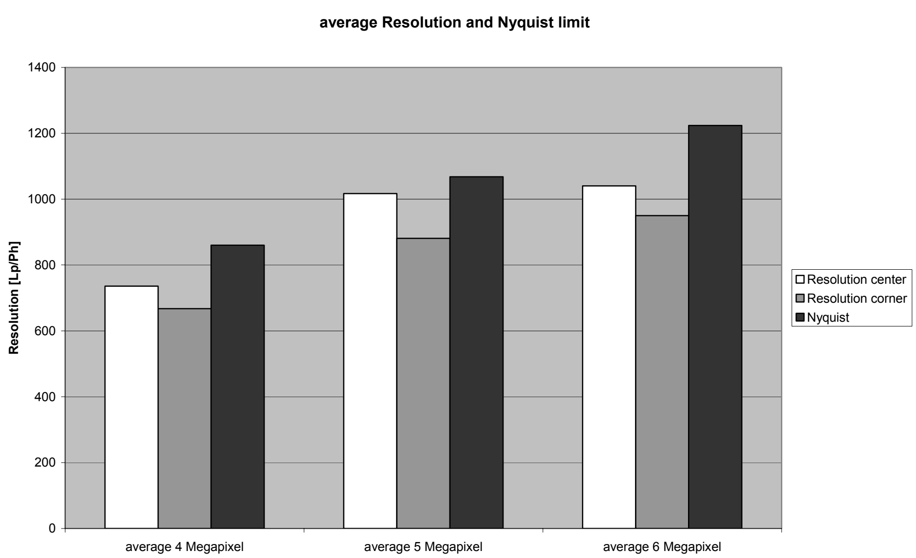

Figure 8: Average limiting resolution for center and corner in combination with the Nyquist limit

Figures 5 and 6 show the limiting resolution for cameras at different positions in the image. The limiting resolution in this case is the frequency where the MTF of the camera reaches a 10% contrast value. Figure 5 shows the deviation of the limiting resolution for a variety of actual 4, 6, and 8 megapixel cameras. Some of the 4 megapixel cameras are better than other 6 megapixel devices and it is even worse if the 6 and 8 megapixel cameras are compared. Looking at the numerous cameras we found that the higher the pixel count, the greater the average distance to the Nyquist limit.

