Smartphone Imaging Trends
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Sr. Smartphone Editor, AnandTech.com
Background

- B.S. - Optical Sciences & Engineering, University of Arizona
- Imaging Technology Lab with Steward Observatory
  - Worlds first curved front-illuminated CCD
  - ITL does BSI processing and characterization for CCDs used in astronomy, other photometric fields
- Thesis/Capstone: Terahertz GRIN Rapid prototyping
  - First THz GRIN objective cheaply fabricated on 3D printer
Background

- **AnandTech.com**, Founded in 1997 by Anand Lal Shimpi
- Smartphones to Servers and Everything in Between
- Everything is a Computer
- Strong Background and Emphasis on Components
- Understand the Pieces to Understand the Pie
Optics 101

- **Index of refraction** - n (unitless)
  - Material property - ratio of how much the speed of light is slowed in a medium

- **Wavelength** - $\lambda$ (m), **Frequency** - $\nu$ (Hz)
  - Essentially “Color”, Human Response 400 - 700 nm

- **Focal Length** - f (m), **Power** - $\phi$ (diopters)
  - Convergence or divergence of light from a system
  - Longer focal length - more magnification, lower focal length, less magnification
Optics 101

- **F-number** - F/# (unitless), F/# = f/d
  - Describes the size of the cone of light accepted by the system / light collection ability. Lower F/# - more light, equal to the ratio of the focal length to diameter of the entrance pupil
  - F-Stops - typically go in $\sqrt{2}$ steps (1.4, 2, 2.8, 4, 5.6) which changes light collection by factor of 2

- **Optical / Image Sensor Format** - eg. 1/3.2” (inches)
  - Sensor size, but nothing to do with sensor size. Originally vidicon glass tube diameter required for some other active imaging area size. Use table.
Optical Systems

- Many different optical systems
  - Rifle Scopes
  - Telescopes
  - Microscopes
  - Viewfinders
  - Illumination / Projection
  - Industrial / Science
  - Internet (Fiber/EDFA)
Camera Systems

- Approximation of the human eye
  - Human eye images field onto retina using crystalline lens which changes index as stretched (focus)

- Objective system
  - Form an image of a scene onto some plane, image a distant object, hence objective

Simple Objective

Telephoto Objective
Imaging Block Diagram

Scene -> Optics -> CMOS Sensor -> Image Signal Processor -> UI/OS/Saved JPEG

Thursday, February 7, 13
Video Block Diagram

- Same fundamental architecture, but with either a crop of the sensor or decimated version of output, then through an encoder for H.264/MPEG4. Encoder usually on SoC.

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Smartphone Context

- Smartphone camera systems have unique constraints
  - Very small throw (z-stack, module often thickest part)
  - Cost ($5-15 for module)
  - Limited materials (Almost always plastic)
  - Unique manufacturing (Aspheres - injection molding)
  - Horrible operating conditions (Every type of scene)
  - Small aperture (Battling ID of phone)
  - All while imaging onto tiny pixels (Impossible problem)
Smartphone Optical System

- Optics usually made of plastic, injection molded into aspheres (complex, nonspherical shapes). Limited to 2-5 elements (2P-5P). Glass uncommon.
- Optical plastics quite limited: Styrene, Polystyrene, ZEONEX, PMMA(Acrylic)
- Doublet: PMMA as Crown, Polystyrene as Flint
- Fixed focal length, fixed aperture (no iris), sometimes an ND filter, no shutter, usually not very fast (f/2.8, 2.4)
- Short focal length (wide), tiny image circle formed
# Example Lens List

*Blue color is new information.*  
*Parenthesis is temporary information.*

<table>
<thead>
<tr>
<th>Pixels</th>
<th>Sensor Size</th>
<th>Sensor Maker</th>
<th>Sensor</th>
<th>Lens Composition</th>
<th>Glass Thickness</th>
<th>Focal Length</th>
<th>CRA (H)</th>
<th>FOV (D)</th>
<th>F No</th>
<th>RI LH100%</th>
<th>Effective Image Circle</th>
<th>Mechanical</th>
<th>Screw Size</th>
<th>Study Design</th>
<th>ES MP</th>
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<tr>
<td>8.0Mega</td>
<td>1/2.9&quot;</td>
<td>Samsung</td>
<td>3H3</td>
<td>5P</td>
<td>0.3</td>
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<td>36.00%</td>
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<td>4.003</td>
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<td>73°</td>
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<td>7.454</td>
<td>1.186</td>
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</tbody>
</table>

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Example System

- “Lens system having wide-angle, high resolution, and large aperture” US 8320061 B2, Chun-Cheng Ko, Hon Hai Precision Industry Co., Ltd. (aka Foxconn)

- an aperture stop;
- a first lens of positive refractive power having a subject-side surface and an image-side surface;
- a second lens of negative refractive power having a subject-side surface and an image-side surface;
- a third lens of positive refractive power having a subject-side surface and an image-side surface; and
- a fourth lens of negative refractive power having a subject-side surface and an image-side surface;

