

Smart Mini-Cameras



Edited by
Tigran V. Galstian

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CHAPTER

1

Lens Design and Advanced Function for Mobile Cameras

Peter P. Clark

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1.1 Introduction

The history of photography has been marked by developments that have dramatically changed the relationship of the photographer to the technology:

Imaging capability: First there was only monochrome, then full color. First only still photography, then cinema and video. Light sensitivity has continuously improved. Most recently, digital imaging has been developed, giving the photographer powerful image-processing and editing capabilities.

Immediacy: Until instant chemical photography became available in 1948, chemical photography required the photographer to wait for processing to see the image. In the 1990s, digital cameras with liquid crystal (LC) displays allowed immediate review of images. Cameras in mobile phones allow immediate electronic distribution of images.

Convenience: Early photographers used plates that needed to be prepared and developed near the camera, so when dry emulsions became available the darkroom did not have to be transported. Single-plate exposures with large cameras gave way to portable roll-film cameras that could make many images without being reloaded. Improvements to film and lenses shortened exposure time, allowing handheld photography of moving subjects and in low illumination. Electronics helped nonexperts, first with automatic exposure control and later with autofocus (AF) systems.

The size of consumer cameras became steadily smaller, from box cameras and folding roll-film cameras to 35 mm cameras, and then to even smaller consumer film formats such as Kodak's disc-camera system. Digital cameras continued the trend toward smaller size cameras, reducing the sensor size, and eliminating optical viewfinders and large strobe systems from most consumer cameras.

The miniature digital cameras that we see in many mobile phones and other products are an important step in that evolution. They allow the consumer the ability to record images at any time, with a device that is always at hand. The miniature camera modules (MCMs) are so small that their impact on the device size and portability is acceptable to the consumer, thus causing a revolution in the acquisition of still and video images. As with any digital camera, the images are instantly seen and using a mobile phone and the Internet, they may be instantly shared with anyone.

Furthermore, miniature digital cameras are being applied to a wide variety of applications in addition to conventional photography. Increasingly, automobiles are being fitted with small cameras for safety monitoring. Insurance companies employ cameras to monitor behavior, reducing accident rates and costs. Mobile-phone cameras are being adapted for technical applications, and even gigapixel "super cameras" are being assembled from large arrays of miniature camera sensors (Brady and Hagen 2009).

Table 1.1a and 1.1b show the comparative data for various types of cameras, configured for general photography. Table 1.1b extends Table 1.1a to include photographic performance information. This is not a complete survey of commercially available products. It is just a sample, intended to indicate trends and illustrate the changes due to camera scale.

TABLE 1.1 Comparison of Camera Formats

(a) Miniature Camera Modules, Digital Cameras, and Film Cameras^a

Inch-Format	Horizontal (mm)	Vertical (mm)	Diagonal (mm)	Area (mm ²)	Megapixels	Minimum Pixel (mm)	Maximum Pixel (mm)	Linear Scale (35 mm ref) (%)	Area Scale (35 mm ref) (%)	Typical Minimum f/number	EFL	Entrance Pupil Diameter
Miniature Camera Modules												
1/6	2.32	1.74	2.90	4.04	1.3-2	0.0014	0.0017	7	0.4	2	2.28	1.14
1/5	2.80	2.10	3.50	5.88	2-3	0.0014	0.0017	8	0.7	2	2.75	1.37
1/4	3.60	2.70	4.50	9.72	3-5	0.0014	0.0017	10	1.1	2.4	3.53	1.47
1/3	4.80	3.60	6.00	17.28	5-8	0.0014	0.0017	14	1.9	2.8	4.71	1.68
Digital Still Cameras												
1/2.3	6.08	4.56	7.60	27.72	12-16.6	0.0015	0.0022	18	3.1	2.8	6.0	2.1
1/2	6.40	4.80	8.00	30.72	16	0.0014	0.0014	18	3.4	2.4	6.3	2.6
1/1.7	7.44	5.58	9.30	41.52	10-12	0.0019	0.002	21	4.6	2	7.3	3.6
1	13.20	8.80	15.86	116.16	14.2	0.0029	0.0029	37	13	2	12.5	6.2
APSC	23.60	15.80	28.40	372.88	12.2-24.7	0.0039	0.0055	66	43	2	22.3	11.1
FULL	36.00	24.00	43.27	864.00	18.1-24.7	0.0059	0.0069	100	100	1.4	34.0	24.3
Film Cameras												
Disc	11.0	8.0	13.6	88				31	10	2	10.7	5.3
APSH	30.2	16.7	34.5	504				80	64	2	27.1	13.5
35 mm	36.0	24.0	43.3	864				100	100	1.4	34.0	24.3
6 × 6 cm	60.0	60.0	84.9	3600				196	385	2.8	66.6	23.8
4 × 5 in.	127.0	101.6	162.6	12903				376	1413	4.5	127.6	28.4

Inch-Format	Typical Minimum f/number	EFL	Relative Central Illumination (%) ^c	Relative Total Light Gathered (%) ^c	Resolving Capability			Closest Infinity Focus, mm (Hyp/2) ^d	
					Diagonal (Airy_Disc_Diameter)	Diagonal (2° pixel)	Pixels (AD_Diameter)		
Miniature Camera Modules									
1/6	2	2.28	49	0.2	1,080	1,036	2.05	2.16	462
1/5	2	2.75	49	0.3	1,304	1,250	2.05	1.48	674
1/4	2.4	3.53	34	0.4	1,397	1,607	2.46	1.23	813
1/3	2.8	4.71	25	0.5	1,597	2,143	2.87	1.01	990
Digital Still Cameras									
1/2.3	2.8	6.0	25	0.8	2,023	2,533	2.68	0.798	1,254
1/2	2.4	6.3	34	1.2	2,484	2,857	2.46	0.650	1,539
1/1.7	2	7.3	49	2.4	3,465	2,447	1.51	0.465	2,149
1	2	12.5	49	6.6	5,911	2,735	0.99	0.273	3,662
APSC	2	22.3	49	21.1	10,581	3,641	0.74	0.152	6,558
FULL	1.4	34.0	100	100.0	23,029	3,667	0.34	0.070	14,277
Film Cameras									
Disc	2	10.7	49	5.0	5,068			0.318	3,142
APSH	2	27.1	49	28.6	12,858			0.125	7,971
35 mm	1.4	34.0	100	100.0	23,029			0.070	14,277
6 × 6 cm	2.8	66.6	25	104.2	22,582			0.071	14,000
4 × 5 in.	4.5	127.6	10	144.5	26,932			0.060	16,697

^a Compared at the same diagonal field of view: 65° full (34 mm EFL for 35 mm format).

^b "Total light gathered" is an estimate of how much light energy is collected to record the image. "Resolving capability" assumes a diffraction-limited lens.

^c 35 mm = 100%.

^d DOF based on the worst case of: 1-2 pixel blur, 2-1 Airy Disc blur, 3-Diagonal/1500 blur.

1.2 Key Optical Definitions

In this section, we introduce some key optical definitions, which are important to understand the operation and performance trade-offs of miniature cameras. These are an incomplete introduction to the optics of imaging systems. Introductory optics texts, such as Smith (2007), should be consulted for more complete information.

Effective focal length (EFL): EFL is the separation of an equivalent ideal thin lens from the image it makes of an infinitely distant object (see Figure 1.1). EFL and subject distance determine the location and size of an image with respect to an ideal thin lens. The EFL may be positive (converging lens), infinite (e.g., a flat window), or negative (diverging), but it may not be zero (see optical power).

Optical power: The inverse of EFL, optical power is often expressed in diopters (inverse meters). It is useful to consider optical power because it easily handles the transition from positive to negative focal lengths. It is also a good way to describe the supplementary lenses sometimes used for focus correction (see Section 1.5.7).

Field of view (FOV): FOV is the extent of the captured image. The FOV may be described in object space or in image space. In image space, it is defined by the size of the sensor, either as x and y dimensions or as a diagonal dimension. In object space, it may be defined by the extent of the photographed object, but we often assume a distant object and measure it as an angle. One must be sure to understand if it is the “full” FOV or the “semi-FOV” (measured from the optical axis). FOVs of MCMs in mobile phones are currently 60° – 75° full (corner to corner).

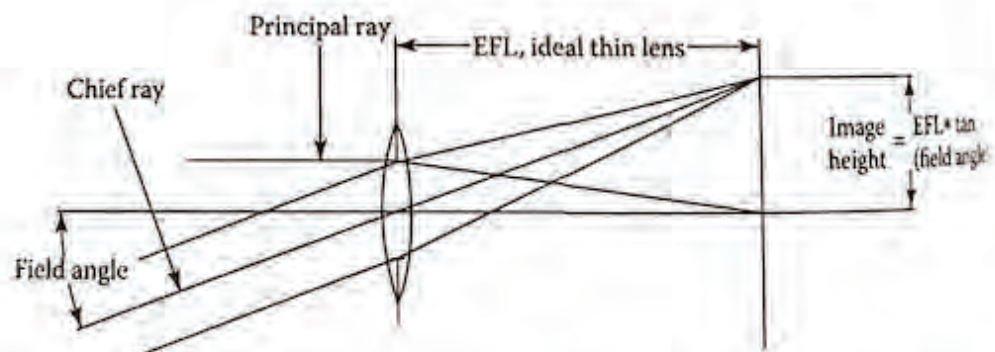


FIGURE 1.1 The relationship between the EFL of a thin lens, the field angle, and the image height. Infinite object distance.

Paraxial approximation: The paraxial approximation describes the behavior of a lens in the limit of small aperture size and FOV, greatly simplifying ray-tracing calculations. It tells us the ideal behavior of a lens system, ignoring geometric errors (aberrations). A real lens system that is designed and built to perform well is usefully characterized by its paraxial behavior.

Paraxial thin lens approximation: Any lens, or combination of lenses with a finite focal length can be substituted paraxially by a single thin lens. In this section, we will show some examples of lens behavior using the thin lens approximation. Figure 1.2, for example, illustrates a compound lens made up of three paraxial thin elements.

Optical axis: A lens system is usually rotationally symmetric about an optical axis. In most cameras, the optical axis is intended to intersect the sensor at its center point, and the sensor surface is normal to the optical axis.

Object space and image space: We will use the term *object space* to refer to the world outside the camera before light enters the lens system, and *image space* to mean after the light exits the optical system (the last lens surface). So, the sensor is in image space and the photographed subject is in object space.

Aperture stop: The aperture stop is the physical feature that limits the light passing through the lens, for the on-axis (central) field point (see Figure 1.2). The aperture stop is usually circular. In many cameras (but not in MCMs) its size is adjustable.

Entrance pupil and entrance pupil diameter (EPD) (see Figure 1.2): The entrance pupil is the image of the aperture stop in object space. We can see the entrance pupil if we look into the front of the camera lens to see the aperture stop. If the aperture stop is in front of the camera lens, the entrance pupil is identical to the aperture stop, but the aperture stop can be inside or behind the camera lens, so the location and size of the entrance pupil are not the same as the (physical) aperture stop.

Exit pupil (see Figure 1.2): Analogous to the entrance pupil, this is the image of the aperture stop in image space (in other words, as seen from the sensor).

f/number (fno): Also known as the relative aperture. Defined paraxially, this is the ratio:

$$fno = \frac{EFL}{EPD}$$

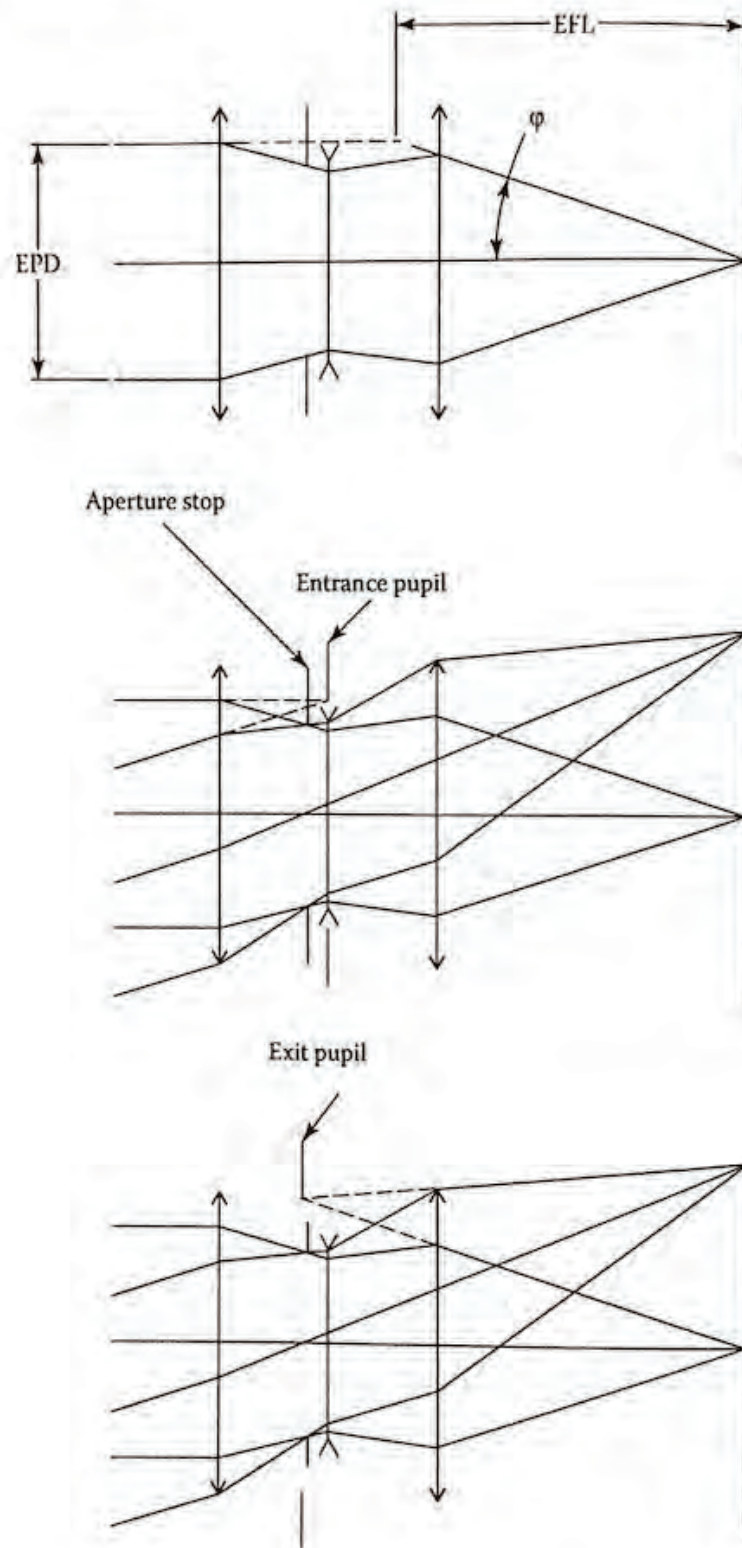


FIGURE 1.2 A triplet lens with three thin lens elements, an infinite object, with constructions from rays illustrating the EFL, aperture stop, and entrance and exit pupils.