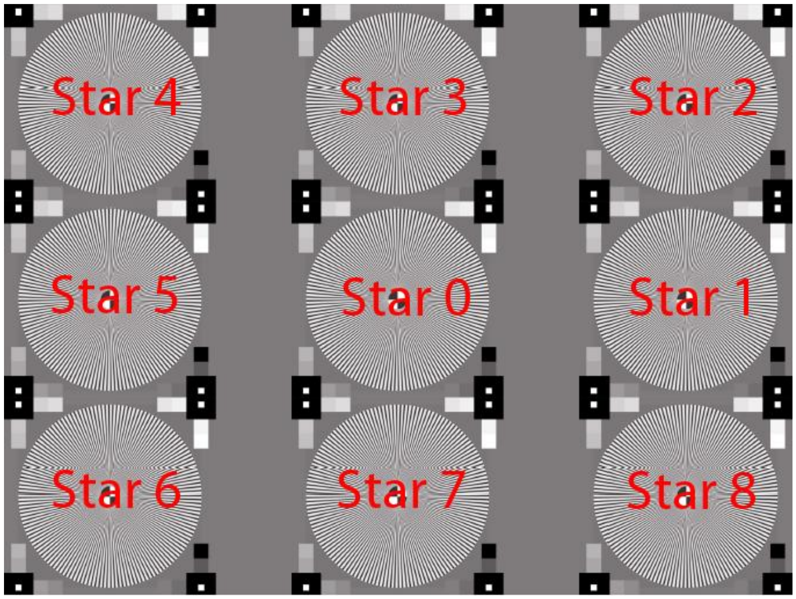

Figure 9: The MTF was measured using 9 modulated Siemens Stars

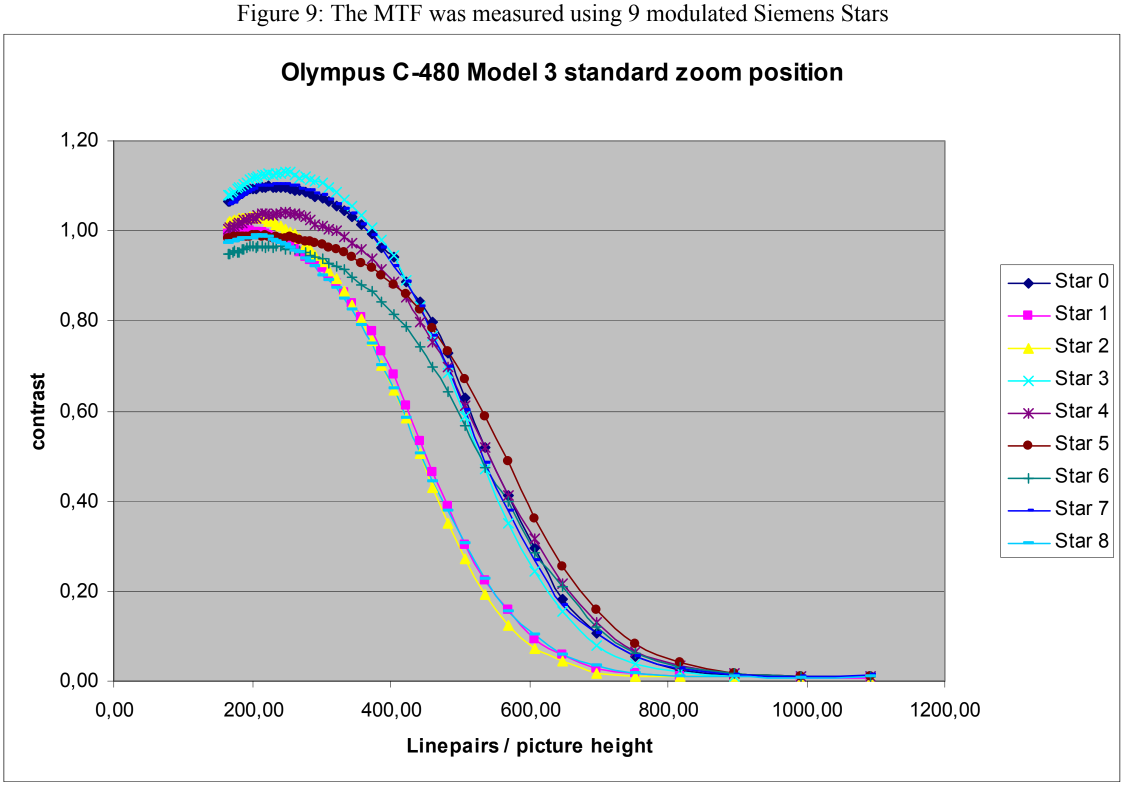

Figure 10: The MTF for the Olympus C-480 shows a centering problem. The stars on the right side 1, 2, and 8 show a lower contrast than the others.

When the pixelpitch (the distance between two pixel centers) decreases, the required level of accuracy for mounting the lenses on top of the sensor increases. Therefore, we now detect more centering and alignment problems than we found a couple of years ago. Also the loss in sharpness – given as the contrast for low frequencies – and in resolution from center to the corners is increasing and a significant quality difference can be found depending on the quality of the lens.

