Zooming in to Multi-Aperture Cameras

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Smartphone vendors' increasing efforts to make devices slimmer, are most strongly limited by the optical requirements of the main camera. More specifically, height limits of conventional optics prohibit the use of imagers larger than *1/3"*, which would result in severe degradation of image quality. In an attempt to increase the pixel count and reduce the pixel size while keeping the sensor area intact, the dynamic range reduces, noise levels increase and the perceived image quality is not necessarily improved. It is therefore appealing to consider other approaches for improving the image quality of mobile cameras, expanding their feature set and enriching the overall user experience, while keeping a slim camera module. To that end, array optics [1, 2] and computational cameras pave an alternative path to the common single aperture cameras. This paper reviews multi-aperture imaging systems in which multiple low-resolution images are combined into a single high-resolution image. It analyzes the resolution tradeoffs and limits of sub-pixel registration and super-resolution processes and proposes different paths for multi-aperture imaging systems. It is worthwhile to mention that there are other approaches for super-resolution and image upscaling, e.g., by transferring information between different image scales, using example database or recurrence of patches within the same image scale or a different image scale [3, 4]. These methods require specific assumptions on the image content, which do not always hold in practice.

Sub-pixel Super Resolution and its Gain

Let us consider an example of *NxN* multi-aperture camera (*N* being the number of apertures in each axis) that is based on an image sensor with *1.4um* pixel size where each aperture comprises *DxD* pixels. The goal of the super-resolution method is to reconstruct a high resolution image, preferably with *NDxND* pixels, with resolution equivalent to that of a single-aperture camera with a large *NDxND* sensor. Assuming each aperture is pointed at the same field of view, sub-pixel shifts among the captured images may result in resolution gain, namely super-resolution, when all the images are combined into a single image. Evidently, the actual shift between the images (disparity) varies and depends on the distance to the object (i.e., parallax), lens positioning, manufacturing tolerances and variations in the effective focal length. For the sake of our discussion, we will assume perfect sub-pixel shifts between the apertures, i.e., the shifts are linearly increasing integer multiples of *p/N* in each direction, where *p* is the pixel size.

Such approach requires the optics to support dramatically higher spatial frequencies, as if they are designed for a camera with a pixel size of *1.4um/N*. This is due to the assumed sub-pixel displacements between the different images that each aperture captures and the reconstruction process (super-resolution) that fuses the images into a single high-resolution image. If the optics' point spread function is much larger than the effective pixel size of *1.4um/N*, then super-resolution cannot be supported by the system. Thus, our analysis includes the resolving power of the optics that is associated with the system. Furthermore, we take into account the fact that each pixel averages light over a finite region, which is determined by the pixel's fill factor (including the effect of its micro-lens), acting effectively as a low-pass filter that limits the spatial resolution in the reconstructed image.

Assuming ideal *F/2.4* diffraction-limit optics, *80%* pixel fill-factor and perfect sub-pixel arrangement among the different apertures, we analyze the attainable resolution. This is illustrated in Figure 1, which includes the frequency response of the pixel, the optical MTF and their product that represents the overall frequency response of the system. Figure 1 shows that the resolving power of the system, i.e., its resolution limit (defined here as *10%* contrast, for which the signal is just above the noise, assuming average imaging conditions) is about *500lp/mm*, which is *1.4* times the sensor's Nyquist frequency (about *357lp/mm* in the case of *1.4um* pixels). This implies that the theoretical upper limit of the super-resolution gain is about *1.4* in each axis, translating to *1.96* times the number of pixels in each aperture, irrespective of the number of apertures (*N≥2*). Consequently, the super-resolution gain is highly dependent on the pixel size and reduces as the pixel size decreases (see Figure 2). The upper limit of the super-resolution gain is *2* (for very large pixels) and it diminishes to *1* for pixels smaller than *0.9um*.

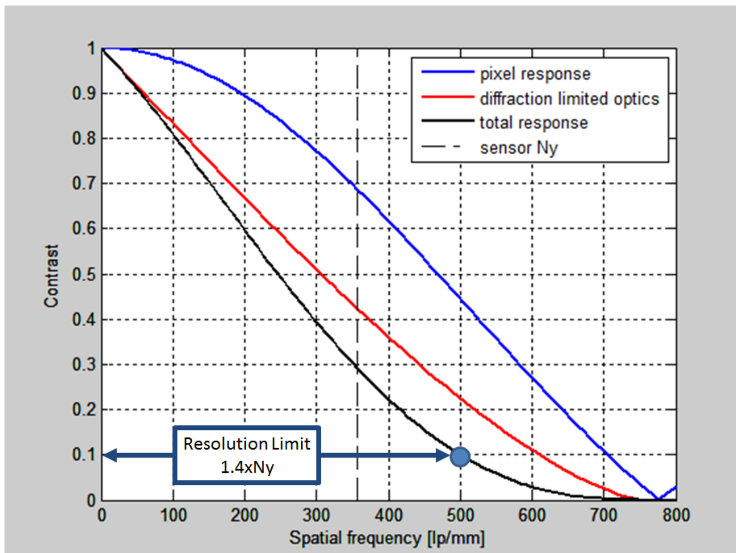

Figure 1: Effect of pixel fill factor and MTF on the resolution limit in multi-aperture imaging systems