More precisely,

$$fno = (2n \sin \varphi)^{-1},$$

where n is the refractive index in image space (usually air, $n = 1.0$) and φ is the angle of the real principal ray (see Figure 1.2). If $n = 1$, $f/0.5$ is the mathematically lowest possible fno , which is unrealizable in a camera; $f/1.0$ is a practical lower limit for camera lenses.

An image's light intensity is proportional to fno^{-2} . Traditional cameras have variable fno settings, often in factors of $2\times$ exposure (f -stops): $f/1.4$, $f/2.0$, $f/2.8$, $f/4$, and so forth. Lower numerical fno s, then, provide more intensity in an image, and their Airy pattern is smaller (see hereafter), but their depth of focus is reduced and their geometrical aberrations may be larger. MCMs almost always have a single fixed fno . Currently, MCM fno s are typically between $f/2.0$ and $f/2.8$.

Rays: Lens design and analysis often model light energy propagation as geometrical "rays." The ray optics or "geometrical optics" model ignores the wave nature of light.

Chief ray: For a given field point, this is the ray that passes through the center of the entrance pupil and aperture stop (see Figure 1.1). The paraxial chief ray approximately tells us the scale of the image on the sensor, and the difference between the "real" chief ray and the paraxial chief ray at the sensor is a measure of distortion (see Section 1.4.4). The difference between chief rays of different colors tells us the lateral chromatic aberration.

Principal ray: This is the ray from the on-axis field point that passes through the edge of the entrance pupil and aperture stop (see Figure 1.1). Wherever the principal ray crosses the axis, there is an image of the object.

Point spread function (PSF): This is the distribution of light intensity in the image of an ideal point source. It might be the optical PSF (the optical image alone) or the recorded image PSF (optical plus sensor, etc.) (see Section 1.4.2).

Aberrations: These are geometric errors of the lens design or construction. Real imaging systems do not behave exactly like the paraxial ideal. If rays are traced exactly, we find that aberrations can keep them from forming perfect geometric images. Aberrations can be classified according to their functional dependencies. Aberrations may change with wavelength, and they often increase

as the FOV and aperture increase. Most aberrations degrade image sharpness, but "distortion" aberrations cause errors of image size and shape without affecting sharpness. Defocus blur may be treated as a geometric aberration. The variation of defocus with wavelength is a form of "chromatic aberration." The correction of geometrical aberrations is the reason for much of the complexity of lens designs: multiple lens elements and aspheric surfaces are used to minimize ray errors in a lens design. Aberrations are also caused by lens fabrication errors, such as incorrect surface shapes and misaligned lens elements.

1.3 Construction of MCMs

1.3.1 Physical Construction

Currently, the mechanical construction of the lens of most MCMs is an assembly of injection-molded polymer parts. The sensor on a flexible printed circuit board is attached to a polymer "holder," which is equivalent to the body of a conventional camera. In a fixed-focus camera, that holder usually has a precisely threaded hole that receives the lens barrel. This thread is used for focus adjustment at assembly, then the barrel is fixed in the thread with an adhesive. The lens barrel contains the stack of lens elements and apertures, centered in the barrel by tight mechanical tolerances ($<10\ \mu\text{m}$). The apertures in the barrel and the stack define the aperture stop of the system and block stray light paths. An infrared (IR)-cut filter (Section 1.3.2.2) may be mounted either in the lens barrel or in the holder.

The complexity of the lens design can vary. A very simple way to describe a lens design is with the number of elements: 1G2P means one glass element plus two plastic. Flat parts such as filters and windows are not counted. Most MCM lens designs at this time are 3P, 4P or 5P.

The prevention of contamination is an important consideration in the design and manufacture of MCMs. Very small specks of dust can cause visible defects in images if they settle close to the sensor.

An alternative method is "wafer-scale" construction. The wafer concept of construction of integrated circuits has been extended to the construction of lenses. A large array of replicated optical surfaces is constructed on each side of a wafer, then several wafers would be stacked together, perhaps even with a wafer of image sensors. Then, the entire assembly would be "diced" apart,

producing hundreds of finished cameras. The technical challenges of this approach are significant, but it promises large cost reductions.

1.3.2 Electrical Construction and Photographic Performance

Electronic Shutter

MCMs generally have no mechanical shutter. The light integration time is started and ended electronically. Complementary metal-oxide-semiconductor (CMOS) sensors (see Chapter 2, this volume, for more details) use an electronic “rolling shutter” scheme. Exposure starts and ends in a raster scan, so different pixels are exposed at different times. If the integration time is short, there may be no time at which all of the pixels are collecting light. This is similar to the operation of the focal plane shutters in some film cameras (typically single lens reflex cameras), and it can cause distortion of images if the camera or the subject is moving during the exposure. It also makes it difficult to synchronize with electronic strobes. Most digital still cameras (DSCs) do incorporate a mechanical shutter, allowing better control of the balance between the flash and ambient exposure.

CMOS Image Sensor

The typical CMOS image sensors used in MCMs are an array of square detectors (pixels) with color filters. The arrangement is usually a “Bayer pattern” with a unit cell of four detectors:

green	red
blue	green

The “raw” image data from the colored pixels are interpolated to produce R, G, and B information for each of the Bayer sites (Fiete 2012). For example, a camera with one 4 megapixel (MP) sensor (2 MP of green detectors and 1 MP each of red and blue detectors) produces image files that have 4 MP $\times$ 3 colors. This is the most common pixel arrangement in larger digital cameras, as well. The need for circuitry and for the isolation of each detector from its neighbors requires that the light-sensitive area of a pixel be significantly less than 100% of its silicon area. This would cause a significant loss of collected light. To improve sensitivity, sensors use an array of microlenses, whose purpose is to make the detectors appear larger. As the pixels become smaller, the fill factor tends to become even lower, increasing the importance of the microlenses.

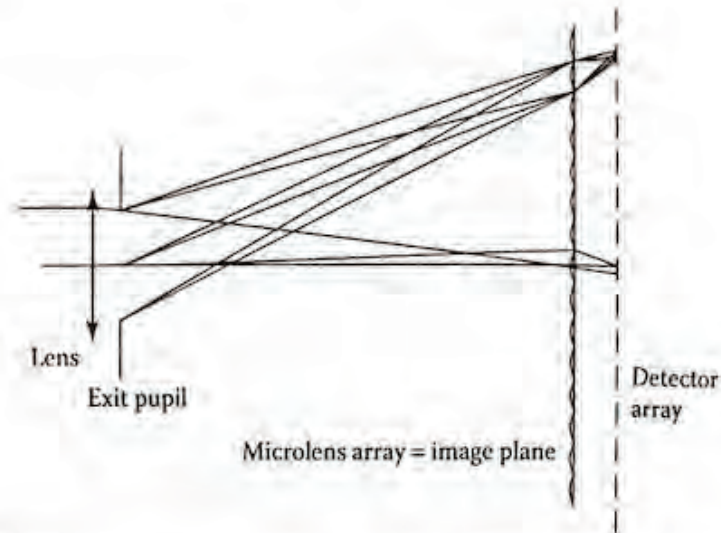


FIGURE 1.3 The microlens array images the exit pupil onto individual pixel detectors, improving light collection efficiency.

Figure 1.3 illustrates the microlens principle schematically. Note that each microlens is making an image of the exit pupil onto the sensitive area of the pixel. If that exit pupil image is smaller than the detector, none of the light that came to the microlens will miss the detector. With this arrangement, the image plane will be the microlens array, *not* the detector array. Notice also that the image sensor's response will be directional. Light exceeding a range of incidence angles might not be detected, or it may be incorrectly sensed by a neighboring detector. This is the source of the chief ray angle (CRA) requirement (Section 1.3.3.4). Since the microlenses serve to collect light, and not to form the image of a scene, they do not significantly affect the image focus or the sharpness, but if they are not made well enough, they could cause errors in exposure and color reproduction.

1.3.2.1 Pixel Size and Image Quality

There is much discussion about pixel size and image quality. Smaller pixels obviously allow higher spatial frequencies to be reproduced, and higher modulation transfer functions (MTFs, Section 1.4.2.2). However, smaller pixels collect fewer photons, so the signal/noise and dynamic range suffer. A good case can be made that the total sensor area correlates well with the subjective image quality, assuming that good design choices are made, but the desire for smaller cameras, lower costs, and higher pixel counts can lead to compromised image quality.

1.3.2.2 IR Sensitivity

Digital cameras with silicon sensors are intended to produce color images from visible light. The sensor's sensitivity, however, reaches its peak in the near IR (NIR). The color filters are not designed to block IR—in fact, all three color filters “leak” NIR radiation, so a separate IR-cut filter is included in the optical system. It usually has a sharp cutoff in the red, blocking light with wavelengths longer than about 650 nm.

1.3.3 Lens Design for MCMs

One could design a lens for these miniature cameras by simply scaling an existing design for a larger format. For example, a moderate wide-angle 35 mm EFL $f/2.8$ lens design for the 35 mm film format might be built at 1/10 scale, becoming 3.3 mm EFL $f/2.8$, appropriate for a 1/4" format miniature camera. The image quality would be excellent. In practice, however, this is not what is done, largely for reasons of production cost and quantity. The cost must be less than one-tenth of the cost of the 35 mm solution, and production quantities can be millions of units per month, far higher than dedicated camera products (Bareau and Clark 2006).

Issues that affect the form of the camera lens design include:

1. *Materials:* To achieve production cost goals, the lens elements and structural parts must be injection-molded polymers. The 35 mm lens elements are made of a variety of optical glasses.
2. *Scale of the elements:* Manufacturing constraints can require the plastic parts to be thicker than the glass parts would be at the larger scale. This, and cost, limits the number of elements in the design. MCM objectives can be 3P, 4P, or 5P, while even fixed focal length 35 mm lenses have at least five glass elements and often more.
3. *Tolerances:* If the performance of the scaled 35 mm design was to be unchanged, the alignment tolerances of the lens elements would have to be scaled by 1/10 $\times$. This becomes very difficult, particularly with plastic parts.
4. *New requirements:* The miniature design may be required to have a shorter length, and CRAs need to be controlled to be lower than the field angles.

As an example, many conventional lens designs distribute optical power symmetrically about the aperture stop, automatically

achieving correction of some aberrations, such as distortion and coma. The CRA requirement forces the aperture stop to be toward the object side of the lens assembly, eliminating that symmetry. To compensate, the design must become more complex. The designer turns to aspheric surfaces to achieve the required performance.

1.3.3.1 Aspheric Surfaces

Traditional glass lenses are almost always produced with spherical optical surfaces, as they are the easiest to make with a grinding/polishing process and they are simple to test (Malacara 2007). Aspheric surfaces can be applied to molded plastic lenses, because once the aspheric tooling is built, the production cost is no higher than that for spherical surfaces.

In the lens design process, aspheric surfaces are not a panacea. They do not allow perfect correction of image quality across the entire FOV, but they do add valuable design variables, similar to adding more lens elements. It is difficult to describe the function of individual aspheric surfaces in these designs. It is the combination of multiple aspherics within the design that enables simultaneous correction of ray aberrations and geometric distortion, along with controlling length, CRA, and relative illumination. Additionally, if not included in the design optimization, alignment tolerances can easily become so small that the design would be impossible to build correctly. The result is that nearly all the lens surfaces of these designs are aspheric and many are dramatically so, with departures from spherical surfaces that are easily seen with the naked eye (Figure 1.4).

1.3.3.2 Optical Materials

Chromatic aberrations are corrected in lens designs with the use of “crown” and “flint” materials, which have different degrees of refractive index change with wavelength (dispersion) (Smith 2007; Kingslake 1983; Kingslake and Johnson 2009). Optical glasses are available with a much wider variety of refractive index and dispersion than optical polymers.