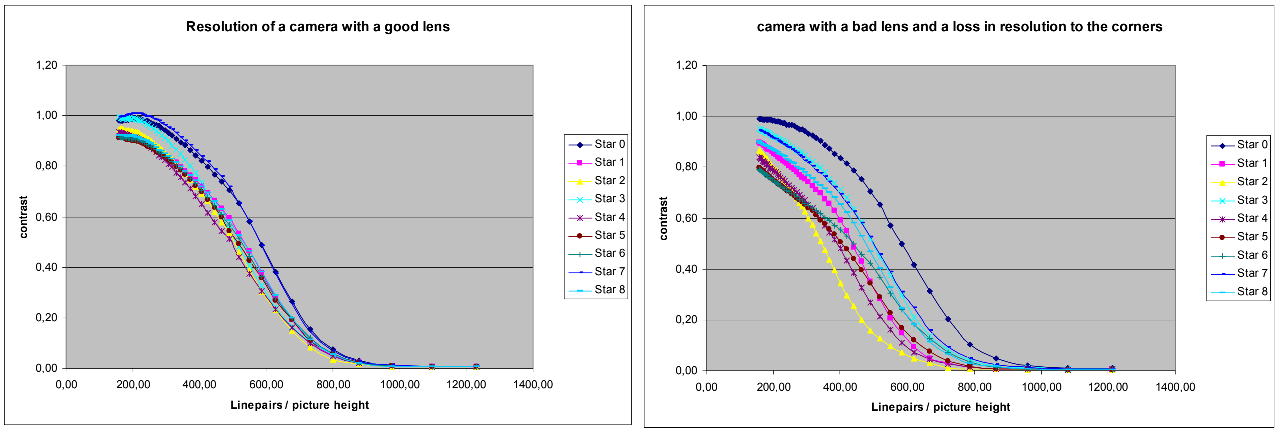

Figure 11: the comparison of the MTFs for a camera with a good and a bad lens.

CHROMATIC ABERRATION

Small pixels also support the visibility of color fringes in the image corners caused by chromatic aberration of the lenses. The chromatic aberration can be measured locating the position of an edge in the image corner for all three color channels separately and calculating the difference for the green reference channel.

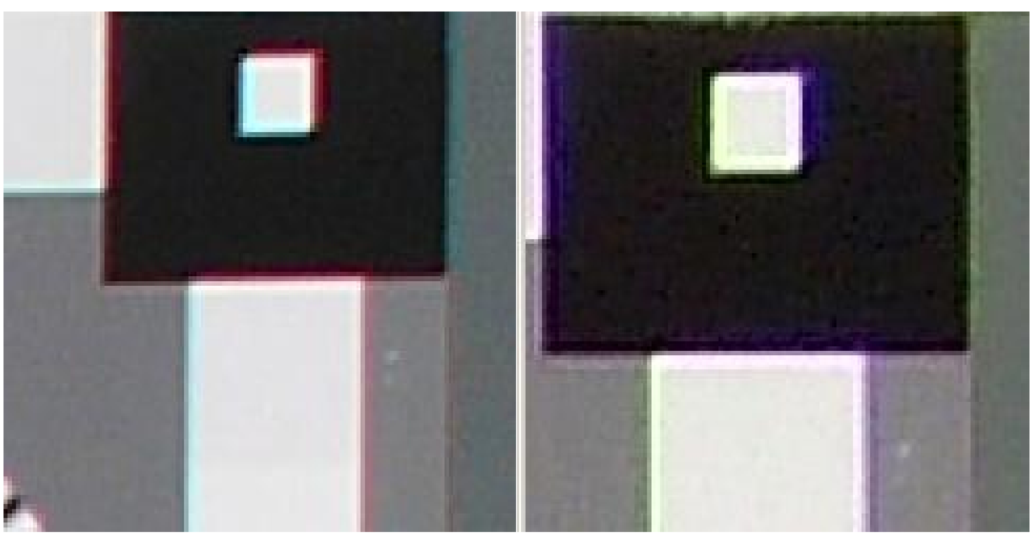

Figure 12: The visibility of chromatic aberration of the lens is stronger for smaller pixels.

