The Computational Array Camera

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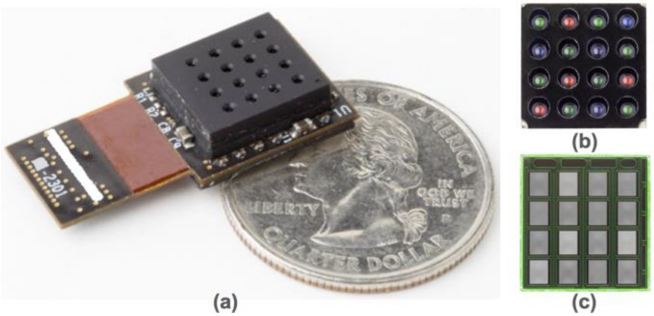


The Camera – past and present

Modern camera evolution

Current consumer camera

Some "computational" features can be added w/o HW modifications (e.g., HDR, video super-resolution, generating panoramas)

*The theoretical **plenoptic camera** captures all information at a point in space*

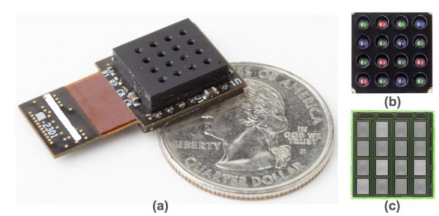
Practical, lower-dimensionality computational camera instantiations

Stanford Array

Lytro

Lytro Illum

Pelican Imaging



Raytrix R11

R&D scope for computational imaging

- Plenoptic image acquisition
  - Camera design, calibration, syncronization
  - Space/time sampling, optimal sampling (aliasing?)
  - Typically, huge amount of data are generated
- Plenoptic processing
  - Reconstruction of imaged scene data, plenoptic representations for specific purposes, feature generation and associated apps (e.g., depth map and usage)
  - Coding (for storage, transmission, display)
  - Formats
- Plenoptic signal communication
  - Transport issues (e.g., error resilience) specific to this domain
  - Bandwidth!
- Rendering/displays, printing
  - Display devices (to take advantage of new imaging capability)
  - 3D printing

Outline

- The plenoptic function
- Computational cameras as codecs
- The Pelican Imaging array camera

The plenoptic function and its parameterizations

The plenoptic function

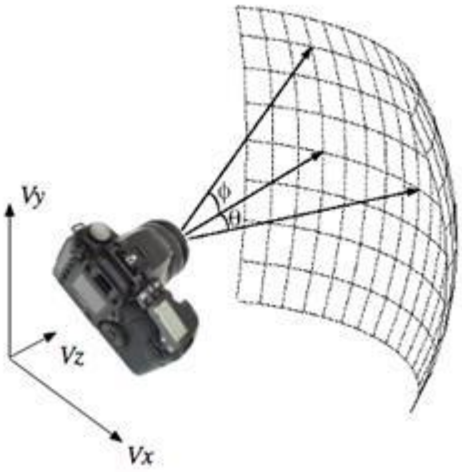
- The *plenoptic function* was introduced formally in [Adelson 1991].
  - Describes all light information collected at a point in space-time

- The plenoptic function is originally a 7D function,

$$f(V_x, V_y, V_z, \Theta, \Phi, \lambda, t)$$

where

- V_x, V_y, V_z viewpoint coords.
- Θ, Φ ray direction
- λ wavelength
- t time

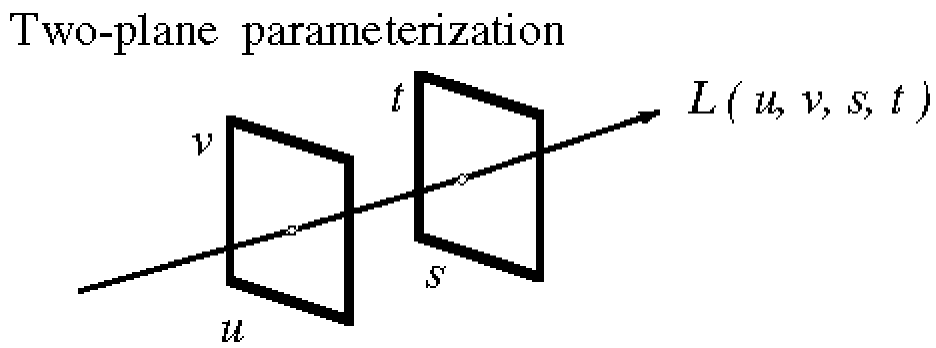


- By fixing various parameters in the plenoptic function, one obtains more restrictive representations.

