Mobile Imaging: The Big Challenge of the Small Pixel

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ABSTRACT

As the number of image sensor pixels in camera phones increases, users expect camera phone image quality to be comparable to digital still cameras. The mobile imaging industry is aware, however, that simply packing more pixels into the very limited camera module size need not improve image quality. When the size of a pixel array is fixed, increasing the number of image sensor pixels decreases pixel size and thus photon count. Attempts to compensate for the reduction in light sensitivity by increasing exposure durations increase the amount of handheld camera motion blur which effectively reduces spatial resolution. Perversely, what started as an attempt to increase spatial resolution by increasing the number of pixels, may result in a reduction of effective spatial resolution. In this paper, we evaluate how the performance of mobile imaging systems changes with shrinking pixel size, and we propose to replace the widely misused "physical pixel count" with a new metric that we refer to as the "effective pixel count" (EPC). We use this new metric to analyze design tradeoffs for four different pixel sizes (2.8µm, 2.2µm, 1.75µm and 1.4µm) and two different imaging arrays (1/3.2 and 1/8 inch). We show that optical diffraction and camera motion make 1.4 µm pixels perceptually less effective than larger pixels and that this problem is exacerbated by the introduction of zoom optics. Image stabilization optics can increase the effective pixel count and is, therefore, an important feature to include in a mobile imaging system.

Keywords: mobile imaging, camera motion, CMOS sensor, effective pixel count, image quality

1. INTRODUCTION

As the number of pixels in a camera phone increases, consumers expect camera phone image quality to become competitive with digital still cameras. At the same time, the mobile imaging industry is aware that there are several image quality tradeoffs incurred when packing more pixels into a fixed and small camera module. For example, the design of optics to match the smaller pixel becomes much more challenging as pixel size approaches the limits of diffraction (Maeda et al '05, Catrysse et al '05, and Fesenmaier et al '08). Color shading (or chromatic aberration) and color crosstalk are other serious image quality problems frequently associated with reducing pixel size (Wueller et al '06).

We believe that a key challenge associated with smaller pixels is the effect that camera motion has upon the effective spatial resolution of captured images. When the size of a pixel array is fixed, the only way to increase the number of imaging pixels is to decrease the size of each pixel. Unfortunately, this reduces the light incident on each pixel. If the camera and scene are fixed, it would be possible to compensate for the reduction in light sensitivity by increasing exposure durations. But longer exposure time increases the amount of handheld camera motion blur (camera-shake) and reduces spatial resolution. Hence, there is a tradeoff between increasing the pixel sampling density and camera motion. In some cases, increasing the number of imaging pixels can reduce, rather than increase, spatial resolution.

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Several recent studies (Farrell et al ’06, Xiao et al ’06, Xiao et al ’07, Nishi et al ’07, Mar Or et al ’07, and Cooper et al ’08) show that camera motion increases with decreasing camera mass. Camera motion also increases when users hold a camera with one hand rather than two (Xiao et al ’07). Clearly, the perceived image quality of camera images depends on many system variables besides the number of imaging pixels. Nonetheless, total “physical pixel count” still remains the single most important figure-of-merit that the mobile imaging industry uses to quantify image quality.

The International Imaging Industry Association (I3A) recognizes the need to develop metrics to quantify the effect that system parameters have upon perceived image quality, both for efficient communication among suppliers and to help consumers in their purchasing decisions. In 2006, the I3A formed the Camera Phone Image Quality project to assist in the development and evaluation of image quality metrics that replace the simple but ill-purposed “physical pixel count” concept. It is with this goal in mind that we propose a metric we refer to as the “effective pixel count” or EPC. The metric is designed to measure the impact that camera motion and pixel size have upon system image quality performance.

2. EFFECTIVE PIXEL COUNT

2.1 Background

Given that the size of a CMOS image sensor is fixed, the only way to increase sampling density and spatial resolution is to reduce pixel size. But reducing pixel size reduces the light sensitivity if the imaging optics is fixed in aperture size (f-number). Hence, under these constraints, there is a tradeoff between spatial resolution and light sensitivity. To quantify the effects of pixel size we need a metric that quantifies both spatial resolution and light sensitivity. There have been many attempts to develop metrics that measure the tradeoff between spatial resolution and light sensitivity. For example, limiting spatial resolution is the most widely used metric for evaluating the performance of night vision systems (Johnson ’58, Fowler et al ’06). This metric is defined as the highest spatial frequency that a night vision system can transmit with sufficient contrast so that the human eye can see it (Pinkus et al ’98). In digital radiography, the detector quantum efficiency (DQE) has been promoted as a critical performance measure of the tradeoff between spatial resolution and noise performance (IEC ’03).