NOISE REDUCTION

Some manufacturers try to solve the noise problem by using a noise suppression filter instead of a larger sensor with larger pixels. These filters are usually a trade-off between noise reduction and resolution. The picture taken with the

Fujifilm E900 (Figure 13) shows the contrast and frequency-dependent noise reduction. The high contrast structures in the facades of the building and the signboard at the train station show all the expected details. In the trees however the low contrast structures are gone.

Figure 13: An image taken with the Fujifilm FinePix E900 at ISO 400.

DIFFRACTION

The sensor size also causes diffraction problems at low apertures. To calculate from which f-stop these problems begin, we have to look at the Rayleigh Resolution Criterion (circa 1879). If we combine this with the discrete positioning of a sensor, it appears that the pixel pitch has to be at least the required distance of the two Airy circles, namely the radius of the circle. This distance is calculated using:

$$r = 1.22 \cdot k \cdot \lambda$$

with

$$k = f - stop$$

$$\lambda = wavelength\ of\ light$$

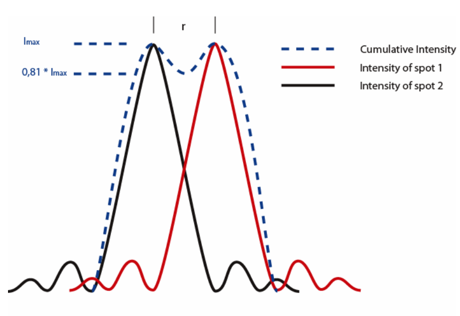

Figure 14: diffraction theory.

Dependency of diffraction on the aperture

f-stop	Radius of the Airy circle [mm]
1,8	0,0011
2	0,0012
2,8	0,0017
4	0,0024
5,6	0,0034
8	0,0049
11	0,0067
16	0,0098
22	0,0134
32	0,0195

Figure 15: diffraction circle for different f-stops

Sensordimensions and limiting aperture

Sensors	sensor height [mm]	width [mm]	diagonal [mm]	Number of Pixels [width]	calculated Pixelsize [mm]	limiting aperture
Canon EOS 1Ds	24	36	43,3	4992	0,0072	**11,8**
Canon EOS 1 D	19,1	28,7	34,5	3504	0,0082	**13,4**
Nikon D 70	15,6	23,7	28,4	3008	0,0079	**12,9**
Fujifilm S3Pro	15,5	23	27,7	3024	0,0076	**12,5**
Canon EOS 20D	15,1	22,7	27,3	3504	0,0065	**10,6**
Sigma SD 10	13,8	20,7	24,9	2268	0,0091	**15,0**
4/3" (z.B. Olympus E300)	13,5	18	22,5	3264	0,0055	**9,0**
2/3" (z.B. sony DSC-F828)	6,8	9,0	11,3	3264	0,0028	**4,5**
Panasonic LX-1 (1/1,65"; 16:9)	5,0	8,9	10,3	2880	0,0031	**5,1**
1/1,8" (z.B. Konica Minolta DiMAGE X1)	5,6	7,5	9,4	3264	0,0023	**3,8**
1/2,5" (z.B. Fujifilm FinePix E 510	4,1	5,4	6,8	2592	0,0021	**3,4**
1/3,2" (z.B. Casio Exilim S100)	3,2	4,2	5,3	2048	0,0021	**3,4**
Fuji S9500 1/1,6"	6,3	8,5	10,6	3488	0,0024	**4,0**
1/3"	3,4	4,5	5,6	640	0,0070	**11,6**