Polymer optical materials differ from glass in some important respects. First, the range of refractive indices and dispersions available is limited. Their refractive index n and size change more rapidly with temperature; n decreases as the temperature increases. Also, some materials can absorb moisture, irreversibly changing their optical properties. Fortunately, a number of nonhygroscopic

FIGURE
1.4 AP
easily seen
shown
the CM

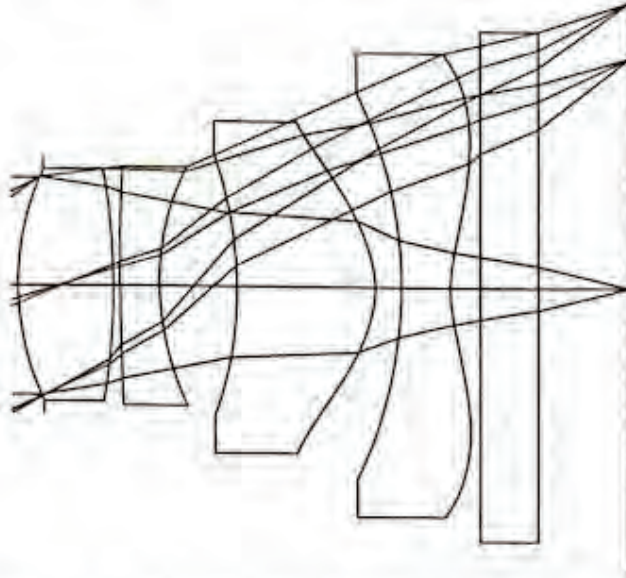


FIGURE 1.4 Cross section of an objective for a miniature camera module. The EFL of this 4P design is 3.4 mm, Total track (TT) = 4.3 mm, $f/\# = 2.3$. The aspheric shapes are easily seen in the third (from *left*) and fourth elements. The actual edge details are not shown. The flat part after the lenses is the IR-cut filter (the vertical line on the *right* is the CMOS plane).

materials have been developed, essentially solving that problem. Finally, polymers' softness and low melting temperatures can affect the quality of vacuum-deposited coatings.

1.3.3.3 Physical Length

MCMs are usually required to be as short as possible, because the customers of mobile devices (that contain them) prefer them to be very thin. The camera lens accounts for most of the module thickness. "Total track" (TT) is the common measure: the TT is the distance from the first surface of the lens barrel to the sensor plane, usually measured at infinity focus.

The length of a lens design may be reduced by redistributing the optical power within the lens. We can illustrate this with a simple sketch of a lens. A thin single-element lens would be separated from the image of an infinite object by its EFL. Real camera lenses have multiple lens elements, so the optical power is distributed along the optical axis. Figure 1.5 shows a system with two thin positive lenses. When the front element has more positive optical power (shorter focal length) than the rear element, the TT becomes shorter even though the system EFL is constant.

This example is intended to be an illustration only. In practice, for MCM lenses, the ratio of TT to EFL is usually between 1.15×

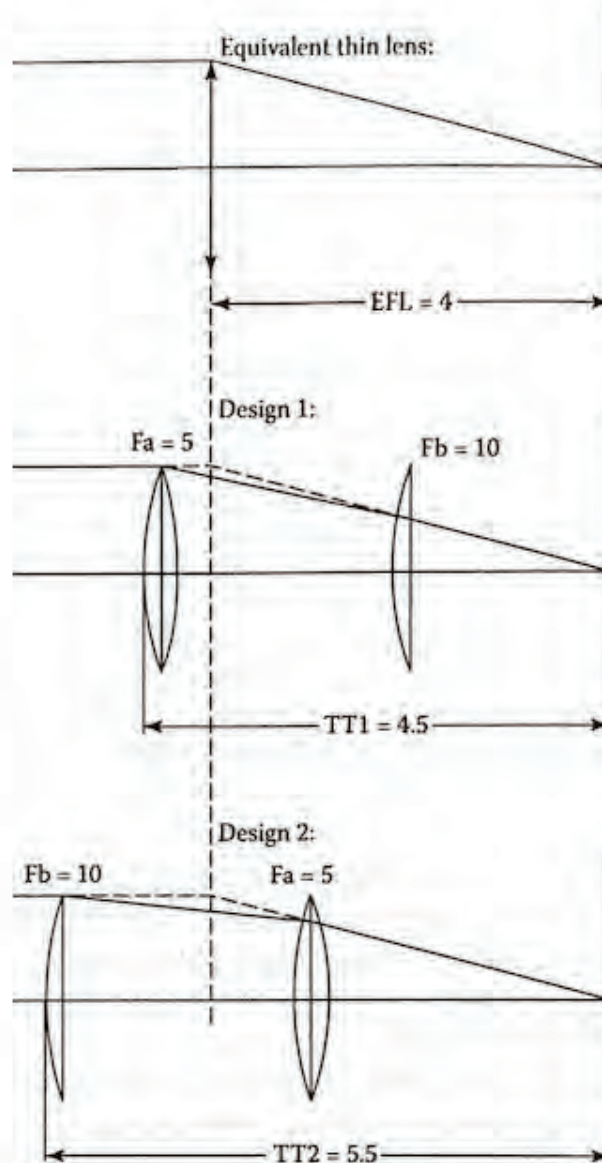


FIGURE 1.5 Redistributing the optical power in a lens design can change its length. In this thin lens example, the EFL is constant, and the TT/EFL changes from 1.125 $\times$ to 1.375 $\times$.

and 1.30 $\times$. Forcing the design to be shorter would make it impossible to control geometrical aberrations. EFLs have sometimes become shorter to help reduce the TT.

1.3.3.4 Chief Ray Angle (CRA)

The CRA can be reduced by moving the aperture stop toward the object space, as shown in Figure 1.6, where the lens is represented as a single thin element. A special case would be reached if the aperture stop was at the front focal plane (separated from the thin lens by its EFL): the CRA would be zero for all fields; the system

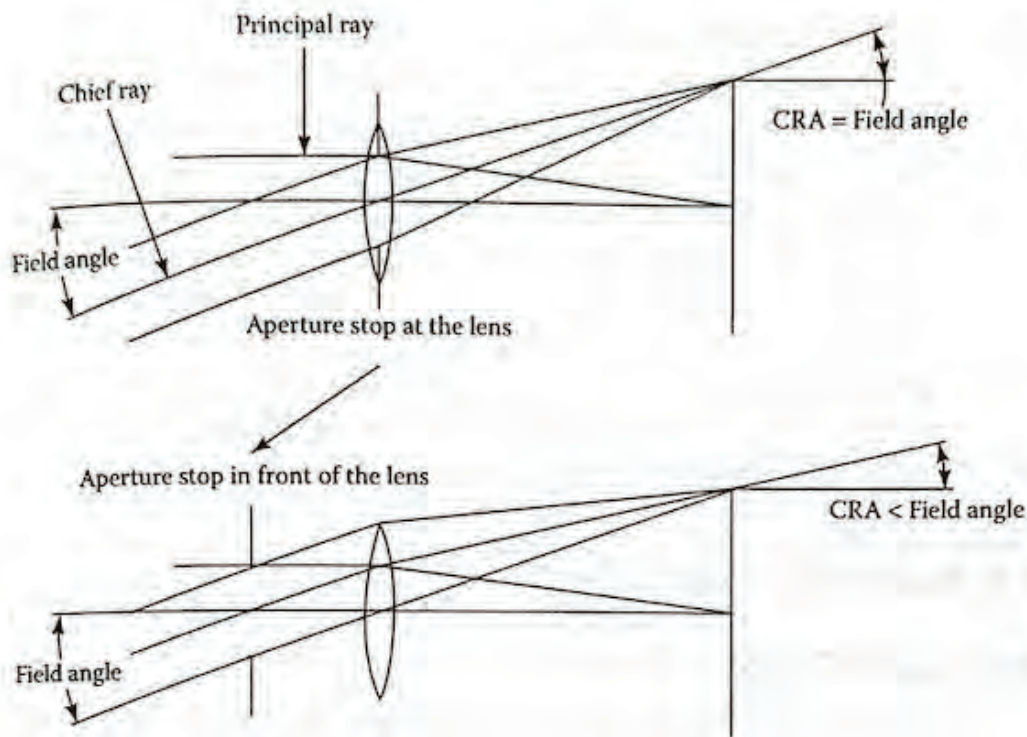


FIGURE 1.6 Chief ray angle is affected by the aperture stop location.

would be “telecentric.” In practice, aspheric surfaces in the lens design can make the relationship of the CRA to the field angle very nonlinear. The CRA often reaches a maximum value at a large field angle, then it actually decreases from that to the corner of the image (see Figure 1.7).

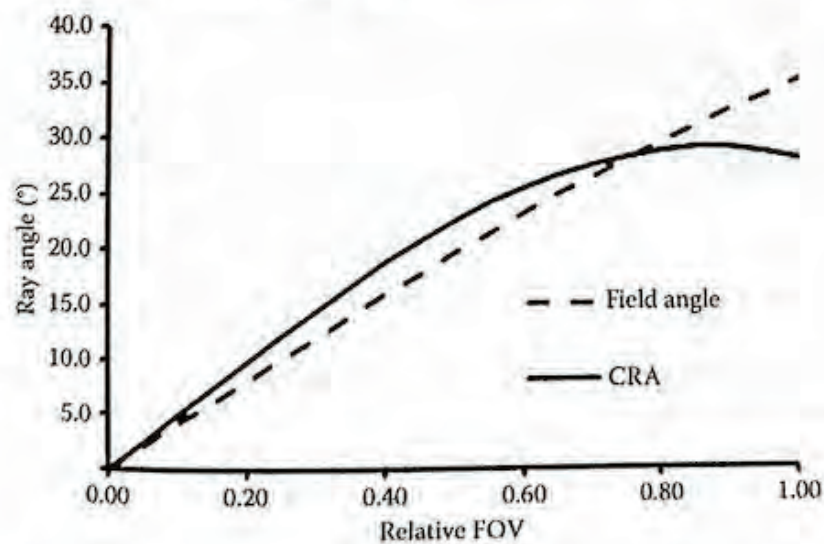


FIGURE 1.7 Typical chief ray angle plot for a miniature camera module. The maximum CRA is limited, and it decreases at the limit of the FOV. This is a 4P design for 1/4" format, 70° full FOV.

1.3.3.5 Lens Design Process

The process of designing a lens for MCMs can be very complex, even with the aid of modern lens design software, and the designs become very different from any traditional glass lens forms. The aspheric surfaces require tracing many rays from many field points (at several wavelengths), and tolerance control can require simultaneously optimizing a number of configurations that include alignment errors. The design and construction of these highly precise optical systems at such low cost and high volume is an impressive and underappreciated accomplishment of modern optical design and manufacturing.

1.4 Basic Performance Aspects

1.4.1 Image Quality

Image quality can have many attributes, which are subjectively perceived and, often, objectively measured (Table 1.2).

1.4.2 Image Sharpness

Sharpness is a subjective quality of an image that tells us how well an object's contrast and details are preserved in the image. It does not consider exposure, color balance, noise, or other tonal errors, and it does not consider geometrical errors that affect only the shape of the image (distortion). Sharpness is often analyzed

TABLE 1.2 Attributes of Image Quality

Subjective Quality	Objective Measurement
Haziness, scatter	Veiling glare (VG) percentage (ISO 9358 1994)
Ghosts, flare	Photograph bright sources
Dark corners	Relative illumination, percentage (ISO 9039 2008)
Distortion (straight lines reproduced as curves, off-axis)	Optical distortion (percentage) or TV distortion (percentage)
Image sharpness	Limiting resolution (ISO 12233 1998) MTF
Image artifacts	Varies
Color inaccuracy	Photograph color chart
Tonal inaccuracy	Photograph gray step chart (ISO 14524 2009)

and measured using MTF and other metrics. Sharpness is never perfect; it can be changed by a number of effects:

1. The PSF is analogous to the “impulse response” of an analog electronic system. The PSF is desirably as small as possible, but in practice, it always has nonzero dimensions because of a number of effects:

- a. Diffraction.

The wave nature of light causes light to be “scattered” (deviated from the original propagation’s direction) from edges, a process called diffraction. In any lens system, light diffracts from the aperture stop, causing the image of a point source to be larger than geometrical optics would predict. If the aperture is round, the lens is perfect, and the incident light is uniform, the PSF takes the form of the Airy pattern, which, for a single wavelength, is a bright core surrounded by a series of rings (see Figure 1.8).

The diameter of the first zero of the Airy pattern is

$$Da = 2.44 \lambda fno,$$

where λ is the wavelength (0.4–0.7 μm , visible light), and the entire pattern scales with the wavelength and the fno.

We see that if the camera gets smaller and the image sensor becomes proportionately smaller, but the fno stays the same, then the Airy pattern becomes a larger fraction of the image. On the other hand, if the EPD remained constant, the fno would decrease proportionately and the Airy pattern/image size would be constant. It is not possible, however, to keep the entrance pupil constant

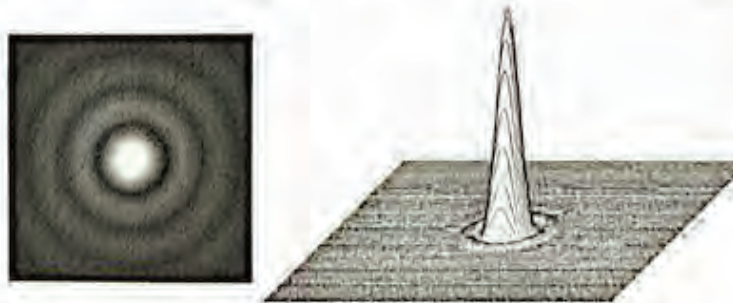


FIGURE 1.8 Image of a point source (PSF) by a perfect optical system with a round aperture stop: the Airy pattern.