The metric we propose in this paper combines the modulation transfer function or MTF (a measure of spatial resolution) with the signal to noise ratio or SNR (a measure of light sensitivity and noise) to quantify the effect that pixel size has upon perceived image quality.

2.2 Definition of the effective pixel count

For a given mobile imaging system at illumination level L, we define the “effective pixel count” or EPC as

$$N_{EPC}(L) = S \times (2 \times f_{50}(L))^2 \qquad (1)$$

where S is the sensor area (mm^2) and $f_{50}(L)$ is the system’s 50% cutoff frequency (line-pairs/mm) after taking into account SNR requirements and camera motion. The factor of 2 converts line-pairs to pixels. We can replace S with N x p^2, where N is the physical pixel count and p is the pixel size (mm) and re-state the equation as:

$$N_{EPC}(L) = 4 \times N \times p^2 \times f_{50}{}^2(L)$$

We calculate the cutoff frequency f_{50} in two steps. First, we determine the minimum photometric exposure time (Farrell et al ’06). In previous studies we showed that sensor SNR must be 30dB or greater to render photon noise invisible (Xiao et al ’05). The minimum photometric exposure, T_{MPE}, is the exposure duration needed to capture an image of a uniformly illuminated achromatic surface with 40% reflectance (comparable to light skin) with less than 3% noise variation (SNR 30dB). The T_{MPE} will depend on the illumination level, L.

Camera motion will affect system MTF, but it has no impact on the SNR of a uniform surface. Therefore, T_{MPE} can be derived independent of camera motion as:

$$20 \times \log_{10} SNR(L, T_{MPE}) = 30dB \tag{2}$$

where SNR is a function of illumination level, exposure time and, many other camera parameters (camera optics, pixel size, sensor noise property and so on (see Farrell et al ’06)).

Second, we derive the system’s MTF as a product of the MTFs of optics, pixel optics and camera motion. Once we have T_{MPE}, we translate camera motion into spatial blur using a one-dimensional linear motion model that predicts the blur circle caused by camera motion during the exposure time, T_{MPE}. Then, we combine the effects of optical blur, pixel size and motion blur to calculate the system MTF.

$$MTF_{sys}(T_{MPE}) = MTF_{optics} \times MTF_{motion}(V, T_{MPE}) \times MTF_{pixel} \tag{3}$$

The MTF_{motion} is approximated as a Sinc function of the motion length during T_{MPE} , and the MTF_{pixel} can be approximated by a pixel size dependent Sinc function, which corresponds to a pixel with uniform spatial response across its area.

Now that we have the modulation transfer function of the entire imaging system, MTF_{sys}, we can determine the spatial frequency at which the amplitude of MTF_{sys} falls to 50% of its’ highest amplitude (f_{50}).

The illumination dependent “effective pixel count” or EPC is calculated by combining the f_{50} value with the other parameters, as defined in Equation 1 (above).

3. PIXEL SIZE TRADEOFF

For any fixed process technology and pixel architecture, decreasing pixel size decreases pixel performance. Without compensating technologies, smaller pixels have lower dynamic range, lower fill factor, worse low light sensitivity, higher dark signal, and higher non-uniformity. Mobile imaging applications have driven innovations in image sensor technologies that significantly compensate for the expected degradation in performance with decreasing pixel sizes. Process modifications including improved micro-lenses, pinned photodiode, dual–gate oxide, floating diffusion, circuit techniques such as device sharing, and active reset, compensate for the many factors that would otherwise reduce performance. But these modifications do not compensate for the spatial blur introduced by camera motion.

There are at least two reasons why camera motion introduces more spatial blur in imaging systems with smaller sensors. First, to obtain the same spatial resolution, pixel size must be smaller in sensors with smaller die size. Hence, the same amount of camera motion will result in more spatial blur. Second, camera-motion increases with decreasing camera mass (Xiao et al ’07).

In this section, we use the EPC metric to evaluate the impact that camera motion, pixel size and sensor array size have upon image quality. We use the ISET Digital Camera Simulation (Farrell et al ’04) to simulate image sensors with different pixel sizes (2.8µm, 2.2µm, 1.75µm and 1.4µm) and different sensor arrays (1/3.2 and 1/8 inch).