Of particular interest:
4D Parameterization of Light Field

- Integral photography [Lippmann 1908]

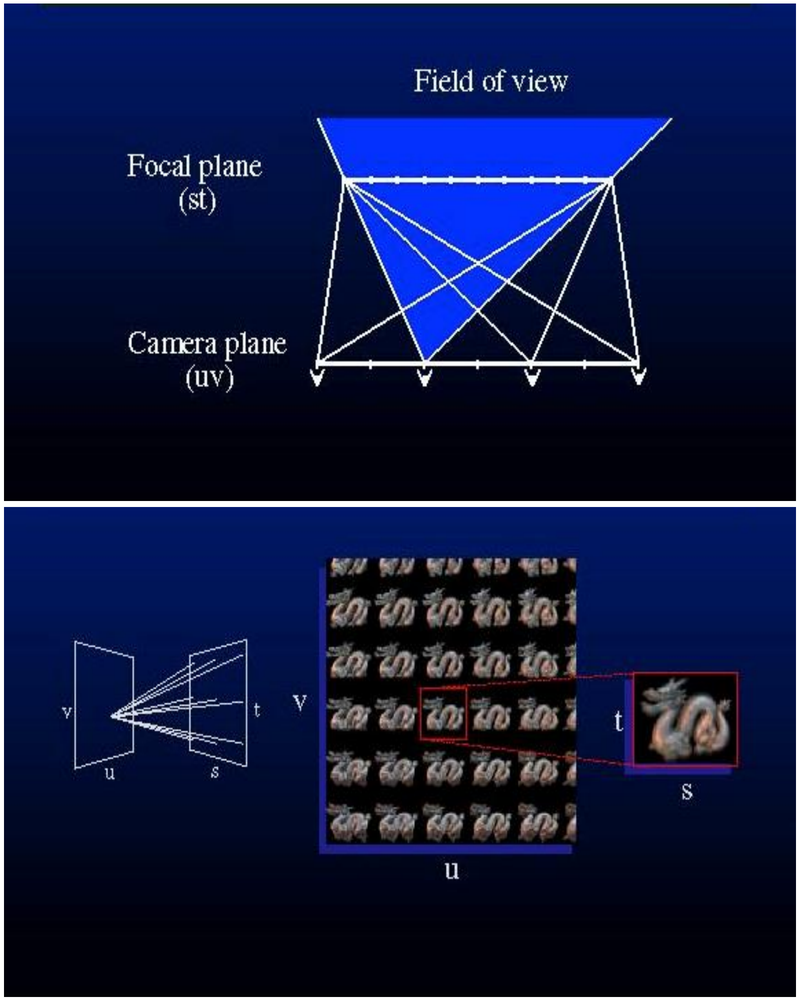
- Light fields are 4D parameterizations of the plenoptic function
  - Light Fields [Levoy 1996] and Lumigraphs [Gortler 1996]: a ray is indexed by its intersection with two parallel planes.