Figure 16: calculation from which f-stop the diffraction problems begin

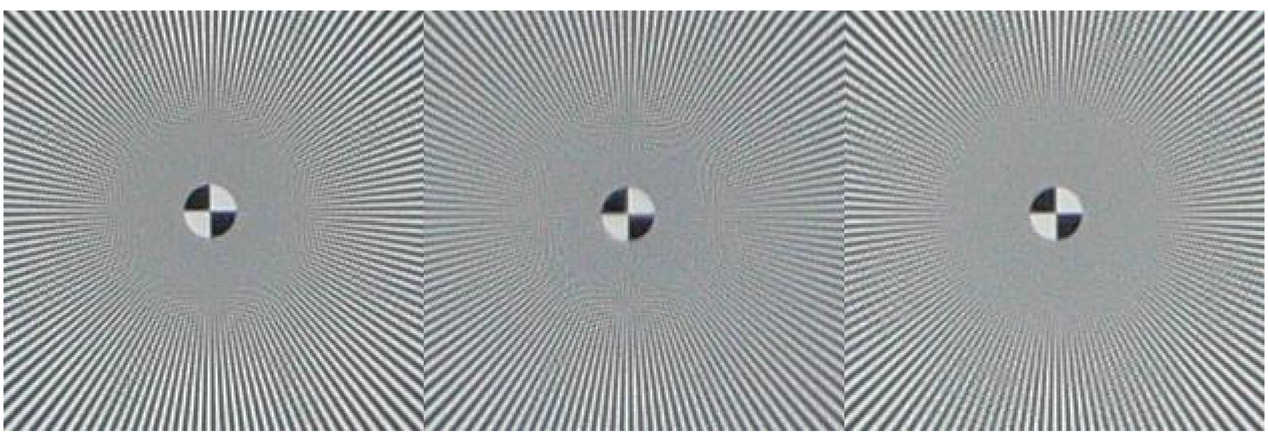

Figure 17: Images taken with a 2.1 micron pixel pitch at f-stop 4, 5.6, and 8

These calculations and the image in Figure 17 demonstrate that diffraction is a problem with current cameras and their small pixel pitches. These problems begin from f-stop 4 and get worse for smaller apertures.

THE IDEAL DIGITAL SLR

The functionality and image quality of existing digital SLR camera equals, without a doubt, the quality of analogue cameras. But there is still some room for improvements.

Live image

Some applications require a live image. For example, when a camera is mounted on a microscope or the "Wolfenbuttel Book Reflector", it may not be possible to look through the viewfinder. Or, cameras capturing images of a scientific experiment may be located in another room for safety reasons. If a live image were available on the implemented pivoted LCD panel, as well as the video output of the camera, it would help tremendously. From there it is just a small step to enable the camera to provide video capture. Keeping the development in storage capacity of existing storage cards in mind this might replace some of the video cameras in scientific applications.

Other problems occur if the optical viewfinder is replaced by an electronic viewfinder. It is common knowledge that electronic viewfinders suffer from low resolution and bad visibility under bright lighting conditions. And there is also an issue of low refreshing frequencies, if the camera is set to a burst mode.

Autofocus accuracy

A study we made in 2004 showed that in many cases the autofocus accuracy of digital cameras is not sufficient. The reason is the required level of precision and adjustment procedures for the "extra" autofocus sensor.

Manual focus

Existing digital SLRs all suffer from lack of ability to manually focus, because the previous screens used to focus in older SLR cameras were replaced by screens without the capability to focus on microprisms or split screen indicators.

Image Quality

The dynamic range, noise and speed of existing sensors are already very good. The best sensor in terms of dynamic range is of course the Fujifilm super CCD version SR. But there is still a lot to do in the areas of colour and luminance. Most cameras still expose the images according to 18% grey which is the technology in the analogue world. For a digital image the exposure should be adjusted to the highlights which should remain unclipped with some restrictions if the contrast in the scene exceeds the range the camera is able to capture. Image processing should be adjusted to the scene-contrast to match the luminance-appearance of the human eye (e.g. the foreground in a sunset scene). The colour as well, should follow a colour-appearance model to create a "pleasing image". Each camera should have a mode that allows the matching of colours to the original scene, as closely as possible. In many situations, however, it might be better to have a specific output referred rendering in the camera as well. Resolution no longer matters as much as it did in the past because all the cameras with 8 and more megapixels have a sufficient resolution for 95% of applications. At the moment I am more concerned about the shrinking in pixel size because this leads to higher noise, lower sensitivity, lower dynamic ranges, and last but not least, diffraction problems at lower apertures. Therefore, the pixel pitch should be higher than 5 microns in order to avoid these problems.