3.1 General simulation assumptions

We simulate imaging systems with diffraction-limited optics and ideal, photon-shot-noise-limited sensors. To minimize the impact of demosaicking algorithms, we assume a monochrome pixel array instead of the common RGB Bayer-pattern array. This simplifies the analysis and provides an upper bound on performance for sensors with color pixel arrays. As indicated in our previous study (Xiao et al '07), camera-motion can be approximated as a linear motion at 4.39 °/sec when an average user holds a typical 100g mobile handset with two hands. Table 1 lists common parameters shared across simulations. Other simulation-specific parameters will be listed in each section.

Table 1: Common system parameters used in following simulations.

F#	2.8 (normal) or 4.9 (3x zoom)	Field of View (normal)	54° diagonal
Pixel peak QE	0.7	Field of View (3x zoom)	19.3 ° diagonal
Pixel fill factor	100%	Pixel half width sensitivity	480nm~580nm
Sensor noise	Photon-shot-noise limited	Camera-motion	4.39 °/sec
Light source	D50	Illumination level	100 to 100,000 Lux
Surface reflectance	0.4	Targeted SNR threshold	33 dB or 1000:1

For a diffraction-limited imaging system, Equation 3 can be simplified as:

$$MTF_{sys} = MTF_{diff} \times MTF_{motion}(V, T_{MPE}) \times MTF_{pixel} \quad (4)$$

3.2 Systems with 1/3.2 inch image sensors

Today's mainstream point-and-shot digital cameras use 1/2.5 inch sensors with around 10 million pixels and 3x optical zoom. Hence, mobile imaging systems with 1/3.2 inch sensor (4.57mm width and 3.43mm height) are regarded as high-tier products that compete with consumer digital cameras. For pixel sizes of 2.8μm, 2.2μm, 1.75μm and 1.4μm, the sensor will have physical pixel count of approximately 2M (1600x1200), 3M (2048x1536), 5M (2592x1944) and 8M (3200x2400) respectively. For an f/2.8 lens with a focal length of 5.6mm, the diagonal field of view of these imaging systems is 54°. Using Equations 1 to 4, we calculate the EPC as a function of ambient illumination level. The results are shown in Figure 1.

The EPC of small pixels falls off very rapidly with illumination level. For example, the EPC for a 1.4μm system is less than 46% its physical pixel count at 100,000 lux. In contrast, the EPC of the 2.8μm system is more than 93% of its physical pixel count at this illumination level. While camera motion is negligible at this high illumination level, diffraction limitation is the dominant factor here.

According to the Rayleigh Criterion, the minimum blur size Δl increases with wavelength λ and F# for diffraction limited optics with circular aperture:

$$\Delta l = 1.220 \times \lambda \times F\# \quad (5)$$

The minimum diffraction-limited optical blur size for f/2.8 optics is 1.88μm for spatial signals with wavelengths at 550 nm. Hence, the spatial resolution of sensors with pixels smaller than 1.88 μm will be limited by the minimum diffraction-limited optical blur and not by the size of the pixel.