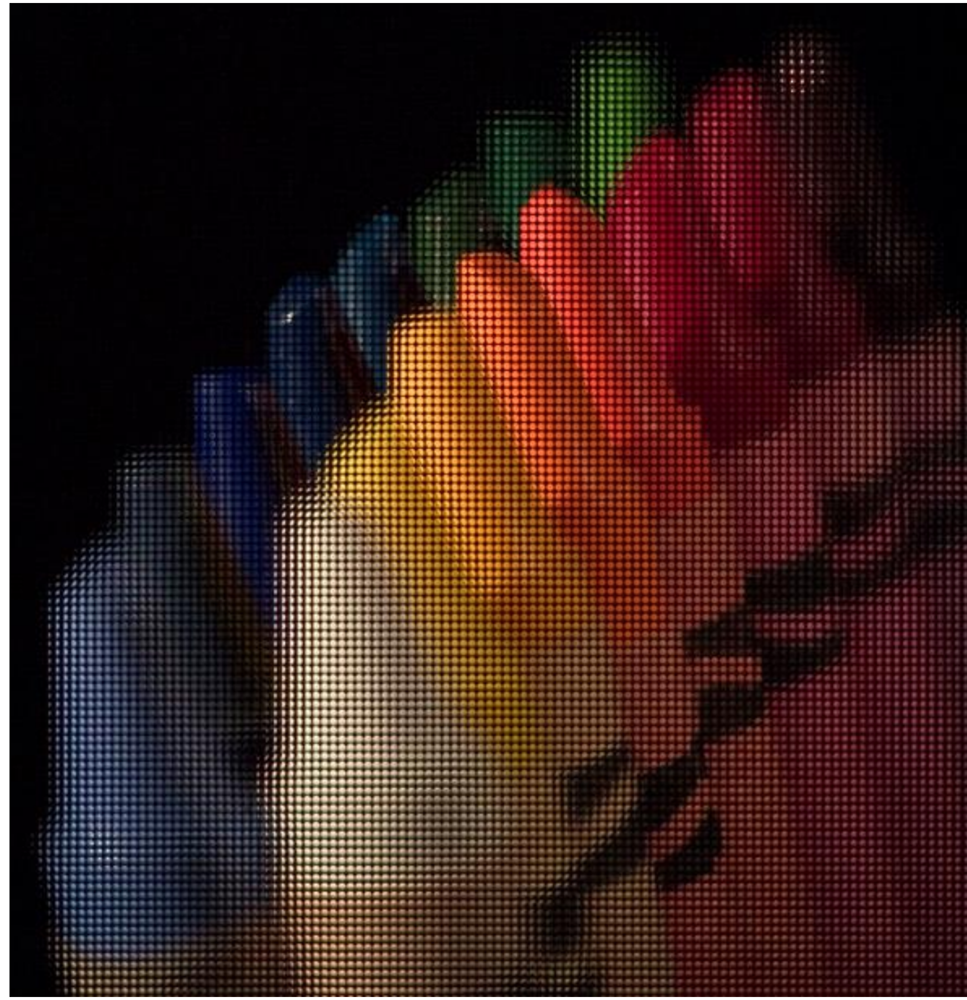
  - Assumption of space free of occluders (to reduce from 5D to 4D); six pairs of planes surrounding the convex hull of the object being imaged

4D Light Field capture

- Spatio-angular capture, whether
  - of the main lens image, using a microlens array (like a relay-lens system) near sensor
  - of the scene, using lens arrays



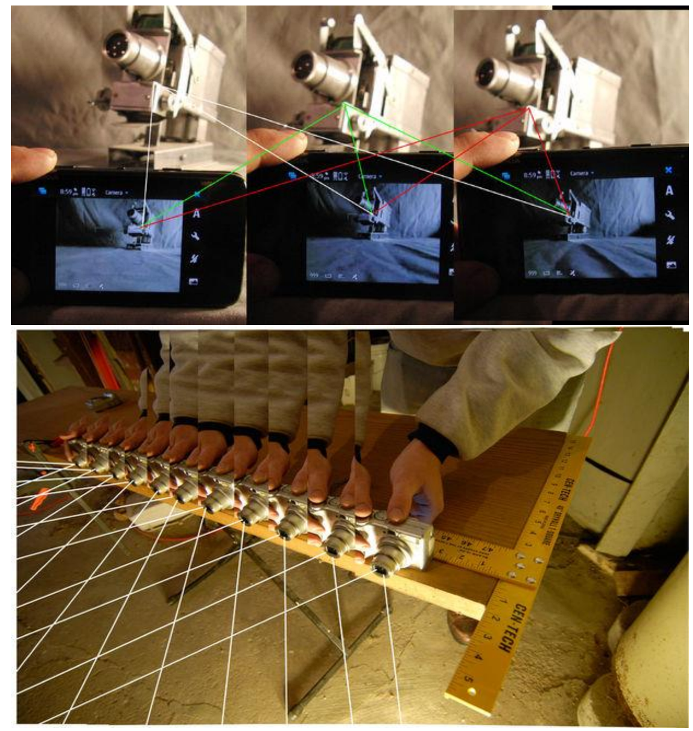
[Levoy 1996]