- as we go to very small cameras, because lens designs at extremely fast (low) fnos become unrealizable.
- b. Geometrical aberrations cause light energy to spread, compared with a perfect point image (Figure 1.9).
 - c. Focus error. Similar to a geometrical aberration.
 - d. Image motion during exposure. This is caused by either camera motion or subject motion. It has a larger influence if the exposure time is long.
2. Pixel count. Sampling theory tells us that information with a spatial frequency (Section 1.4.2.2) higher than the Nyquist frequency = (sampling frequency)/2 cannot be reproduced.
 3. Pixel size. The sensitive area of an individual pixel affects sharpness, just as the PSF of the lens does.
 4. Image processing. Digital filtering techniques may be used to adjust image sharpness. Increasing the contrast (MTF) of a range of spatial frequencies is commonly done in digital photography. Digital sharpening causes some increase in noise and image artifacts, such as "ringing" at the edges, but a well-chosen degree of sharpening is usually beneficial.

One way to think about the imaging process is to consider the final image to be the convolution of the original object with the system's PSF. The PSF is, in this way, the "paintbrush" that creates the image.

The PSF and the optical transfer function (OTF) are alternative ways to describe the same thing. The OTF is the Fourier transform of the PSF. The PSF describes image quality in space; the OTF describes image quality in terms of spatial frequencies. It is often more convenient to use the OTF (and its modulus, MTF)



FIGURE 1.9 Example of a geometrical PSF of an aberrated star image from a grid of traced rays (*left*), and a similar PSF including the wave nature of light (*right*). The shape and size of the images compare, but the details differ significantly.

because in frequency space the OTFs may be combined by multiplying, which is simpler than convolving PSFs (see Goodman 2005).

1.4.2.1 Limiting Resolution

Limiting resolution is a measure of sharpness, determined (usually visually) by inspecting an image of a test target that has features that vary in size. The smallest feature that is judged to be recognizable is the limiting resolution. The optometric Snellen chart is a good example, as are the USAF 3-bar target (Figure 1.10) and some features in the ISO 12233 chart (ISO 12233 1998). Resolution testing can be useful, but it can be affected by the operator's judgment, and it emphasizes the smallest visible details, rather than the contrast of larger features in the image, which may correlate better with subjective image quality.

1.4.2.2 MTF

1.4.2.2.1 Spatial Frequency

A sinusoidal object varies in intensity from $I_{\min}$ to $I_{\max}$. An image is information presented spatially in two dimensions, whereas most signals (audio, radio, etc.) are one dimensional (1D; time). Just as a 1D signal may be described by its temporal frequency content, any image may be built from a summation of sinusoidal intensity functions, over all azimuths and frequencies (Figure 1.11). The spatial frequency of a sinusoidal object of period, P , is $1/P$, and its units are inverse length (cycles per millimeter, for example). A sinusoidal object is described completely by its frequency, azimuth, phase, and by the maximum and minimum intensities. Figure 1.12 shows the “modulation” of such an object. An imaging system can alter the phase and

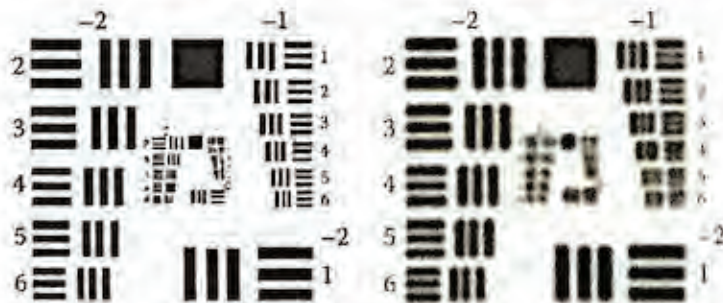


FIGURE 1.10 Limiting resolution. A portion of the USAF target (original, *left*, and blurred, *right*). The feature number (-1,3) at the right is the smallest with three bars visible in both orientations.



FIGURE 1.11 Sinusoidal objects. Spatial frequency examples: high frequency, mid frequency, and low frequency at a different azimuth angle.

modulation of the image of a sinusoidal object. This concept is useful because optical imaging systems behave as linear systems, and the reproduction of an image may be described by the system's frequency response (see Section 14.2.2.2).

1.4.2.2.2 OTF

The OTF is the spatial frequency response of an optical imaging system, including the amplitude and phase responses (Smith 2007;

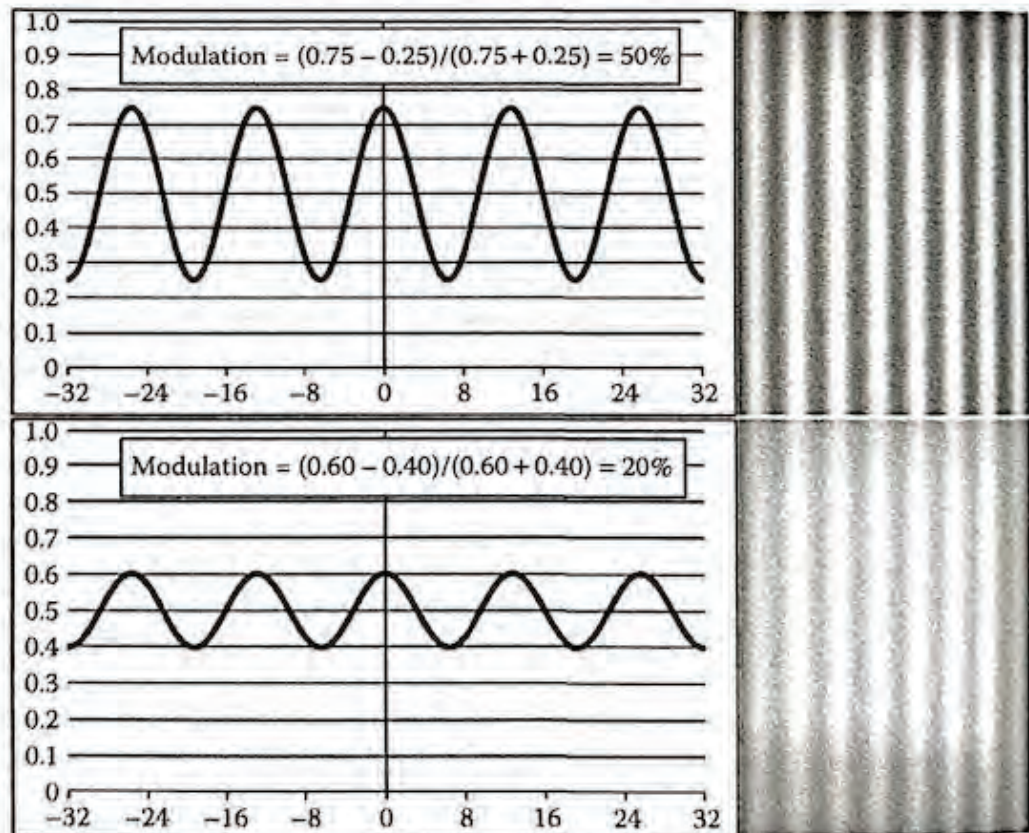


FIGURE 1.12 Two sinusoidal objects. 50% modulation and 20% modulation. Modulation = $(I_{\max} + I_{\min}) / (I_{\max} - I_{\min})$.

Goodman 2005). The MTF is the modulus of the OTF. It refers only to the amplitude component, ignoring the phase errors. An ideal imaging system would have 100% MTF at all frequencies, but even an ideal lens (geometrically perfect) reduces the MTF because of diffraction caused by its aperture. If a lens is not geometrically perfect, it may suffer from aberrations, or defocus, and the MTF is further reduced. Figure 1.13 is an example of MTF (spatial frequency) curves for a perfect lens, and for the same system with varying degrees of aberrations. MTF at zero spatial frequency is always unity. In Figure 1.12, the photograph on the right could be the image of the object on the left formed by a system with 40% MTF.

1.4.2.2.3 Digital Sharpening

While the optical system and the detectors inevitably reduce MTF, it is possible to improve sharpness in an image by post-processing the information. A digital filtering algorithm may be used to amplify the image signal as a function of spatial frequency. Noise will be amplified, as well as the signal, and if the gain is too high there will be visible artifacts, such as “ringing” at the edges. Nevertheless, digital imaging systems almost always incorporate some degree of digital sharpening. Interestingly, silver halide emulsions would often have some “sharpening” built

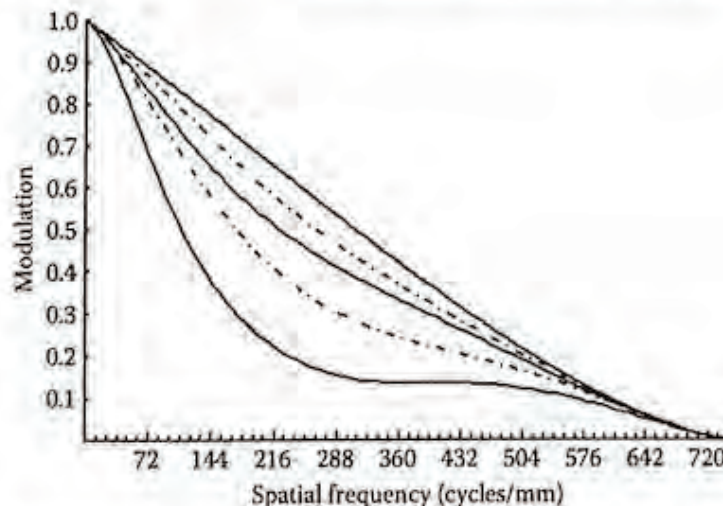


FIGURE 1.13 MTF versus the spatial frequency for an optical system. On-axis it is geometrically perfect (the highest curve in this figure), but off-axis, geometric aberrations reduce the MTF. Notice that MTF(0) is always 1.0 (100%). The off-axis field point curves apply to 50% and 100% of the FOV for this system. There are two curves for each because the MTF is different in the tangential and the radial directions. MTF is zero above 722 c/mm, which is the diffraction cutoff frequency for this lens.

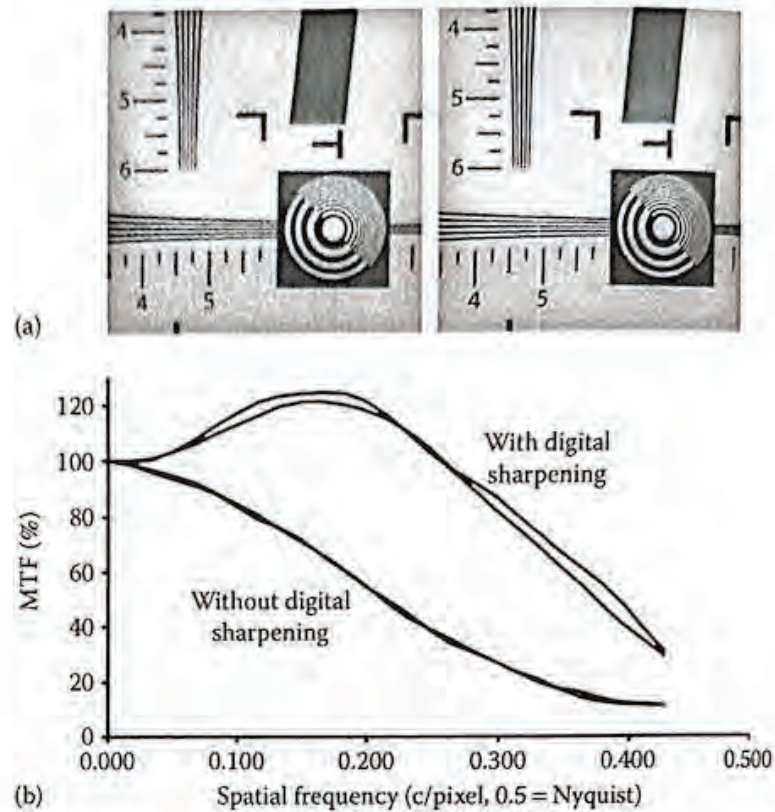


FIGURE 1.14 (a) Image of a test target, without (*left*) and with (*right*) digital sharpening. With sharpening, exaggeration of the edges is visible. (b) Measured MTFs from the two images in (a). MTFs greater than 100% are not possible in the unprocessed optical image.

in, due to the adjacency effect—film MTFs could be greater than unity over a range of spatial frequencies (Fiete 2012). See Figure 1.14a and 1.14b for an example of measured MTFs with and without sharpening.

1.4.3 Relative Illumination

Relative illumination is the ratio of image intensity off-axis to image intensity on-axis. Generally, illumination decreases as the field angle increases. It is influenced by the geometry of the relationship between the aperture stop and the flat image plane. If the camera lens is represented as a perfect thin lens with the stop in contact, CRA = field angle, and illumination falls off in proportion to $\cos^4(\text{field angle})^4$.