Metadata

It would also be very nice to add at least some of the metadata to the images right after capturing them. This of course is already the case with the technical metadata specified in the Exif standard [8]. However, if an interface would enable the photographer to add some description metadata, i.e. author, date, place, and part of the caption as well, it would be especially useful for journalists.

Raw

From the user's point-of-view, a standardised image RAW format like Tiff/EP or Adobe DNG would be very useful for integrating the image processing into the various workflows required for different applications. Unfortunately, this is more a political issue and there are no technical restrictions for implementing a standard format.

A proposed solution for the live picture and focus problems

First of all, to enable the sensor for fast autofocusing, as well as to achieve sufficient image frequencies for video capture, the sensor used in that camera should have a good windowing capability. This means that it should not be necessary to read out a complete or even a quarter of an image to acquire the data for a good autofocus. It should be possible to strip down the read-out to “a few” selected pixels for exposure measurement and autofocus and for the appropriate video resolution. This windowing would allow fast signal processing and video modes up to the required 30 frames per second.

Using such a sensor would replace the camera’s complete autofocus system, which in turn would lead to higher focus accuracy due to the fact that the same sensor can be used for both focus-measurement and imaging. To increase the focus speed even more, it might be helpful to locate the objects by using an additional active autofocus system for pre-focussing.

Since electronic viewfinders are not sufficient in camera use in any situation, an optical viewfinder is still necessary. A mirror with a reflection of 30%-50% has been proposed in order to ensure live preview on the LCD or video output, as well as the use of an optical viewfinder. Since the glass plate mirror will introduce spherical as well as chromatic optical errors, it is better to mount it on a pivot as is common on a conventional SLR or dSLR camera. The errors may be small enough to still have a sufficient preview and video quality, but for high resolution images blur and colour fringes may appear. To minimize errors, it should be investigated as to whether or not a certain shape of glass on the back of the mirror or a coating will lead to a reduction. It should swing up or downwards to avoid these problems when capturing the final image. Turning the mirror out of the optical path during exposure will also increase the illuminance on the sensor by about one f-stop.

Sony with its DSC-R1 showed that a fast autofocus system based on the imaging sensor in the camera is possible and the principle of CMOS technology allows a sufficient windowing, although it can not be found in the actual sensors. Hopefully we will find these sensors in the future.