[Ng 2005]

Brief overview of computational cameras*

* Extensive literature available, this is a sparse sampling



Credit: http://www.instructables.com/id/DIY-Camera-Array-1-Computational-Photography-Prim/

Computational camera as codecs

- Optics and/or camera structure (e.g., case of arrays) “encode” the imaged scene in various ways

- Typically, the closely-adapted digital processing “decodes” the information to produce the desired features of the computational camera

- (As usual, an image/video codec may be inserted between the two, esp. given the volume of data that may be generated).

Computational camera codecs (contd.)

- Aspects of such devices can just as well be cast in the language of information theory

- E.g.,
  - what constitute "good" views of the scene?
    - Viewpoint entropy [Vasquez 2001],

$$I = -\sum_{i=1}^{n} \frac{A_i}{A_t} \log \frac{A_i}{A_t},$$

where n is the number of facets of objects seen in the scene,
A_i is the projected area of face *i* over the sphere centered at viewpoint
A_t is the total area of the sphere

  - how "efficient" is the information transfer across acquisition & processing

  - efficient source coding of generated data, e.g., MPEG-4 Part10 predictive Multiple View Coding (MVC), or "just-in-time" (JIT)-decode representations (e.g., [Lelescu 2004])

The “encoding” of acquisition: Approaches [1]

- Object Side Coding
  - Involves an optical element attached to a conventional lens
  - Examples include:
    - Catadioptric Lenses (Lens + mirrors) [Chahl 1997, Baker 1999, Lelescu 2002]
    - Bi-prism Stereo [Lee 1998]

- Pupil Side Coding
  - Involves an optical element attached to the pupil plane of conventional lens
  - Examples include:
    - Cubic Phase Plates [Dowski 1995]
    - Coded Aperture [Levin 2007]

The “encoding” of acquisition: Approaches [2]

- Focal Plane Coding
  - Involves an optical element placed close to the sensor/detector
  - Examples include:
    - Pixel-wise control of exposure [Nayar 2003]
    - Use of microlens arrays [Adelson 1992], [Ng 2005], [Lumsdaine 2009], [Georgiev 2010],
    - Attenuation masks [Veeraraghavan 2007]

- Illumination Coding
  - Spatial or temporal control of flash to code captured images
  - Examples include:
    - Robust 3D using space-time stereo [Zhang 2003]
    - High speed 3D reconstruction using structured light, e.g., [Gong 2010]
    - Kinect [Microsoft]

The “encoding” of acquisition: Approaches [3]

- Camera clusters and arrays

- No optical coding need be involved, but “coding” occurs due to information capture across individual cameras
  - Additional coding may involve high-frequency scene information captured in phase-offset aliased array images

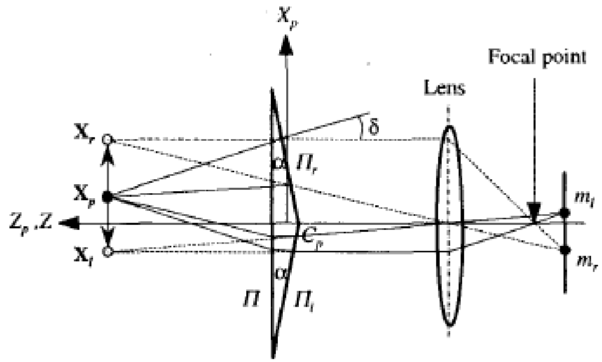
- Examples include:
  - Multi-baseline stereo [Okutomi 1993]
  - TOMBO array [Tanida 2001]
  - Flexible Camera Arrays [Nomura 2007]
  - Stanford Camera Array [Wilburn 2005]