In practice, relative illumination is also influenced by other factors. For example, if the CRA can be reduced, as in Figure 1.15, relative illumination is increased. Figure 1.15 shows the relative illumination function for the classic $\cos^4$ case and for a design

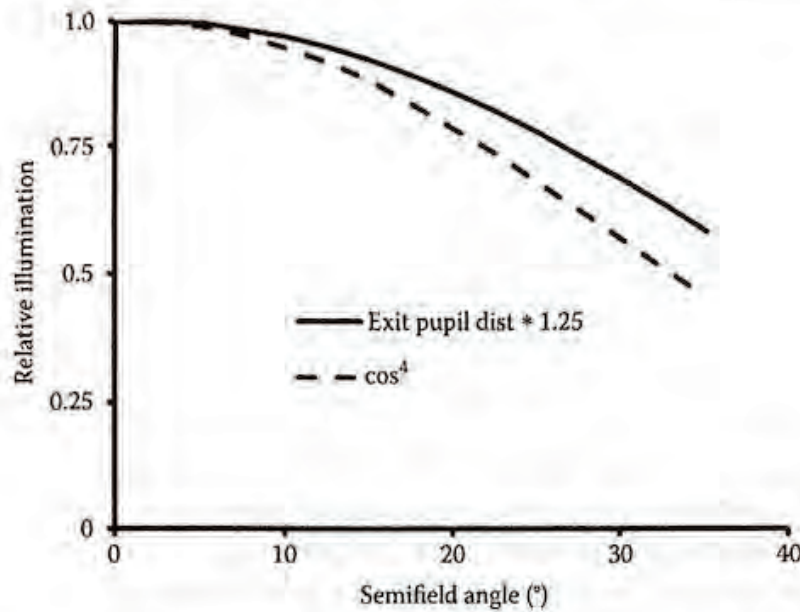


FIGURE 1.15 Relative illumination can be changed by changing the exit pupil distance.

where the CRA is lowered by increasing the exit pupil distance. Also, the lens design can cause distortion of the shape and size of the entrance pupil, changing the relative illumination—and affecting other aberrations too, particularly distortion.

Relative illumination in MCM lenses is frequently specified as not less than 40%–50% in the corners. The dark corners in the optical image (referred to as “lens shading”) are at least partly corrected by digital processing, at the cost of increased noise.

1.4.4 Dynamic Range

Loosely speaking, the dynamic range of an image is the ratio of the light intensity between the lightest and darkest distinguishable levels. In digital cameras, it is strongly dependent upon pixel size, because larger pixels can detect more photons before reaching saturation. Cameras with a limited dynamic range can lose information at the light and dark extremes of a scene, giving an unpleasant flatness, particularly to highlights (ISO 14524 2009).

1.4.5 Distortion

Optical distortion is an aberration that causes a geometric displacement of the image, and not a loss of sharpness. Distortion can be a property of the lens design, and it may be thought of as a variation of the image magnification with the field. In lens design,

the convention is to calculate distortion as a percentage (Smith 2007; ISO 12233 1998):

$$\text{Distortion} = \frac{\text{Real chief ray height}}{\text{Paraxial chief ray height}} - 1.$$

If distortion is positive, it is often referred to as “pincushion” distortion. If it is negative, it is called “barrel” distortion. Sometimes, distortion can be more complicated—varying from positive to negative as the field changes.

An alternative measure of distortion is called “TV distortion.” In fact, there are several suggested methods for measuring TV distortion. For example: If we make a photograph of a grid that nearly matches the picture format, TV distortion is the following:

$$\text{TV distortion} = \frac{\text{Average of left and right vertical edges of the image}}{\text{Vertical height of the image at the center}} - 1.$$

TV distortion is easy to measure from photographs; it measures the effect upon a straight line that is near the edge of the photograph, which is a source of user objections.

The specifications for distortion in MCM lenses are typically <1%–2% optical, <1%–1.5% TV. Usually, higher distortion values are accepted if the FOV is larger.

Figure 1.16 shows some examples of distortion (they are more severe than usual in an MCM for easier visualization). It is not unusual to see a higher order, as shown in Figure 1.16d, in an MCM because of the complex aspheric surfaces in the lens.

1.4.6 Sampling and Aliasing

Digital imaging systems employ regular arrays of small detectors, to “sample” the light image (Fiete 2012; Goodman 2005). The goal is usually to reconstruct the image accurately, but the sampling process imposes a limitation. The Nyquist–Shannon sampling theorem tells us that if the light image being sampled contains no information at spatial frequencies higher than half of the sampling frequency, called the Nyquist frequency, then the image may be perfectly reconstructed from the sampled data. Higher-frequency content in the light image, however, cannot be distinguished from low-frequency information, so it will be

inaccurately reproduced, producing low-frequency artifacts in the reconstructed image. This process is called "aliasing."

To illustrate, a digital image sensor with pixels spaced at 1.4 microns will have a sampling frequency of $1/0.0014 \text{ mm}^{-1} = 714 \text{ cycles/mm}$. Its Nyquist frequency is 357 cycles/mm.

Aliasing may be eliminated by low-pass filtering the light image before detection, but it is not possible to do this perfectly without losing image sharpness. Some cameras (e.g., DSCs) use birefringent antialiasing filters that create multiple copies of the PSF, usually in a square array of four points. Some have used aspheric elements designed to increase blur. Small digital cameras use a single image sensor with color filters, such as a Bayer pattern array. In such systems, aliasing becomes color dependent,

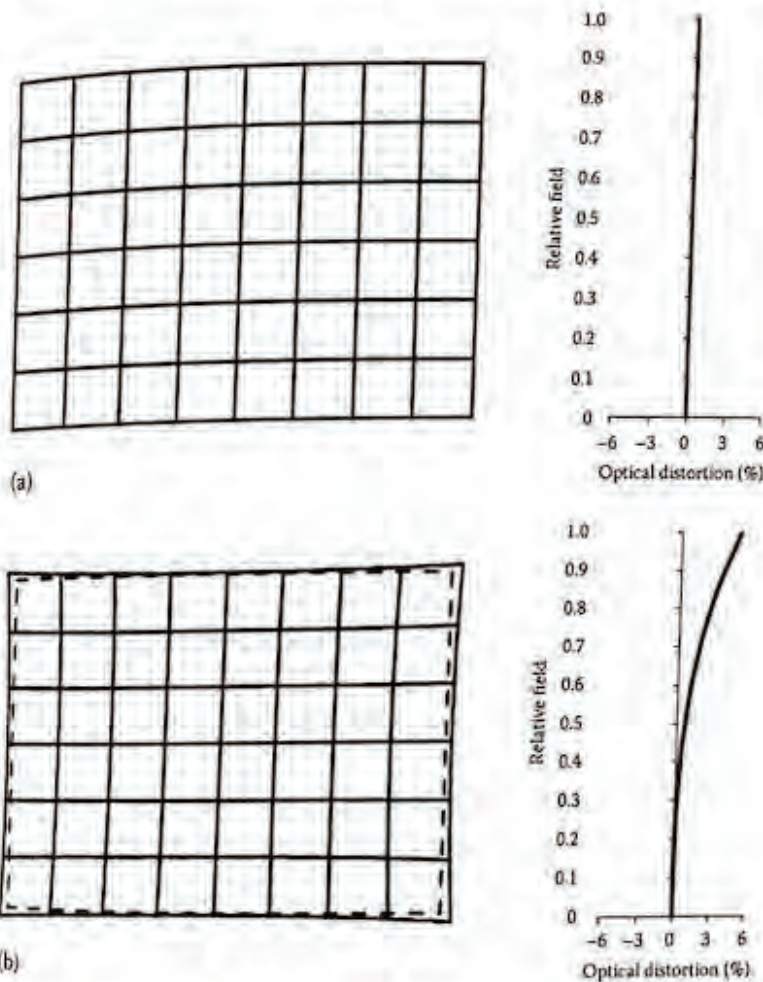


FIGURE 1.16 Distortion of various orders. (a) Zero distortion. Straight lines in the object are straight in the image. (b) Pincushion distortion (+5% optical, +3.9% TV). (c) Barrel distortion (-5% optical, -4.0% TV). (d) Higher order (-3.6% max optical, 0% TV).

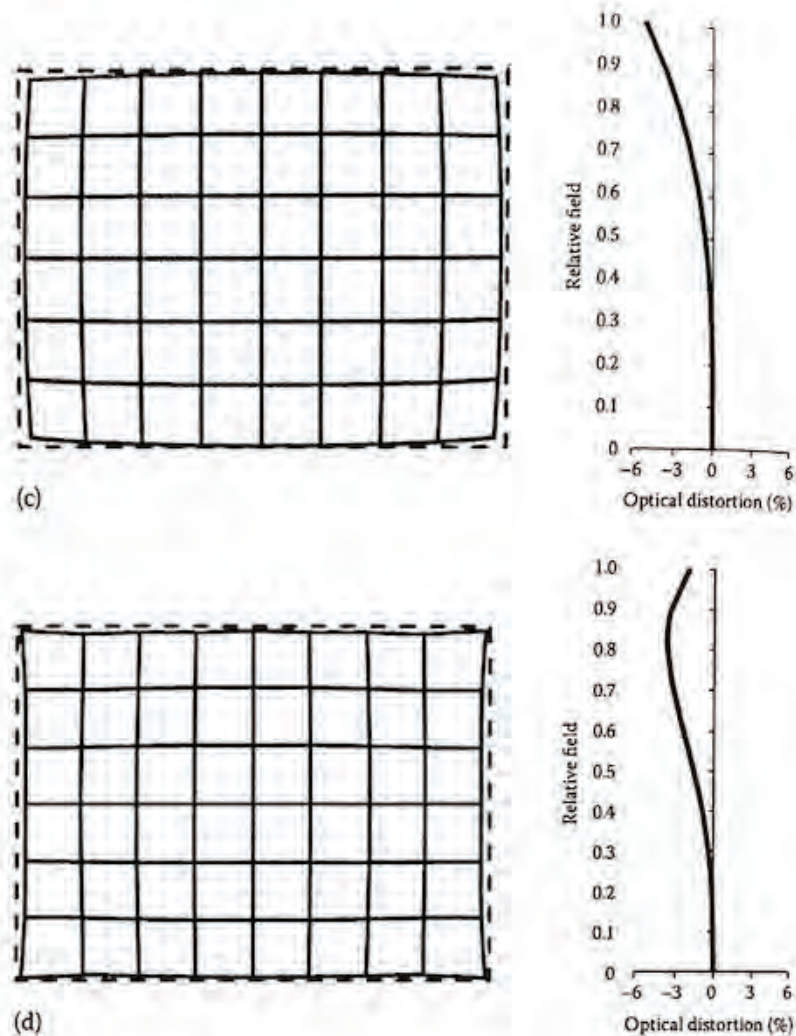


FIGURE 1.16 (Continued)

because the red, green, and blue samplings are different. Some image-processing methods are used to reduce the subjective effects of color aliasing. Systems with multiple sensors, or with unusual sensors that can detect all three colors in the same pixel, can have a significantly better aliasing performance.

1.4.6.1 Aliasing in MCMs

MCMs almost always use Bayer array sensors, and they do not usually have antialiasing filters. MCMs' image sharpness is closer to "optics-limited" than larger cameras, because the pixels are so small. If we compare the Airy disc diameter to the pixel, a full-frame DSC (35 mm format) is likely to have an $f/2.0$ lens, and 6 micron pixels. The MCM lens will have a slower f no (larger diffraction PSF), and 1.4 micron pixels. We can create MTF plots for both cases (Figure 1.17). The dashed line is the system MTF

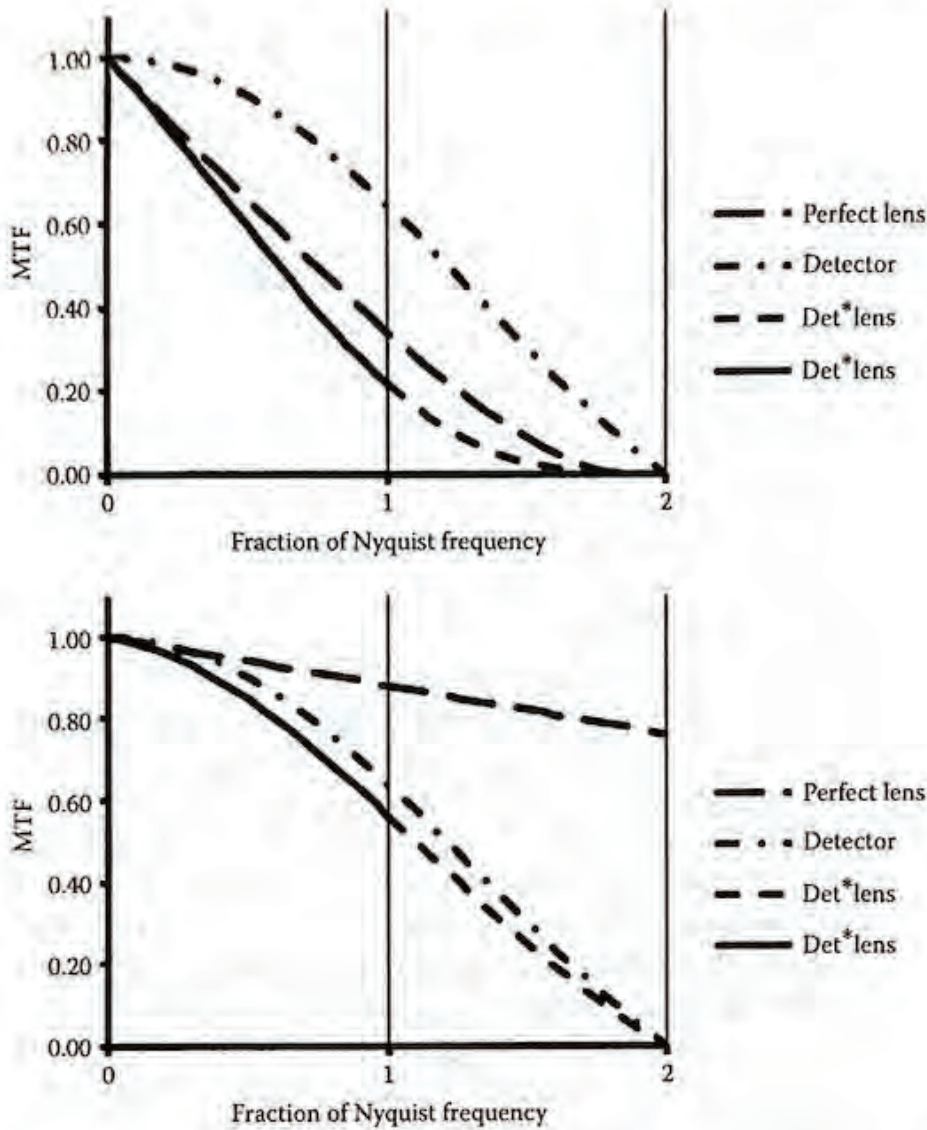


FIGURE 1.17 Aliasing comparison, 1/4" MCM (*top*), full-frame DSC (*bottom*). The area under the dashed MTF curve is the potential for aliasing if the object has a frequency content higher than Nyquist.

at frequencies above the Nyquist frequency. The integral of the system MTF above the Nyquist frequency tells us how severe the aliasing will be, assuming that the object has content at frequencies above Nyquist. It is apparent that the DSC has the greater need for an antialiasing filter.