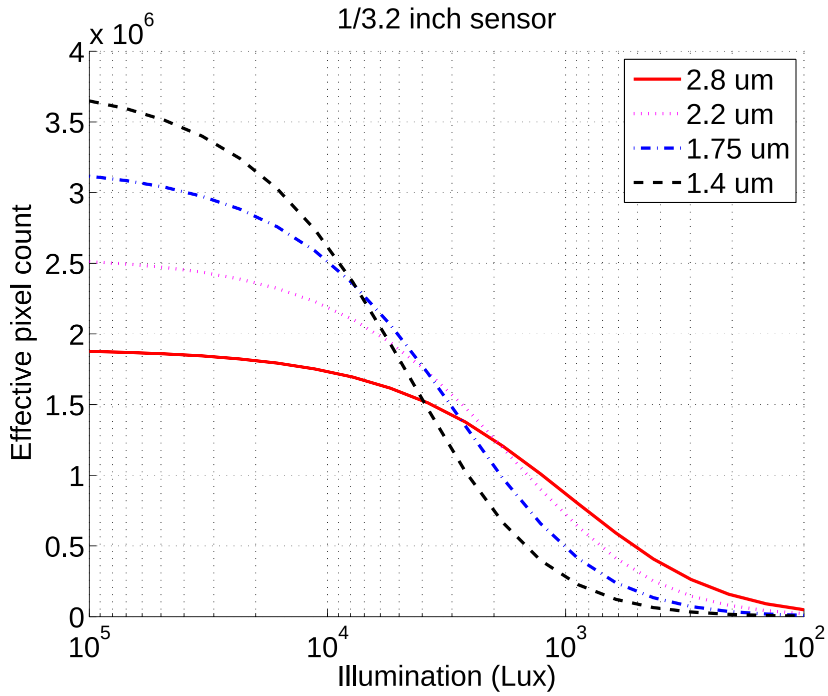

Fig. 1. Effective pixel count as a function of illumination level for imaging systems with 1/3.2 inch sensors at four different pixel sizes (2.8µm, 2.2µm, 1.75µm and 1.4µm).

When camera motion is taken into account, the EPC of the small pixel sensors is actually lower than the EPC of large pixel sensors. Specifically, notice that at 7500 lux, the EPC for a sensor with 1.4 µm pixels is less than the EPC for a sensor with 1.75µm pixels. At 5500 Lux, it is less than the EPC for a sensor with 2.2 µm pixels. And at 4000 Lux it is less than the EPC for a sensor with 2.8 µm pixels. When the illumination drops below 1000 lux, the EPC for a sensor with 1.4µm pixel is even lower than VGA resolution (640x480) or 4% of its physical pixel count. This analysis predicts that in high-tier mobile imaging systems with 1/3.2 inch sensor arrays, 1.4 µm pixels are only marginally better than 1.75 µm pixels at very high illumination level (7500 Lux) and are significantly worse at lower levels of illumination.

3.3 Systems with 1/8 inch image sensors

The previous analysis illustrates the disadvantage of using smaller pixels (1.4µm for example) in high-tier mobile imaging systems based on 1/3.2 inch sensor arrays. We can apply the same analysis to low-tier mobile imaging systems based on 1/8 inch sensor arrays. In order to maintain the same field of view as the 1/3.2 inch systems, the focal length is now reduced from 5.6 mm to 2.24 mm. All other parameters remain the same. With the reduced sensor size, the physical total pixel count is 640x480, 800x600, 1024x768, and 1280x960 for pixel sizes of 2.8µm, 2.2µm, 1.75µm and 1.4 µm, respectively.

Figure 2 shows the EPC as a function of illumination level across 1/8 inch imaging systems with different pixel sizes. In contrast to Figure 1, smaller pixels perform relatively better for 1/8 inch imaging systems than that for 1/3.2 inch imaging systems. For example, 1.4 µm pixels in 1/8 inch imaging systems retain EPC advantage over 1.75 µm pixels at illumination levels as low as 3000 Lux while the same pixels in 1/3.2 inch imaging systems lose the EPC advantage over 1.75 µm pixels at 7500 Lux.

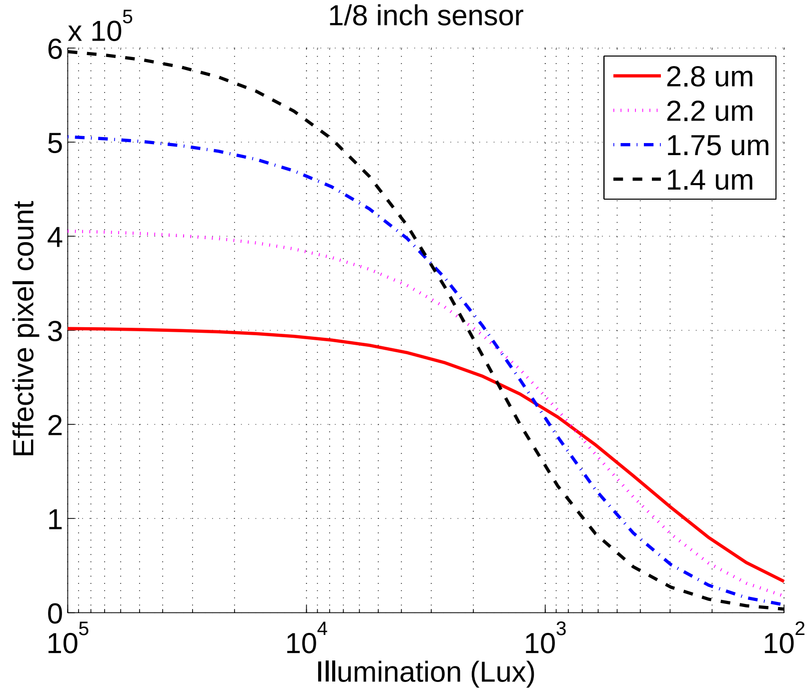

Fig. 2. Effective pixel counts as a function of illumination level for imaging systems with 1/8 inch sensors at four different pixel sizes (2.8µm, 2.2µm, 1.75µm and 1.4µm).