<table>
<thead>
<tr>
<th>TABLE 3</th>
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<tbody>
<tr>
<td>F(mm)</td>
<td>F/No</td>
<td>2ω</td>
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<td>2.10</td>
<td>2.05</td>
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## Example Prescription

<table>
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<th>Surface</th>
<th>R(mm)</th>
<th>D(mm)</th>
<th>Nd</th>
<th>Vd</th>
<th>k</th>
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<tr>
<td>S0</td>
<td>infinity</td>
<td>0.13</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>S1</td>
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<td>1.54</td>
<td>56.1</td>
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<td>-1.02</td>
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<td>—</td>
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<td>S3</td>
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<td>0.30</td>
<td>1.63</td>
<td>23.4</td>
<td>-0.5019</td>
</tr>
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<td>—</td>
<td>—</td>
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<td>1.53</td>
<td>56.0</td>
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<td>—</td>
<td>—</td>
<td>-0.8953</td>
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<tr>
<td>S7</td>
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<td>1.53</td>
<td>56.0</td>
<td>-3.4234</td>
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<tr>
<td>S8</td>
<td>0.67</td>
<td>0.42</td>
<td>—</td>
<td>—</td>
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<tr>
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<td>1.52</td>
<td>58.6</td>
<td>—</td>
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<tr>
<td>S10</td>
<td>infinity</td>
<td>0.36</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Image plane 60</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</tbody>
</table>
Example 5P System (LG)

First Element

Final Assembly

Last Element
Lens then goes into a module
Camera Module

- Lens assembly
- VCM (Voice Coil Motor) - electromagnet / speaker which moves the lens to focus
- IR Filter / AA filter
- CMOS sensor
- Packaging and ribbon flex cable
- Drop that module into a phone
Imaging Block Diagram

Scene → Optics → CMOS Sensor → Image Signal Processing → UI/OS/Saved JPEG
## CMOS Sensor Trends

<table>
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<tr>
<th>Type</th>
<th>Diagonal (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Area (mm²)</th>
<th>Crop factor</th>
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<tbody>
<tr>
<td>1/4&quot;</td>
<td>4</td>
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<td>2.4</td>
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<td>10.81</td>
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<td>1/3.6&quot;</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>8.65</td>
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<td>3.42</td>
<td>15.5</td>
<td>7.61</td>
</tr>
<tr>
<td>1/3&quot;</td>
<td>6</td>
<td>4.8</td>
<td>3.6</td>
<td>17.3</td>
<td>7.21</td>
</tr>
</tbody>
</table>

- Rear CMOS size commonly around 1/3.2” or 1/4”
- Front CMOS smaller, but lower resolution 1/6”, 1/7”
- Size of CMOS sensors are relatively fixed, trend is more of smaller pixels
## CMOS Sensor Trends

<table>
<thead>
<tr>
<th>Generation</th>
<th>n-3</th>
<th>n-2</th>
<th>n-1</th>
<th>n</th>
<th>Future (?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size (µm)</td>
<td>2.2</td>
<td>1.75</td>
<td>1.4</td>
<td>1.1</td>
<td>0.7</td>
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<tr>
<td>Area (µm^2)</td>
<td>4.84</td>
<td>3.06</td>
<td>1.96</td>
<td>1.21</td>
<td>0.49</td>
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<tr>
<td>Area Ratio</td>
<td>1.00</td>
<td>0.63</td>
<td>0.40</td>
<td>0.25</td>
<td>0.10</td>
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<tr>
<td>Waves, λ (@ 700 nm)</td>
<td>~3</td>
<td>~2.5</td>
<td>~2</td>
<td>~1.5</td>
<td>~1</td>
</tr>
</tbody>
</table>

- Pixels : CMOS :: MHz : CPU - (MHz race, pixels)
- Pixels can’t get much smaller, or they’ll be sub one wave in size (weird quantum effects begin)
- >=5 MP (1.4µm), BSI is a necessity not just for sensitivity
BSI / FSI

* FSI - Traditional way of imaging onto a CCD/CMOS, through metal gating, incurring reflections

* BSI - Requires removing material using wafer scale chemical or abrasive lapping, image directly into active region of sensor. Significantly higher QE.
Dirty Secret - IT’S A LIE