1.4.7 Stray Light

Stray light refers to light that takes an unintended path to get to the image. In this context, it does not include the sharpness-decreasing effects of lens defocus, aberrations, and diffraction. Instead, there are two broad categories: flare and veiling glare.

1.4.7.1 Flare, Ghosts

Flare, often called ghosts, can be difficult to diagnose, because there are many possible sources. Light from bright sources in front of the camera (maybe within the FOV, maybe not) can end up on the sensor where it does not belong. There may be paths around the lenses that were unintended, or there may be reflections from a structure within the camera, or reflections from the lens surfaces. There is no consistent objective measure of flare, because its appearance can vary widely. It is often tested by photographing a bright source over a wide range of camera angles. Flare can be minimized by the use of antireflection coatings on lens surfaces, by control of lens surface shapes to avoid focused reflected images on the sensor, and by the use of internal baffles (Figure 1.18).

1.4.7.2 Veiling Glare

VG is caused by scattering of light (ISO 9358 1994). It is distinct from flare or ghosts because it has little structure in the image. VG is the overall haziness in a photograph, increasing the black level. Defined as the fraction of the average exposure of a photograph that is scattered (uniformly) across the photograph, it is usually caused by scatter from hazy, damaged, or dirty optical components. The most common measurement method is to photograph a small black object in a white field. Frequently, an integrating sphere is used to create the hemispherical white field that illuminates the lens system (Figure 1.19). VG is often under 5%. VG may be reduced by avoiding out-of-field light—the photographer's lens hood does this. The effect of VG may be somewhat reduced by image processing to reset the black level of the image.

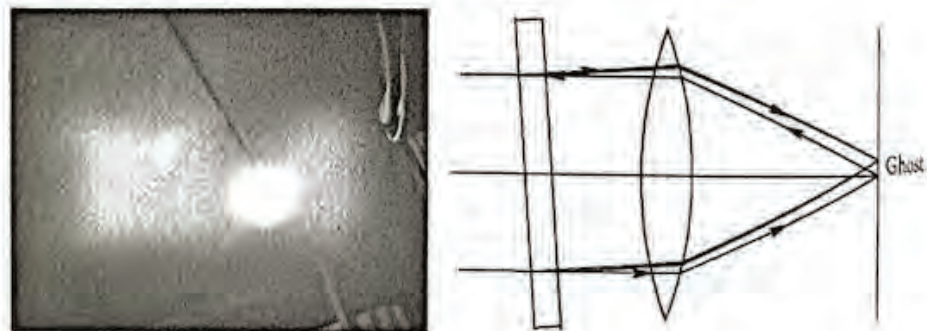


FIGURE 1.18 Ghost image example. Light from the lamp's image is reflected from the sensor, and then re-reflected by the two surfaces of the window. A ghost image is seen to the left of the lamp. 5 MP mobile-phone camera.

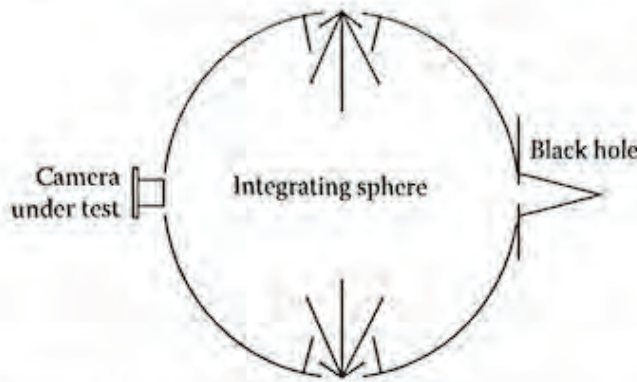


FIGURE 1.19 Schematic of the veiling glare test.

1.5 Focusing Issues in MCMs

1.5.1 Simple Thin Lens

To a paraxial approximation, an imaging system creates a 3D “image” in image space of the object space volume. Every plane normal to the optical axis in the object space is imaged in a plane in image space. The familiar, simple thin lens equation describes the focus distance relationships:

$$\frac{1}{\text{EFL}} = \frac{1}{z} + \frac{1}{z'},$$

where z is the object plane to the lens distance, and z' is the lens to the image plane distance (see Figure 1.20). The algebraically equivalent form of this equation, in which distance is measured from the front-focal and back-focal planes of the simple lens, is

$$\text{EFL}^2 = s s',$$

where $s = z - \text{EFL}$ and $s' = z' - \text{EFL}$.

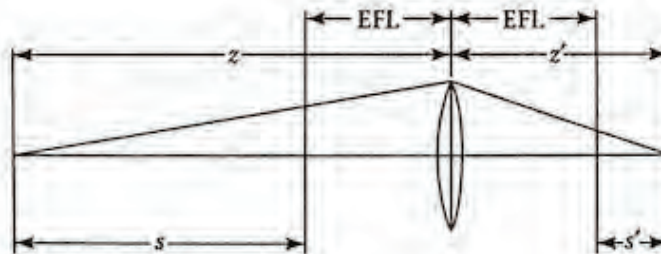


FIGURE 1.20 Variables in the thin lens equations.

So, we see that closer objects are imaged further behind the lens, and the focus shift from an object at infinity is

$$s' = \frac{EFL^2}{s}.$$

As long as $s \gg EFL$, s may be considered to be equal to the object distance, which is almost always the case for miniature cameras, whose EFLs are very short.

1.5.2 Depth of Field and Depth of Focus

The depth of field and the depth of focus are the range of acceptable focus, measured in object space (...field) or image space (...focus). The photographer is concerned with the depth of field.

Determining the depth of field requires us to have an upper limit for acceptable blur in an image. Blur due to defocus may be measured geometrically by tracing a principal ray. The blur diameter, B , is twice the absolute value of the ray intercept on the image plane (see Figure 1.21).

1.5.3 Fixed-Focus MCMs

Many miniature cameras have no focus adjustment capability, so they have a limited range of subject distances with acceptable sharpness. Best focus is usually set so that sharpness is just acceptable for infinite objects, and best focus is found at a closer distance, referred to as the "hyperfocal" distance, H . The blur at $H/2$ is approximately the same as the blur at infinity, so the camera will have acceptable sharpness from infinity to $H/2$. If the limit of acceptable blur is some multiple, k , of the pixel dimension, P , then for a lens set to the hyperfocal distance, $f_{no} = S'/(kP)$:

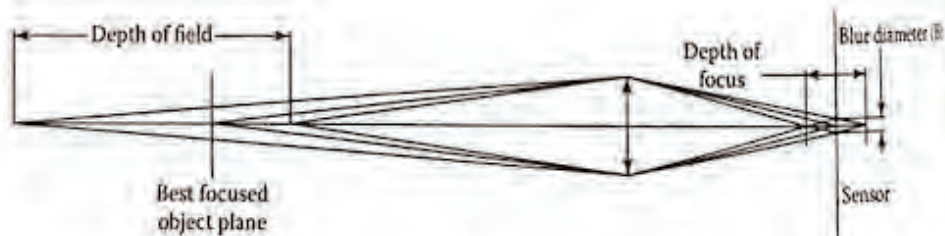


FIGURE 1.21 Depth of field and depth of focus. Depth of field is not usually symmetrical about the best focus distance.

$$\text{fno } k P = \frac{\text{EFL}^2}{H}$$

and

$$H = \frac{\text{EFL}^2}{(\text{fno } k P)}$$

Example: EFL = 3 mm, f/2.8, $P = 0.0014$ mm, $k = 2$ pixels:

$$H = 9/(2.8 \times 2 \times 0.0014) = 1148 \text{ mm and}$$

$$S' = \text{fno } k P = 0.008 \text{ mm.}$$

So, this fixed-focus camera will have acceptable sharpness for objects from infinity to 574 mm.

1.5.4 Adjustable Focus MCMs

Adjustable focus MCMs are often required to focus from infinity (zero diopters) to 100 mm (10 diopters), so fixed focus may not be adequate. If we want to build a camera that can photograph closer objects sharply, it needs to have some means of focus adjustment. One way to accomplish this is by allowing the distance between the lens and the sensor to be adjustable, so the best focus plane can be closer to the sensor. The motion required to focus from infinity to the closest distance, $S_{\min}$, is approximately proportional to $1/S_{\min}$:

$$S' = \frac{\text{EFL}^2}{S_{\min}}$$

If EFL = 3 mm again, and $S_{\min} = 100$ mm, we need 0.09 mm of motion, and another question may be asked: If the focusing could be done in discrete steps, rather than continuously, what is the smallest number of steps that would be required? The following calculation helps to answer:

$$\text{No. of steps} = \frac{S'_{\text{total}}}{(2 S'_{\text{hyperfocal}})} = \frac{0.09 \text{ mm}}{(2 \times 0.008 \text{ mm})} = 5.7 \text{ focus steps.}$$

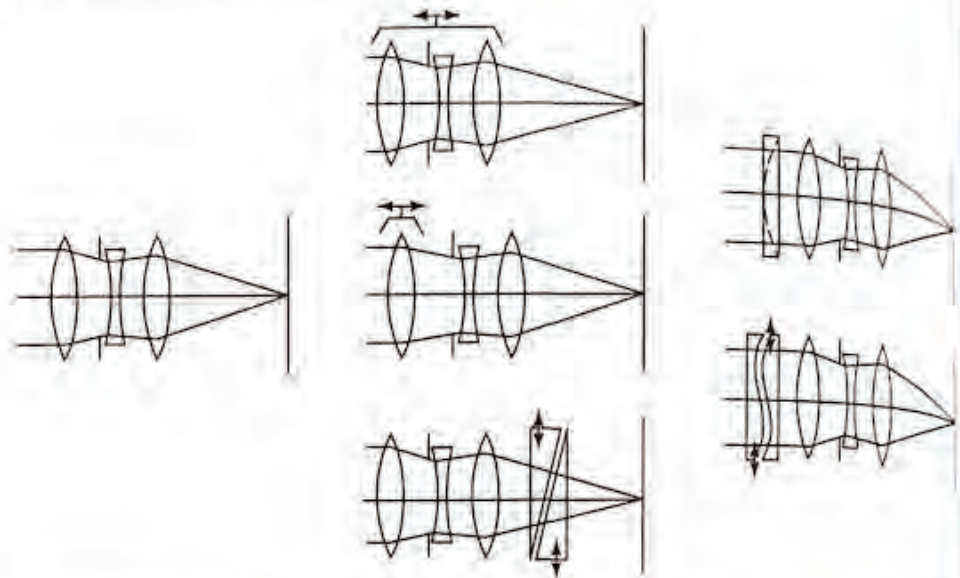


FIGURE 1.22 Means of focusing MCMs. (*Left*) Fixed focus. (*Center*) Axial distance adjustment. (*Top to bottom*: Unit focusing, front element, and wedge prism.) (*Right*) Adjust optical power. (*Top*: Liquid, LC, or deformable. *Bottom*: Alvarez lens.)

The strategy of moving the entire lens, just described, is common. It is referred to as “unit focusing.” Some systems move only part of the lens (“partial lens focusing”)—perhaps just the front element. Partial lens focusing is attractive because the mass to move is usually much smaller, and if the EFL of the moving part is shorter than the EFL of the entire lens, the length of the motion can be reduced. The drawback, however, is tighter mechanical tolerances for decenter and tilt, and also the possibility of a larger aberration variation with focus change. The partial lens focusing method requires a special lens design and probably an advanced lens suspension system.

Other methods are possible. Figure 1.22 illustrates some focusing strategy alternatives: We could move only part of the lens, or we could effectively adjust the lens to sensor distance with a wedge prism set. Also, we could focus by changing the optical power of the lens system. Some of these methods are described in the following sections.

1.5.5 AF Systems

Before AF systems were first developed in the 1970s, photographers needed to adjust the camera focus. Originally, they would replace the film or plate with a ground glass screen, allowing direct inspection of the image. Since then, some cameras have required the photographer to estimate the distance to the subject and set a distance scale on the camera, some have used optical

range finders to measure the distance and couple it to the lens motion, and “reflex” cameras have allowed ground glass focusing without moving the film.