  - Pelican Imaging Camera Array [Venkataraman 2008]

The encoding of acquisition:
A few category examples

Object Side Coding

- E.g.,
  - Bi-prism stereo [Lee 1998]



  - Catadioptric omnidirectional capture and processing [Lelescu 2002]

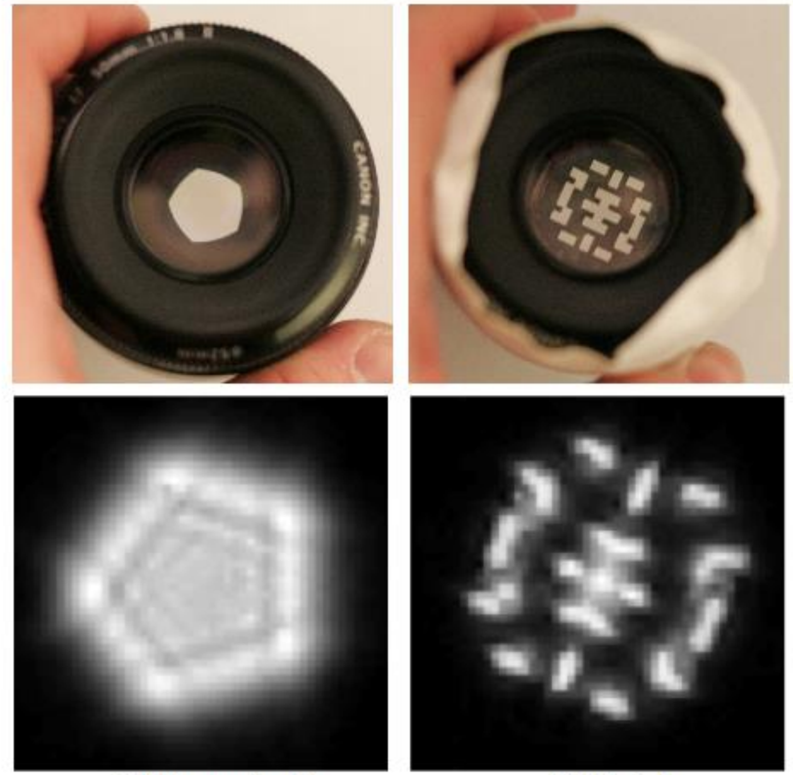
Pupil Side Coding

- Extended depth of field (EDOF) through wavefront coding, e.g., [Dowski 1995]
  - A standard optics is modified by a phase mask
  - The phase mask alters the wavefront such that point-spread function does not change appreciably

- Phase-mask optics "coupled" with a deconvolution process enable a large-DoF image recovery , since the blur kernel is largely invariant with distance, e.g., on-sensor EDOF solution [Lelescu 2009].

Pupil Side Coding [Levin 2007]

- Patterned occluder within the aperture of the camera
  - Creates a coded aperture
  - The aperture filter can now discriminate between depths
- Recover the scale of the blur which allows one to
  - Determine the depth (since the scale of the blur is dependent on depth)
  - Recover the image by inverting the blur at each depth level



(a) Conventional (b) Coded

Figure 3: Left: *Top, a standard Canon 50mm f/1.8 lens with the aperture partially closed. Bottom, the resulting blur pattern. The intersecting aperture blades give the pentagonal shape, while the small ripples are due to diffraction.* **Right**: *Top, the same model of lens but with our filter inserted into the aperture. Bottom, the resulting blur pattern, which allows recovery of both image and depth.*

Focal Plane Coding [Adelson 1992]

- By placing a lenticular array close to the sensor plane of the main lens, the resulting 'plenoptic' camera provides depth cues