Similarly, 1.4 µm pixels in 1/8 inch imaging systems retains EPC advantage over 2.2 µm pixels at illumination levels as low as 2200 Lux instead of the 5500 Lux cutoff for 1/3.2 inch systems. The EPC advantage of 1.4 µm pixels in 1/8 inch sensor arrays over 2.28 µm pixels extend to 1600 Lux compared to the 4000 Lux cutoff for 1/3.2 inch systems. Finally, the EPC for 1.4 µm pixels in 1/8 inch sensor arrays is 30% of its physical pixel count at 2000 Lux whereas the EPC for 1.4 µm pixels in a 1/3.2 inch sensor array is only 9% of the physical count at the same 2000 Lux.

While 1.4µm pixels lose EPC advantage over larger pixels under low light for both 1/3.2 inch and 1/8 inch sensor arrays, they are more suitable for imaging systems with smaller die size (or low-tier products) than for imaging systems with larger die size (or high-tier products) since they can retain relatively higher proportion of the physical pixel count for smaller die size at the same illumination level.

4. IMPACT OF IMAGE-STABILIZITION AND ZOOM OPTICS

In this section, we consider the impact that zoom optics and image-stabilization (IS or anti-shake) have on the EPC metric. In the following analysis, we compare 4 different optical systems with 1/3.2 inch image sensors and 1.75µm pixel (5 Megapixel physical pixel count):

- Optics with normal field of view (F# = 2.8 and focal length = 5.6mm)
- Optics with 4x IS function that reduces camera-motion to ¼ of original (F# = 2.8 and focal length = 5.6mm)
- 3x Zoom optics without IS function (F# = 4.9 and focal length = 16.8mm)
- 3x Zoom optics with 4x IS function (F# = 4.9 and focal length = 16.8mm)

The results for all four scenarios are shown in Figure 3.

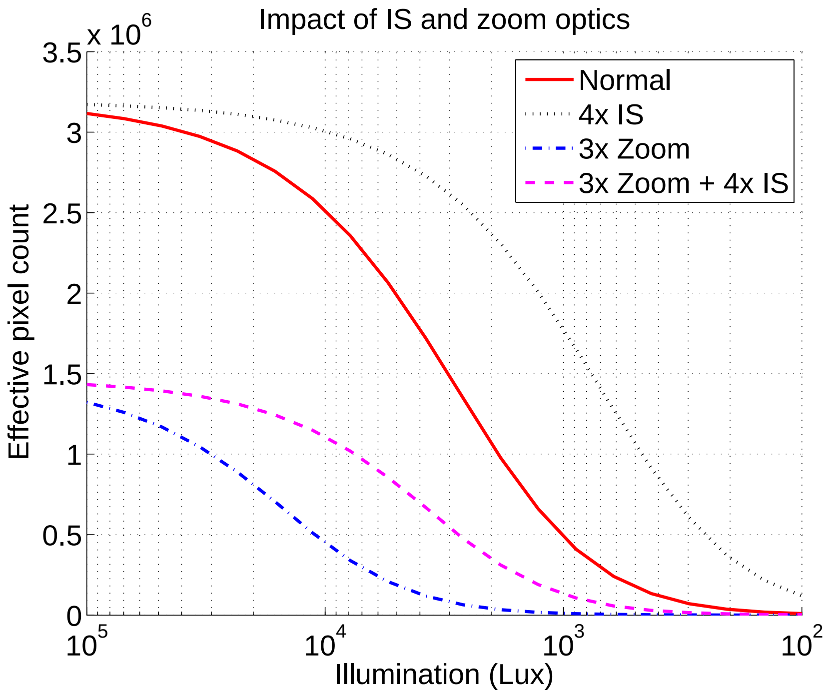

Fig.3. Impact of IS and zoom optics on the effective pixel count (1/3.2 inch sensor with 1.75um pixel and 5M total physical pixels).

4.1 The benefit of IS optics

The benefit of the optics with 4x IS function (reducing camera-motion to ¼ of original) for normal field of view is quite significant as it can maintain 2Megapixel EPC at 1300 Lux instead of 5500 Lux for optics without IS function. From an alternative perspective, optics with IS function can achieve 3 times as many EPC as optics without the IS function at 1300 Lux.