AF systems have employed a number of means to judge image focus. Some have used active systems (IR or ultrasound) to measure the subject distance. Others have automated the optical range finder, looking for a correlation of two optical images. In digital cameras, including miniature digital cameras, the simplest method is to continuously collect image data, and compute a “focus score” (FS; more properly, a sharpness score). The FS is usually determined from a subsection of the image, the region of interest (ROI). The ROI is usually in the center, but it can be set by the user in some devices. The AF algorithm changes the focus setting, and then readjusts the focus, trying to maximize the FS. Different focusing technologies may require different algorithms, and the AF algorithm for a still photograph is likely to be different from the continuous AF algorithm that is required for video recording.

One of the goals of an AF system design is to minimize the response time. For still photography, the AF process starts when the shutter button is pressed. The time that the AF algorithm takes to find and set the best focus adds to the “shutter lag.” Naturally, camera designers strive to minimize the shutter lag; in many camera systems, it is on the order of 1 s. Some cameras achieve much shorter times. The response time in video systems should be fast enough for the system to track moving objects and to respond quickly to sudden scene changes.

1.5.6 Mechanical Systems

Currently, the focus adjustment of MCMs is most commonly accomplished by an electromechanical arrangement called a voice coil motor (VCM; discussed in Chapter 3, this volume). As the name suggests, it is a drive very much like the one in a loudspeaker, with a fixed permanent magnet and the lens mounted on a suspension arrangement with wire coils that can be energized to move the lens. This arrangement can work very well, but it requires careful design and manufacture of the suspension. It is important to keep the lens from tilting as it moves, and care must be taken to overcome gravity effects and hysteresis.

Other mechanisms of discrete movements of MCM elements (to achieve AF) are known, such as microelectromechanical systems (MEMS), piezo elements, and shape memory alloys. However, to date, none of these has been widely applied in AF MCMs.

1.5.7 Electrically Variable Lenses

Much effort has been invested in developing tunable lenses—lens elements whose optical power can be varied by electrical signal. This is a way to focus the camera without any conventionally moving parts. Currently, three approaches to this are known to this author: electrowetting liquid lenses, deformable lenses, and LC lenses.

Adding a tunable optical element to a fixed camera lens has great potential for AF without moving parts. The tunable element should be located reasonably close to the aperture stop. If it is not near the stop, its diameter must grow, because of the camera's FOV. Tunable lenses have a limitation on the "optical path difference" (OPD) between their center and edge. If we wish to achieve a camera focus variation of, say, 0 to $+P$ diopters (the subject distance from infinity to $1/P$ m), in a camera whose entrance pupil diameter is EPD (mm), the optical path difference across the aperture stop must be

$$\text{OPD}_{\min} \approx \frac{(\text{EPD}/2)^2 P}{2000} \text{ (mm)}.$$

If the tunable lens is assumed to be thin, and we consider the paraxial principal ray and chief ray heights on the tunable lens (Y_{prin} and Y_{chief} , respectively), then we can calculate the OPD required for the tunable lens to achieve the focus range:

$$\frac{\text{OPD}}{\text{OPD}_{\min}} \approx \frac{(\text{abs}(Y_{\text{prin}}) \pm \text{abs}(Y_{\text{chief}}))^2}{Y_{\text{prin}}^2}.$$

We can look at a paraxial example: If the camera lens is a thin lens (see Figure 1.23), 3 mm EFL, $f/2.4$, and 65° full FOV.

Table 1.3 shows the $\text{OPD}/\text{OPD}_{\min}$ required for 100 mm close focus distance.

If the tunable lens is placed in the image plane, it loses its focusing ability completely. This paraxial exercise is approximate, but it illustrates the importance of the location of the tunable lens in the optical system.

It should be understood that the addition of a tunable lens of any type affects the aberration balance of the camera system. Usually, sharpness will be optimized for the more distant end of the focus range, because (a) more distant photographs than close-ups are taken; and (b) while many distant scene subjects are at "infinity"

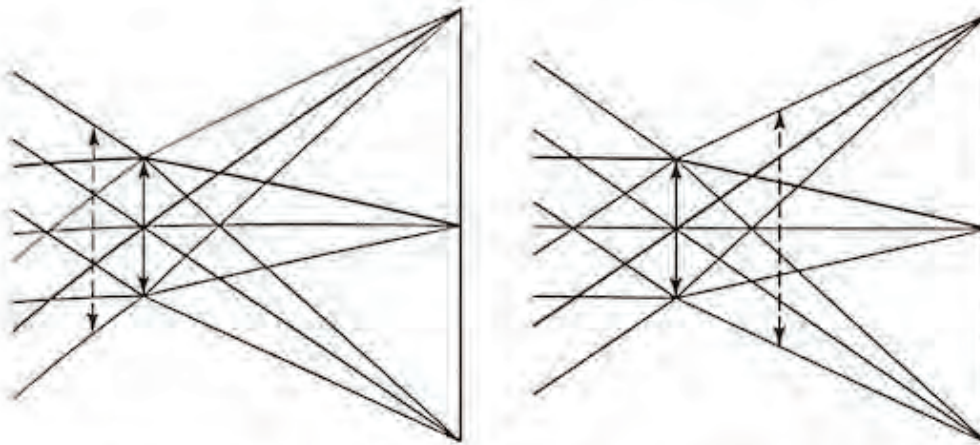


FIGURE 1.23 (a) A tunable lens (*dashed*) is located ahead of the entrance pupil (*left*) and (b) after the exit pupil (*right*). Increasing the distance from the pupil increases the OPD required to focus (Section 1.5.7).

across the entire FOV, close subject focus can vary widely with the field, so slightly less corner sharpness can be acceptable.

1.5.7.1 Electrowetting Liquid Lenses

As discussed in Chapter 5, this volume, electrowetting liquid lenses have the form of a cell with two flat windows that contain two immiscible liquids (oil and water). The oil and water arrange themselves like a doublet lens, with a curved interface between them. The geometry of the cell is such that the curvature of that interface changes as a voltage is applied to the part. The oil has a higher refractive index than the water, so the optical power changes. The material choice is critical. For example, it is important that the densities match closely, to avoid gravitational and thermal issues. Quite large optical power variation is achievable.

1.5.7.2 Deformable Lenses

Generally, deformable lenses are made with a liquid or polymer core material that is flexible. The edges are mechanically squeezed

TABLE 1.3 OPD/OPD_{min} Required for 100 mm Close Focus Distance

Tunable Lens to Pupil (mm)	Case A (Figure 1.23a)	Case B (Figure 1.23b)
0	1.0×	1.0×
0.5	2.3×	2.6×
1.0	4.1×	6.4×
1.5	6.4×	16.5×

or stretched (e.g., by piezoelectric actuators), changing the curvature of the lens surface.

1.5.7.3 LC Lenses

As discussed in Chapter 6, this volume, LC lenses use the birefringence of LC materials to create a gradient-index optical element. Applying an electric field to an LC will rotate its molecules, and if the electric field is controlled spatially, the LC material will behave like a tunable lens.

1.5.7.4 Other Optical Focusing: Lateral Motion

Focusing in discrete steps may be accomplished by moving separate fixed focal length lenses in front of the camera. The extra lenses can be quite weak, so mechanical tolerances would be reasonable, but the volume required for the lenses and the actuator has kept this idea from being implemented in mobile devices.

It is also possible to achieve continuous focusing by using complementary unsymmetric aspheric elements (the “Alvarez” lens is an example); one may be fixed and the other may translate linearly or rotationally. These have been used in a small number of larger format cameras, but they are not yet in commercial miniature cameras (Plummer et al. 1999; Zhou et al. 2012).

1.5.8 Alternative Approaches

1.5.8.1 Software Focusing and Extended Depth of Field

As discussed in Chapter 4, this volume, several proprietary methods have been developed that eliminate all physical focusing, using special optical designs and sophisticated image processing to provide sharp images over a wide range of object distances. We will not describe them in detail here, but two general approaches have been seen:

1. *Extended depth of field (EDOF)*: A special optical design is produced with aberrations that reduce the variation of the PSF with focus. The recorded image is unsharp, but processing can then restore sharpness by deconvolving that constant aberration. All distances within the range of capability are acceptably sharp.
2. *Chromatic focusing*: The camera lens is designed with an intentionally uncorrected chromatic aberration. Chrominance and luminance are separated for processing, and the sharpest color information is used in a higher proportion in the luminance channel.

These descriptions are greatly oversimplified, and are intended only as descriptions of the principles.

EDOF systems have obvious strengths and weaknesses:

Strengths:

- No moving parts or physically tunable optics.
- No “shutter lag” due to focusing.
- AF decision errors are eliminated.

Weaknesses:

- Special optical designs may be difficult to design, manufacture, and test.
- Complex image processing in the device.

Image artifacts:

- Noise may be amplified. Algorithms can result in some spatially varying image artifacts.
- Somewhat unnatural results—photographers may prefer less depth of field.

1.5.8.2 Light Field Photography

Recently, some unconventional advanced photography systems have been developed. One of these is “light field photography” (Ng 2006). This approach enables EDOF, or refocusing after acquisition, using a special sensor arrangement. A simple statement of the principle is that the entrance pupil is spatially divided into a number of smaller segments, and image data are collected for each of those subpupils (see Figure 1.24). We might think of each subpupil as creating a long depth-of-field image (high fno). Light from the separate subpupil images is combined, spatially shifted, to give us a post-focused image. The post-processing options are flexible, allowing post-focusing or extended focusing. Another way to look at it is to realize that the light field sensor records angular information as well as spatial information. Much more pixel data are recorded for the construction of a finished photograph than a conventional digital camera photograph and much more processing must be done to display it.

1.5.8.3 Array Cameras

It has been proposed to create a thinner camera system by building an array of smaller, lower-resolution cameras to replace a

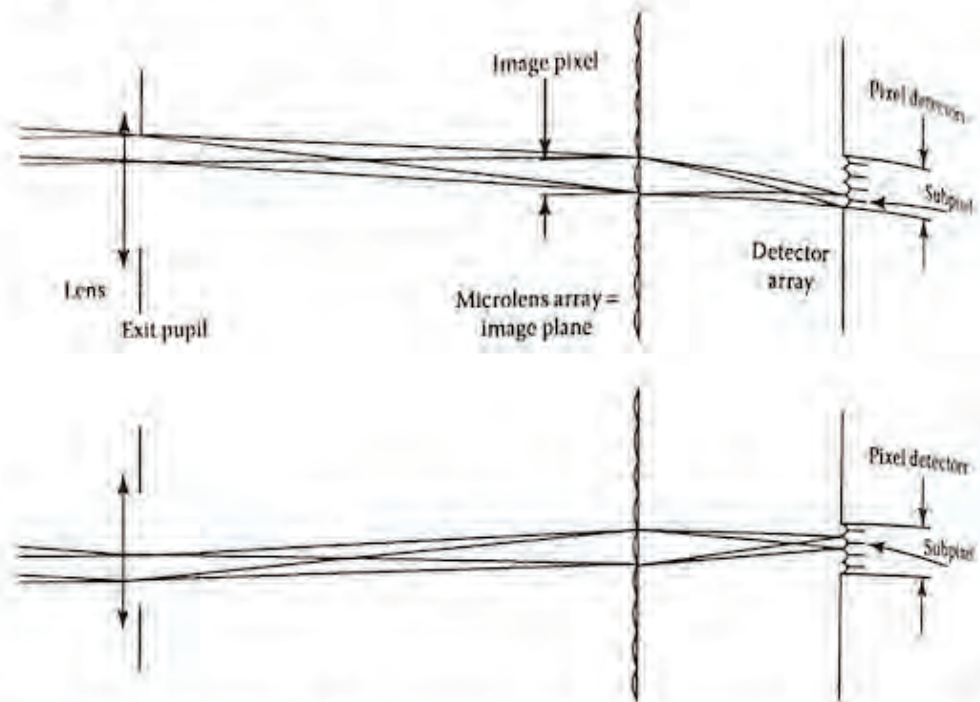


FIGURE 1.24 Light field photography principle. Four subdetectors can be seen behind each microlens. Each subpixel sees light only from a portion of the exit pupil. Two cases are shown, seeing the same pixel of object space, but using different parts of the lens pupil.

single, high-resolution device. While many arrangements are possible, an example would be to replace one N -MP camera with four $N/4$ -MP cameras (Figure 1.25). The pixel dimension would remain the same. Each “quarter camera” might have the same FOV as the full camera, so the lenses could be $1/2\times$ scaled versions of the original—half as long, with the same fno . The FOV, pupil area, and total detector area would be unchanged, so the system’s total light collection is unchanged. Each of the quarter cameras could have a single color filter, instead of a filter array on the sensors. If two cameras were green, and one each red and blue, they might be arranged so that the pixel centers formed the familiar Bayer pattern when projected into object space. The big difference, compared to the full camera, is that the pixels will be twice as large in object space, overlapping each other. This would reduce the MTF somewhat, because the size of the sensitive area of the pixels affects the object space PSF. It also reduces aliasing. Other arrangements of array cameras, plus sophisticated image processing, might give us improved imaging in the future: maybe a wide dynamic range, post-acquisition focusing, etc.