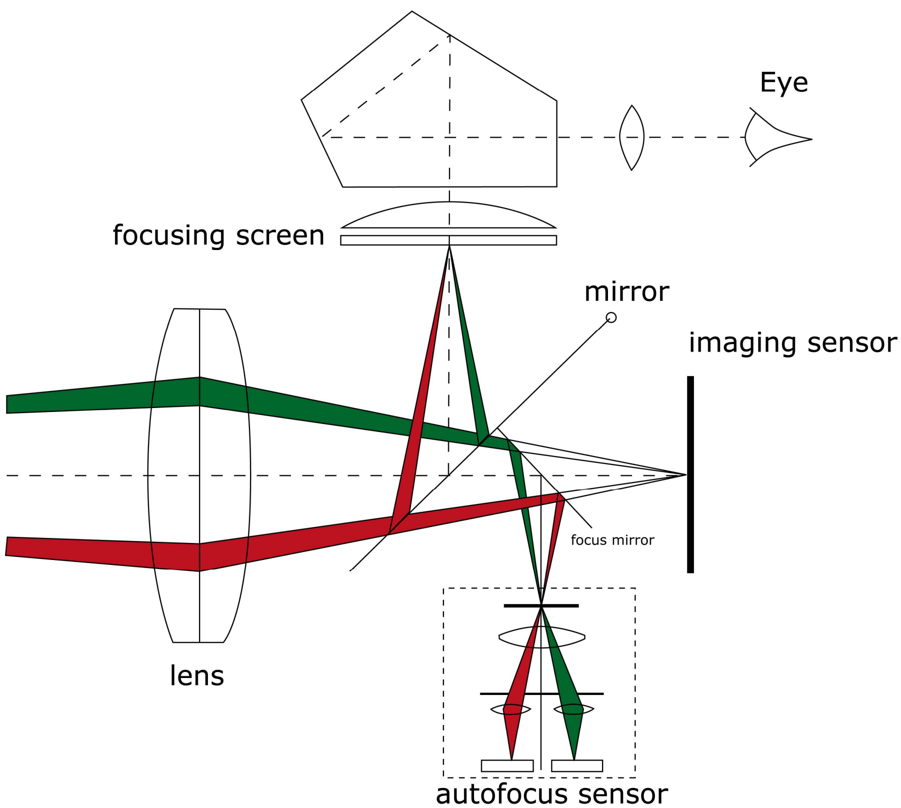

Figure 18: Principle of a conventional SLR or digital SLR system

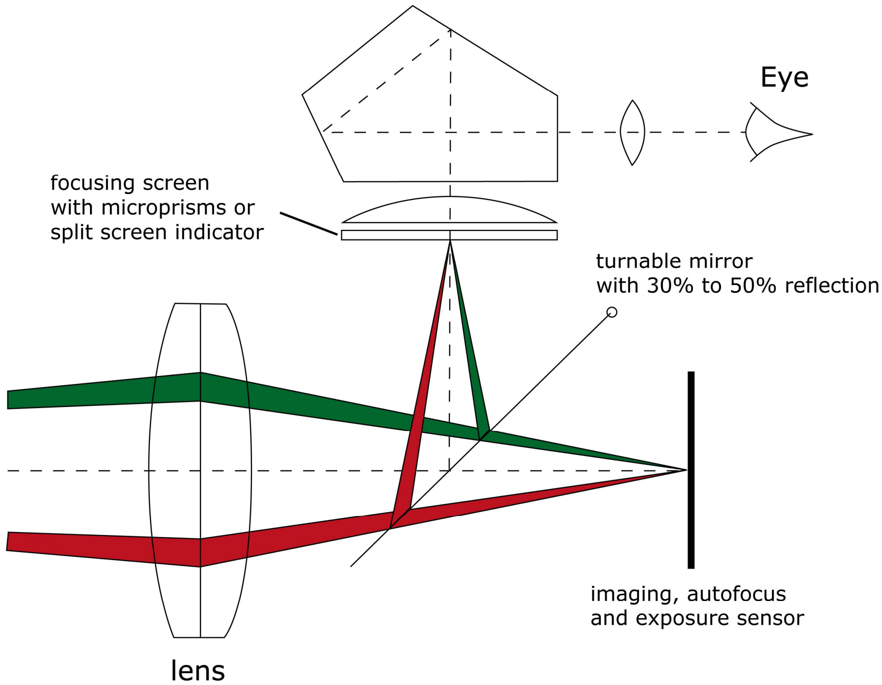

Figure 19: Principle of the proposed new system

CONCLUSION

Most of the problems we find in today's digital consumer cameras are related to their small sensor and pixel sizes. Some of these problems are resolution limitations, limited dynamic ranges, noise problems, chromatic aberration, diffraction limits, etc. To keep the cameras small it seems to be necessary to solve these problems using intelligent image processing algorithms. But as we have seen, these algorithms also have their limitations. Therefore my expectations for the future are that the pixel count should stay on the level of actual cameras for smaller cameras. The sensors should be larger for advanced and bigger cameras. Furthermore, I would like to see new ideas like the ones mentioned above for the digital SLRs, instead of keeping the old SLR principle.

ACKNOWLEDGMENTS

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