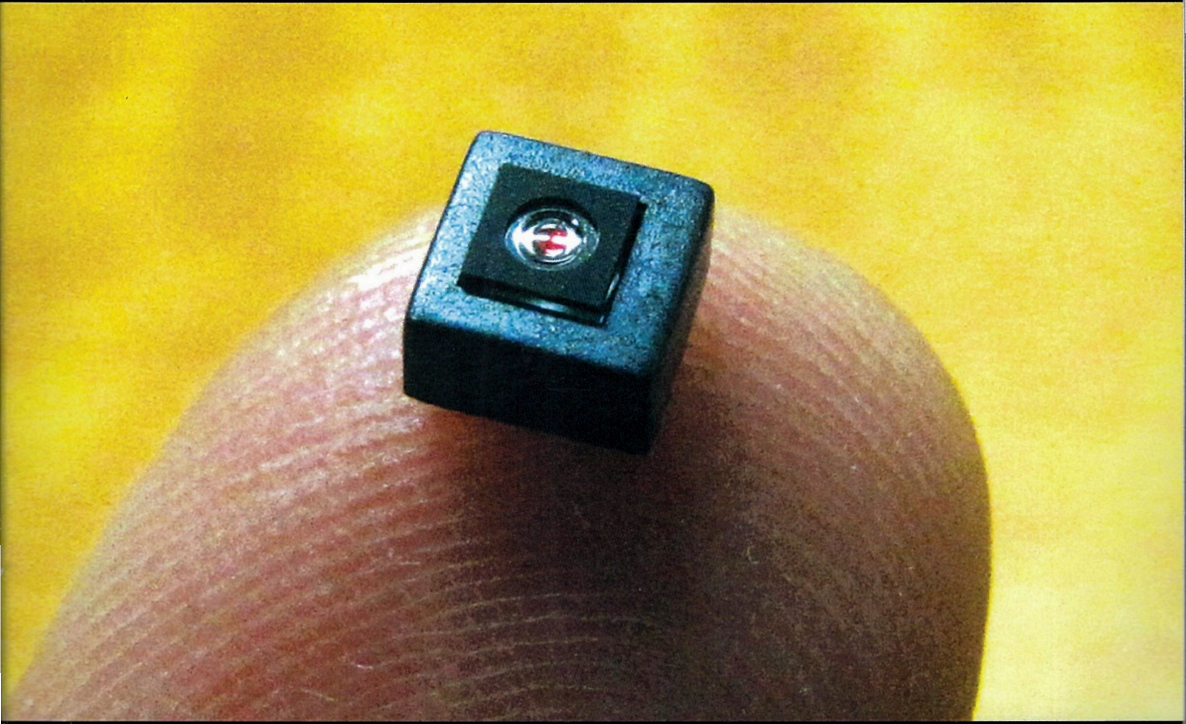
Smart Mini-Cameras



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CHAPTER 1

Lens Design and Advanced Function for Mobile Cameras

Peter P. Clark

Contents

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.

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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
APS-C	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
APS-H	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

(b) Some Photographic Characteristics[b]

					Resolving Capability				
Inch-Format	Typical Minimum f/number	EFL	Relative Central Illumination (%)[c]	Relative Total Light Gathered (%)[c]	Diagonal (Airy_Disc_ Diameter)	Diagonal (2*pixel)	Pixels (AD_Diameter)	Depth of Field (Diopters)[d]	Closest Infinity Focus, mm (Hyp/2)[d]
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
APS-C	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
APS-H	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 tradeoffs 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).

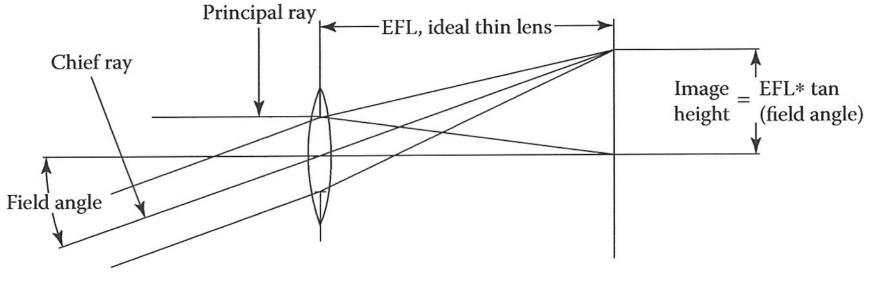

FIGURE 1.1 The relationship between the EFL of a thin lens, the field angle, and the image height. Infinite object distance.

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:

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

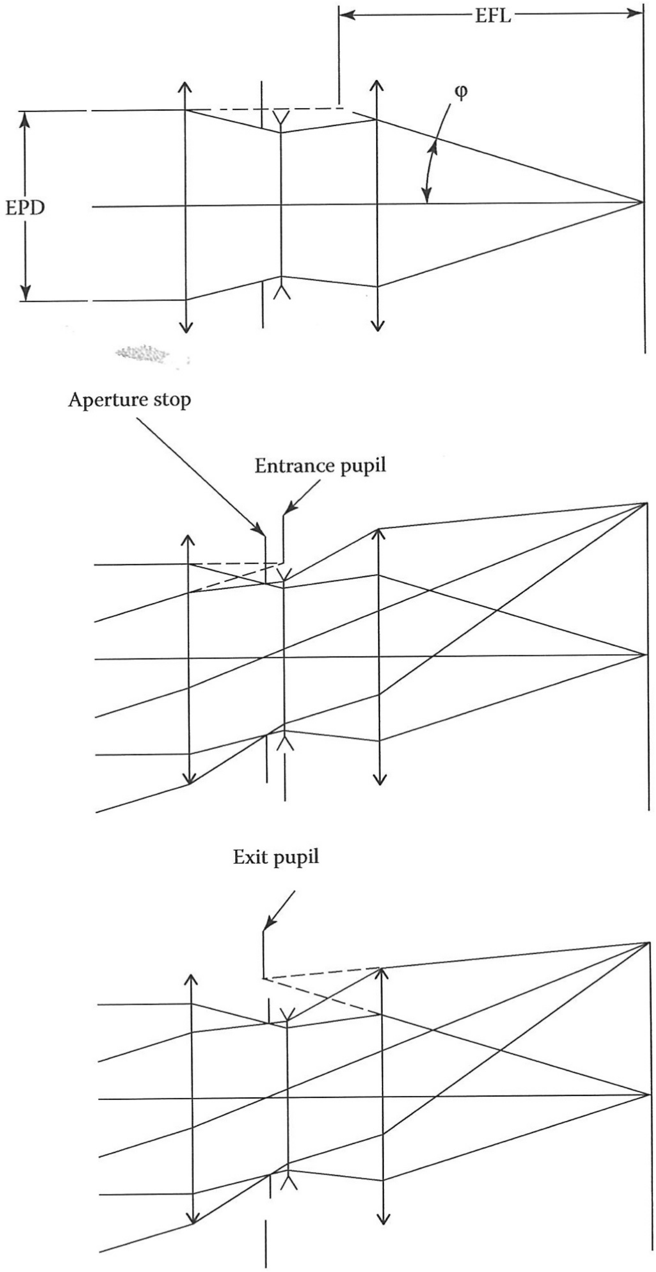

FIGURE 1.2 A triplet lens with three thin lens elements, an infinite object, with constructions from rays illustrating the EFL, aperture stop, and entrance and exit pupils.

More precisely,

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

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× exposure (f-stops): f/1.4, f/2.0, f/2.8, f/4, and so forth. Lower numerical fnos, 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 fnos 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 μm). 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,