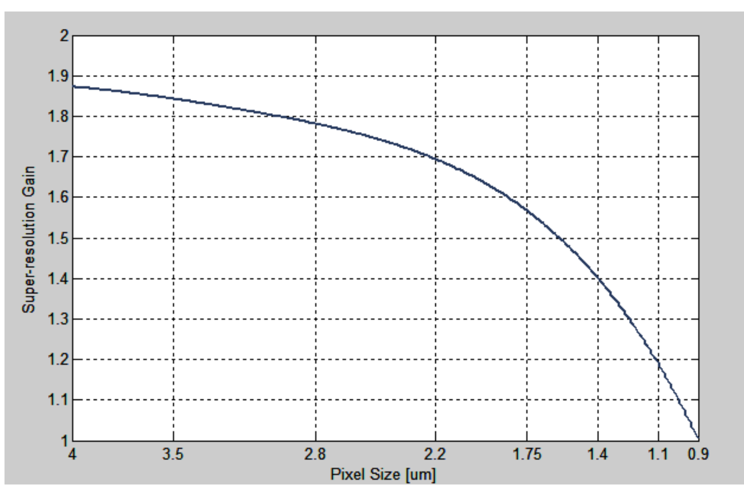

Figure 2: Effect of pixel size on the super-resolution gain in multi-aperture imaging systems

The above discussion solely relates to spatial resolution. It is interesting to note that additional benefits can be gained (e.g., noise performance, HDR, 3-D,…) when combining images from different apertures.

High-Resolution Dual-Aperture Imaging Systems

Assuming the total number of pixels (or sensor area) in an imaging system is fixed the analysis in the previous section led us to research dual aperture imaging systems, such as the one shown in Figure 3.

Figure 3: Dual-aperture camera

Depending on the application and implementation, such a camera can be *30%* thinner than single aperture cameras and can offer higher effective resolution and better SNR. Instead of relying heavily on sub-pixel shifts in the high-resolution image reconstruction process, we employed different color filter schemes in the different apertures prioritizing chroma resolution in one aperture and luma resolution in the other. As an example, one aperture is completely clear and the other aperture uses a special CFA with a repetition of a *3x3* macro-cell in which the color filter order is GBR-RGB-BRG (see Figure 4). This implies that the Red and Blue pixels are sampled at a higher frequency than in a Bayer CFA, and the luminance component is also sampled. The two images are fused to form a high-resolution image.

G	B	R	G	B	R	G	B	R	G	B	R
R	G	B	R	G	B	R	G	B	R	G	B
B	R	G	B	R	G	B	R	G	B	R	G
G	B	R	G	B	R	G	B	R	G	B	R
R	G	B	R	G	B	R	G	B	R	G	B
B	R	G	B	R	G	B	R	G	B	R	G
G	B	R	G	B	R	G	B	R	G	B	R
R	G	B	R	G	B	R	G	B	R	G	B
B	R	G	B	R	G	B	R	G	B	R	G
G	B	R	G	B	R	G	B	R	G	B	R

Figure 4: Color filter array using a 3x3 macro-cell

Compared with a single aperture Bayer camera, such variants of dual-aperture camera can result in high effective resolution and one Exposure Value (EV) difference in noise performance as seen in Figure 5.

Figure 5: Low-light scene – single aperture (left) and dual-aperture (right)

Furthermore, instead of recovering loss of resolution, we were looking for ways to further increase the effective resolution (compared with single aperture cameras) at the center of the field of view and by that obtain zooming functionality. Hence, we further designed and analyzed dual aperture systems in which the two apertures have different optics, which comply with predefined height constriction, and obtained a true continuous optical zoom with high SNR and resolution across the entire zoom range. Preliminary results are seen in Figure 6 and demonstrate the potential of this approach.

Figure 6: Digital zoom (left) vs. Dual aperture optical zoom (right)

Conclusions

In this paper the authors made an attempt to define the upper bounds on the one hand and to point out opportunities on the other hand of multi-aperture imaging. In particular, the paper shows new means to create new types of computational cameras with superior imaging performance (e.g., in low-light) and the qualities of optical zoom, a feature that exists in most compact DSCs and is absent in smartphones and tablets. To that end, the authors believe that carefully designed multi-aperture cameras are key to answer increasing demand for high quality imaging in mobile devices.

References

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