- We can’t resolve pixels that small to begin with... Oops....

```python
from numpy import *
from scipy import *
from pylab import *

f = 3.63E-3 # 3.63 mm focal length HTC One system
b = 1.4E-6 # 1.4 micron standard modern pixel size, 1.1 newer, 1.65 micron older
fno = 2.0 # HTC One S F/2.0

fnos = linspace(1.2,2.8,100) # HTC One - F/2.0, iPhone 4S - F/2.4, SGS3 - F/2.6
bscale = linspace(0.7E-6,1.65E-6,100) # Range of pixel sizes

zh = - f**2 / (b * fnos); # hyperfocal distance
zn = zh / fno # nearest point in focus (hyperfocal/2)
diff = (2.44 * 700E-9 * fnos)/1.0E-6 # airy disk first zero diameter 84% energy here
deltazprime = 4.88*700E-9 * fno ** 2
deltaz = (4 * deltazprime * f ** 2) / ((deltazprime)**2 - 4*(f - 3.7E-3)**2)

cla()
clf()
plot(fnos,diff)
title('Airy disk diameter as a function of F-Number')
xlabel('F/#')
ylabel('Spot size in microns')
savefig('fnosspotsize.png')

cla()
clf()
plot(fnos,zn)
title('Hyperfocal distance as F/#')
xlabel('F/#')
ylabel('Hyperfocal dist')
savefig('hyperfocalfixedpixel.png')

cla()
clf()
zh2 = - f**2 / (bscale * fno); # hyperfocal distance fixed f=2.0
plot(bscale/1.0E-6,zh2/2)
title('Hyperfocal distance as pixel size')
xlabel('Pixel size (microns)')
ylabel('Hyperfocal dist')
savefig('hyperfocalfixedfnos.png')
```
Dirty Secret - IT’S A LIE

- Airy Disk - Assumes perfect optics, limited only by diffraction (ideal system)
- Rayleigh Criterion - camera example, before two points blur together
- Can’t resolve that pixel size! Oops.
Hyperfocal distance

Distance after which everything is in focus
Imaging Block Diagram

Scene → Optics → CMOS Sensor → Image Signal Processing → UI/OS/Saved JPEG
ISP - Image Signal Processor

- ISP usually onboard SoC, sometimes discrete
- ISP Roles
  - Demosaicing - Sensor just senses photons, need Bayer color filter atop sensor to determine color. RGBG / GRGB, interpolate to RGB for each pixel.
  - 3A - Autofocus, Autoexposure, Autowhitebalance
  - Correction for lens imperfections - Lens shading, geometry/distortion, vignetting, try to fix image
  - Noise reduction, filtering, HDR, cleaning up, JPEG
  - This is the controller for CMOS / Focus assembly
Imaging Block Diagram

Scene → Optics → CMOS Sensor → Image Signal Processing → UI/OS/Saved JPEG
Camera UI/UX

- Minimalist to highly customizable
- Still evolving, Many still making horrible mistakes
  - Low res/fps preview, wrong preview, broken UI, not enough controls, laggy
- Smartphone platform again unique - needs balance of speed and simplicity to be successful
Same fundamental architecture, but with either a crop of the sensor or decimated version of output, then through an encoder for H.264/MPEG4. Encoder usually on SoC.
Video Encoder

- Usually on SoC, sometimes external
- Takes frames from CMOS, encodes to format of choice
  - Example Exynos 5 Dual: Multi-format Video Hardware Codec: 1080p 60fps (capable of decoding and encoding MPEG-4/H.263/H.264 and decoding only MPEG-2/VC1/VP8)
  - Imagination Technologies, Qualcomm, TI, Others
- Not all are born equal. OEMs frequently not using full potential
- 15-20 Mbps H.264 1080p30 High Profile = Current
Video Block Diagram
Quality - What do you mean?

- Image “sharpness” - MTF (Modulation Transfer Function) or FT of PSF (Point Spread Function)
  - What is the highest frequency that can make it through the optical system before contrast reverses
- Aberrations - 3rd order and higher (wavefront error)
  - Spherical
  - Coma
  - Astigmatism
  - Field Curvature
  - Distortion

Cutoff frequency: \[ v_0 = \frac{2NA}{\lambda} = \frac{1}{\lambda(F/\#)} \]
Aberrations

- No system is perfect - good design balances out aberrations with other aberrations
- Center of field is easy, most aberrations blow up strongly at edge of field (by square or cube)
- Sphere not the perfect shape, ellipse is
Chromatic Aberration

- Axial chromatic aberration
  - Each color comes to focus at a different point, because materials refract different colors differently
- Transverse chromatic aberration
  - Each color is deviated differently laterally on the image plane
- Fix with Achromatic doublet
Things to look for

- Scrutinize extreme field angles
- Distortion
- Chromatic fringing
- Loss of contrast (MTF falling off)
- Vignetting
- Lens shading correction errors
- Test charts - objective measures
- Don’t always tell full story
Things to look for
Things to look for
Things to look for
Things to look for
Things to look for
Things to look for

- Processing related
  - Aggressive noise reduction (loss of high frequency details to smooth regions of chroma/luma noise)
  - Sharpening kernels (halos around high frequency regions to artificially increase sharpness)
  - Moire (artifact of bad demosaicing algorithms)
  - Too much compression (artifacts)
  - Missed focus
  - Bad AWB, unnatural colors
MB vs MPs

- 4000+ images from smartphones - statistical analysis

Thursday, February 7, 13
MB vs MPs
Smartphone Imaging

- Smartphones rapidly displacing and disrupting traditional P&S market. Connected camera and smartphone blurring together
  - Smartphone OEMs without P&S business at disadvantage
- Imaging performance still volatile, changing each gen.
- Miniaturization approaching limits of physics
  - Needs computational photography techniques to improve beyond limits
- It’s incredible smartphone cameras are as good as they are now