4.2 The impact of zoom optics

Zoom optics at its telephoto position (or full-zoom position) usually has a much larger F# (4.9 vs 2.8) and longer focal length (16.8mm vs 5.6mm) than at its normal position. A larger F# not only reduces the total light throughput at the focal plane, but also makes diffraction-limitation more severe (Equation 5). Longer focal lengths also amplify camera motion on the focal plane. Thus it is not a surprise that all these factors significantly reduce the EPC of a mobile imaging system with zoom optics.

As shown in Figure 3, even at illumination levels of 100,000 Lux, the 3x zoom without an IS system can achieve an EPC of only 1.3 M (which is less than 43% of its counterpart without zoom optics). Again, this is mainly due to the diffraction limitation with a F# of 4.9. According to Equation 4, its minimum diffraction-limited spatial resolution is 3.29µm at 550nm wavelength which is significantly higher than its pixel size of 1.75µm. Its EPC decreases dramatically as illumination level drops. Hence, it would be unwise to design a higher physical mega-pixel imaging system with a zoom lens. While the addition of the IS function improves the EPC significantly for the zoom optics, its maximum EPC is still severely limited by the diffraction.

5. DISCUSSION AND FUTURE DIRECTIONS

5.1 Discussion

The results of our analyses clearly indicate that the EPC of 1.4µm pixel pixels is significantly limited by camera-motion and diffraction, specifically for high-tier mobile imaging systems with large sensor arrays. For example, the EPC for imaging systems with 1.4 µm pixels in a 1/3.2 inch sensor array is only marginally better at very high illumination levels and quickly drops below the EPC of larger pixels at lower illumination levels. In contrast, low-tier mobile imaging systems (1/8 inch sensor) with small pixels (1.4µm) retain an EPC advantage over larger pixels at much lower illumination levels.

For high-tier mobile imaging systems with zoom optics, the increased diffraction and camera-motion limits the EPC much more significantly than for systems without zoom optics. While optics with IS function can help increase the EPC at lower illumination levels, the pixel size must be much larger than 1.4 µm to offset the impact that diffraction limitations have on the EPC. On the other hand, optics with IS function can significantly improve the EPC for mobile imaging systems without zoom optics.

5.2 Future directions

Similar to other widely-used metrics in other imaging industries, the proposed "effective pixel count" or EPC metric combines the system MTF and SNR performance into a meaningful figure of merit. The EPC metric we propose in this paper uses a 50% cutoff frequency and an SNR threshold of 30dB. It is important, therefore, to investigate the relationship between users' perceptions of image quality and different thresholds for MTF and SNR. We also neglected demosaicking issues by assuming a monochrome pixel array. While we believe the results of monochrome pixel arrays serve as an upper bound on the performance of color sensor arrays, we would nonetheless like to understand the impact that different color filter array patterns and demosaicking algorithms have upon the PEPC. De-noising algorithms and electronic image stabilization methods also warrant further research as they directly impact the MTF and SNR of mobile imaging systems.

6. CONCLUSION

The mobile imaging industry is becoming increasingly aware that simply packing more pixels into the very limited camera module size does not necessarily improve image quality. In particular, the reduced pixel size along with smaller camera phone mass will introduce significant camera motion during image capture and thus reduce the effective spatial resolution of the captured images. The key question for the mobile imaging industry is how small pixel size can decrease before it has a negative impact on perceived image quality. To answer this question, we propose the "effective pixel count" (or EPC) as a metric to evaluate the relationship between pixel size and image quality performance. Similar to metrics used in other imaging industries, this metric combines the system MTF and SNR performance along with camera-motion. We use the EPC metric to analyze the design tradeoffs of four different pixel sizes (2.8µm, 2.2µm, 1.75µm and 1.4µm) for a high-tier (1/3.2 inch sensor) and a low-tier (1/8 inch sensor) mobile imaging system with or without zoom and image-stabilization (IS) function. The results show that a 1.4um pixel is not suitable for high-tier mobile imaging system due to limitations imposed by optical diffraction and camera motion. Mobile imaging systems with zoom optics also need much larger pixel sizes due to the effects of diffraction and camera motion. On the other hand, optics with IS function can significantly increase the EPC of mobile imaging systems and is necessary to address the big challenge of the small pixel.

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