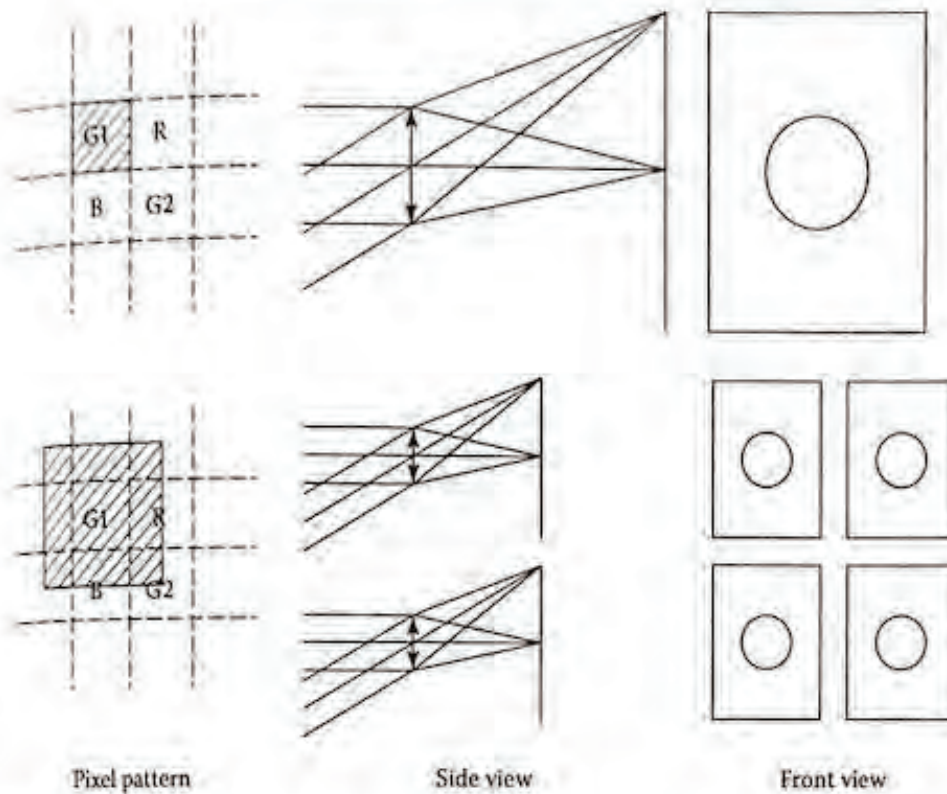


FIGURE 1.25 Four half-scale cameras in an array compared with the original. (*Left*) The pixel patterns seen to scale in object space. Each detector is two times larger in the array camera, but the Bayer pattern can be retained if the cameras are aligned.

1.6 Adapting Mobile Device Cameras to Special Applications

Miniature cameras are almost universally available in mobile phones, tablets, and laptop computers. Various “apps” may be created that operate the camera and process the images, so it is attractive to use them as a means for data collection that is widely available, portable, low cost, “smart,” and connected. External hardware can be built to provide optical input, for microscopy, spectroscopy (Gallegos et al. 2013), and other types of optical measurements. Many applications can be imagined in commerce, science, medicine, etc.

When designing instruments to interface with miniature cameras, we need to consider their characteristics:

1. *Input characteristics:*

- a. Entrance pupil: All of the light collected must get into the entrance pupil. It is essential to know its size and

- location. Fortunately, it is not difficult to measure from outside the camera with a good measuring microscope.
- b. FOV: The size of the recorded object space, usually measured angularly, is important to know. Assuming that distortion is well-corrected by the camera lens, height in the image will be proportional to $\tan(\text{field angle})$.
 - c. Angular size of pixels: Again, the pixel pattern divides $\tan(\text{FOV})$ evenly. The FOV and the pixel size are also easy to determine by photographing a known target at a known distance.
2. *Spectral characteristics:*
- a. The IR-cut filter will block light beyond about 650 nm.
 - b. The red/green/blue (RGB) color filter array is designed to provide pleasing color pictures, but for technical use, the images may need to be calibrated for spectral sensitivity variation.
3. The normal output of the camera will have been processed to provide visually pleasing photographs.
- a. The preprocessing "raw" image may be desired for technical applications, but it might not be available to the app.
 - b. Processed images will probably have undergone image processing:
 - i. Gamma correction. Pixel values are given a nonlinear relation to light exposure.
 - ii. Lens shading correction. Corners are lightened.
 - iii. Color interpolation, providing RGB information for every pixel location.
 - iv. Automatic white balance correction. The software attempts to optimize color balance based upon image data.
 - v. Sharpening. MTF is boosted at some spatial frequencies.
 - vi. Noise reduction.
 - vii. Compression (.jpg files are typically compressed with consequent loss of information).
4. *Camera operation:*
- a. The camera may have an AF system that adjusts the lens focus.
 - b. Autoexposure. Integration time and gain may be automatically adjusted.
 - c. Image stabilization. Not very common yet, but cameras may have a system that corrects for camera shake.

Which issues are important should be determined by the needs of the application, of course. The device may allow camera operation conditions to be set by the software. It may be necessary to disable some automatic functions, for example.

1.7 Advanced Capabilities of MCMs

1.7.1 Image Stabilization Systems

Image stabilization systems, described in Chapter 7, this volume, are intended to reduce the effect of camera motion (shake) on the recorded images. In still photography, camera motion during an exposure can result in loss of sharpness. Correcting camera shake in still photography will allow the photographer to make longer handheld exposures, which is a great benefit in low-light situations. With video, camera motion can cause instability of the scene, which is not dependent upon scene brightness. Like any free body, a camera can move in six axes, three translations and three rotations. If the object distance is large, pure translations have very little effect upon the image, so x , y , and z motions are generally not corrected. All three angular tilt modes, however, can cause loss of sharpness or disturbing image instability. Small tilts about the x - and y -axis (pitch and yaw) cause lateral shifts of the image, and rotation about the optical axis (z -axis—roll) causes rotation of the image.

1.7.1.1 Optical Image Stabilization

If the mobile device has a gyroscopic sensor, it can be used to acquire tilt information in real time. Tilt data are used to move some components of the imaging system to cancel the image motion. We can think about this problem as a control system that responds to inputs over a range of temporal frequencies. There must be a low-frequency roll-off, since the camera should not try to correct slow changes, and there will be a high-frequency roll-off because we do not expect very high-frequency shaking to have significant amplitude. Within the frequency range, the maximum amplitudes required to correct will vary, based upon the human camera shake. The phase delay of the correction must be small, or the correction will be ineffective. The correcting motion may be accomplished in several ways: (a) tilting of the entire camera module; (b) lateral movement of the image sensor, or of the lens

or part of the lens; or (c) using a tunable lens technology to create an adjustable prism. Usually, roll is not corrected in optical image stabilization (OIS) systems—moving lenses or thin prisms cannot rotate the image.

1.7.1.2 Software Image Stabilization

Video may be post-processed to stabilize the images. It is more difficult to improve the sharpness of still images after the fact, but it is possible to imagine schemes that would acquire many short exposure (underexposed) images, then to align and add them after acquisition. There would be a noise penalty, and this would extend the exposure time.

1.7.2 Zoom

Most conventional still and video digital cameras come with “zoom” optics and consumers have come to expect all digital cameras to have zoom lenses, sometimes with very large zoom ratios. The user can change the EFL of the taking lens continuously, which changes the size of the image on the sensor. MCMs could also, in principle, have zoom optics, but in most products today (mobile phones, tablets, and laptop computers) the space and cost constraints force fixed focal length optics and the optical zoom technology has not yet (2013) been widely adopted for MCMs.

Conventional optical zooms work by moving groups of optical elements along the optical axis. Usually, two motions are necessary, because one motion will typically change the focal length and it will also change the focus setting. A second moving group is needed to restore the focus. The optical design of a zoom system is often quite complex, requiring more components, and the relative aperture (f_{no}) is slower than a nonzoom design might achieve. A zoom design may cause the exit pupil to shift axially, which should be considered when working with a “microlensed” digital sensor.

Miniature versions of conventional zoom lens designs would have more lens elements, at least two moving or tunable groups, and they would occupy much more volume within the product. Nevertheless, optical zooming is a desirable feature, and the work being done today may be found in future products. Meanwhile, an MCM has been introduced that has an unusually high-resolution sensor and a highly corrected nonzoom lens, maximizing the “digital zoom” capability in a mobile-phone camera.

1.7.3 Stereo 3D Photography

Still photography has been extended to stereo 3D for many years, sometimes with great success in the marketplace. In recent years, 3D motion pictures have become much more popular, so there is increased interest in stereo 3D. Some consumer cameras and video cameras produce 3D images, and stereo 3D is a natural application for MCMs.

Stereo 3D is the familiar idea of recording two independent images, with separated entrance pupils, and displaying those images separately to the viewer's two eyes. If done well, the viewer perceives the depth of a natural scene. We will briefly describe the conditions for stereo 3D.

The display of 3D images is an important component of the system. We will not discuss it in detail here, but we will assume that the images are seen at a comfortable focus distance, with matching magnification and little distortion.

The recording cameras should ideally be identical, aimed parallel to each other, and simply shifted by a distance that we will call the stereo baseline.

Three first-order parameters of the recording/display systems are important (Figure 1.26):

1. *Angular magnification:*

$$Ma = \frac{\tan(\text{viewed object angle})}{\tan(\text{recorded CRA})} = \frac{Ubar'}{Ubar}$$

2. *Stereo baseline magnification:*

$$Mp = \frac{\text{Viewer's pupil distance or eye separation}}{\text{Recorded stereo baseline}} = \frac{P'}{P}$$

3. *Apparent infinity distance:*

$$Z_{inf} = \frac{P'}{(2U')}$$

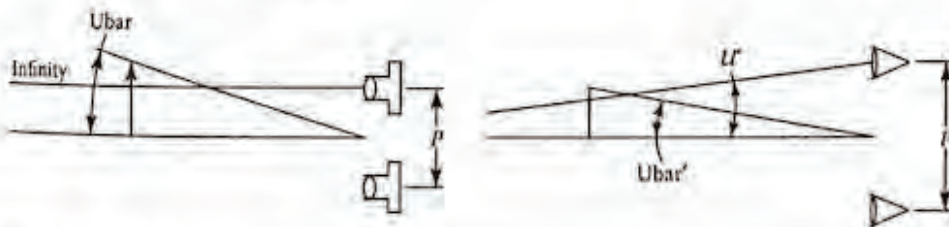


FIGURE 1.26 Schematic demonstration of the stereoscopic recording concept.

If we know these three parameters, we can understand the imaging of the 3D space.

Notice that the focus of the acquisition cameras and the display system does not change the 3D relationships; only the sharpness is changed. One fundamental difference of viewing a stereo 3D image is that while the 3D volume is reproduced, the *focus* of the images is not 3D; the original images are conventional photographs, with limited, fixed depth of field, and the display system gives us one fixed apparent best focus distance, regardless of the apparent depth of the object. This focus "disparity" does not usually disturb the illusion of reality for the viewer.

If the viewed volume is to be a 1:1 reproduction of the object volume (a condition called "orthostereo"), all three of the first-order parameters must be constrained: The two magnifications must be unity and the infinity convergence must be zero. If the angular magnification changes, the imaged volume will be stretched or compressed. If the stereo baseline magnification changes, the reproduced volume will be uniformly scaled up or down in x , y , and z . If the infinity convergence is not zero, x , y , and z are not reproduced accurately, but the scene is usually perceived as undistorted, because the human response seems to be based on angle differences, not the true angles; the brain decides that the most distant plane is infinity, and we interpret the rest of the scene based upon that assumption.

It is interesting to note that if only the stereo baseline magnification is varied from the orthostereo case, the result is a uniform magnification change. For example, if the camera baseline is half of the user's eye baseline, $M_p = 2$, and the reproduced volume appears $2\times$ magnified to the user; a $2 \times 2 \times 2$ cube 10 cm from the camera will appear to be a $4 \times 4 \times 4$ cube 20 cm from the viewer. Likewise, large baseline photography can make a cityscape look like a miniature model.

When designing a stereo 3D system, some human factors should be considered to ensure comfortable viewing. First, although humans are tolerant of some error in horizontal convergence, angular disparity in the vertical direction should be avoided. Vertical disparity can obviously be caused by camera or display-aiming errors, but it can also be the result of a left-right mismatch of magnification, keystone distortion caused by nonparallel camera axes, unequal rotation of images about the optical axis, or rotation of the viewer's eye baseline from the display baseline. Some of these concerns become more serious in systems with very large display FOV.

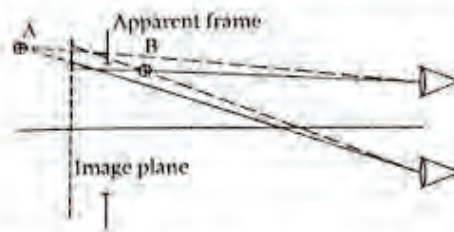


FIGURE 1.27 Geometry of the stereo frame.

As mentioned, focus errors can be less critical, but for comfortable viewing, we should try to keep the apparent display distance reasonable. If it is not adjustable, aiming for 1–2 m (1/2 to 1 diopter) would work well for most people.

We have not mentioned the “frame” created by the edges of the stereo photograph (Figure 1.27). The frame also appears at an apparent distance, which might be closer or farther than the subject of the photograph. It may seem more natural to the viewer if the frame is as close as the nearest part of the image, giving the feeling of looking through a window at the scene. If the image field is rectangular, the frame distance may be adjusted simply by cropping the left and right edges of the two channels. Remember that, in the strange world of stereo 3D, the binocular distance of the frame is independent of its focus distance, which is the same as the rest of the image.

It is easy to imagine the broad application of MCMs to stereo acquisition, because of their low cost and small size. The challenge is more to provide convenient display methods.

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