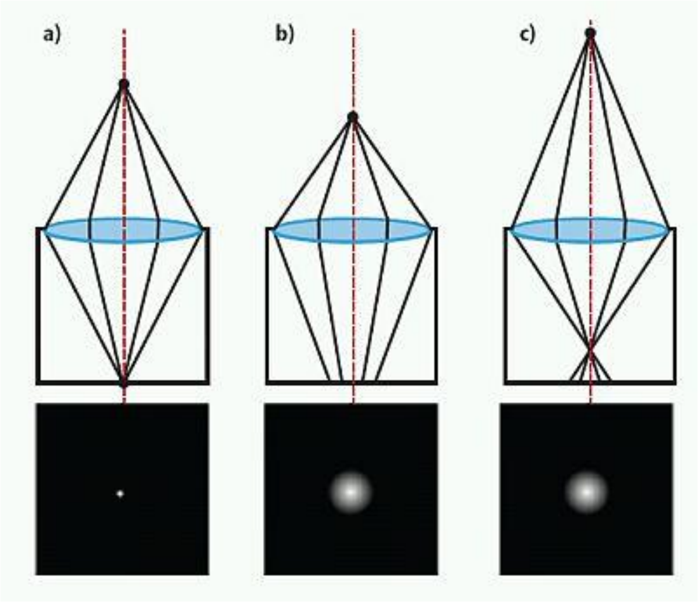


FIGURE 1. In a conventional camera, only a 2-D image is captured at the sensor plane. Because of this, it is impossible to tell whether the point being imaged is further from or nearer to the image plane

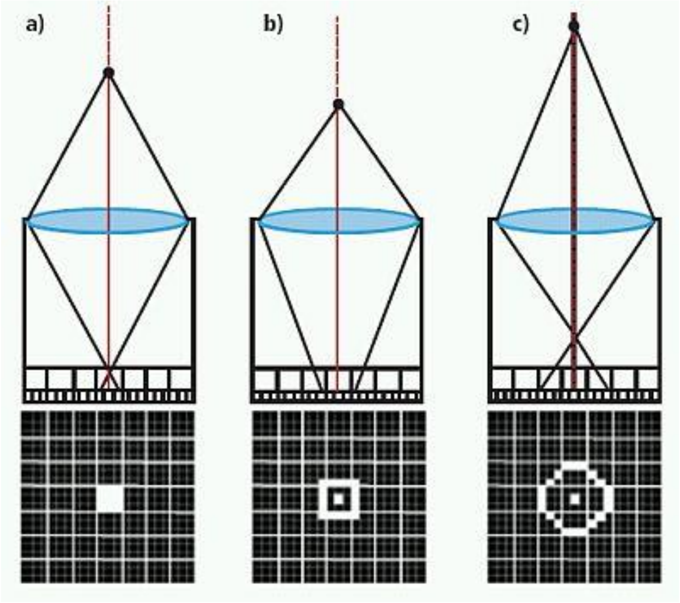
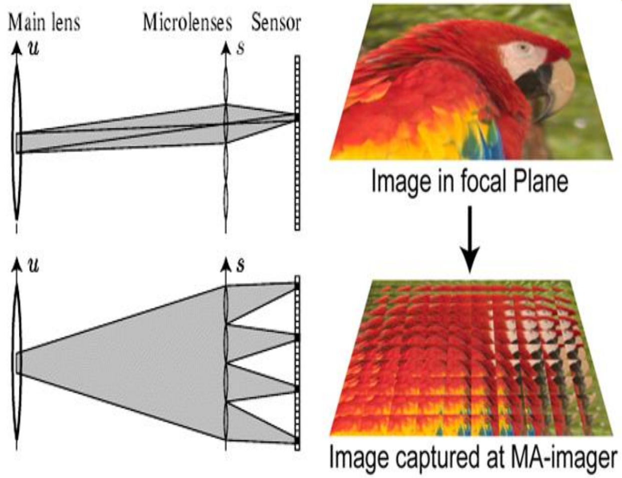


FIGURE 2. In a plenoptic camera, an array of microlenses is used to sample the angular information of light rays. When the object is out-of-focus point, a blurred spot is formed on the microlens array, but depending on the incident angle of the light, different pixels will be illuminated.

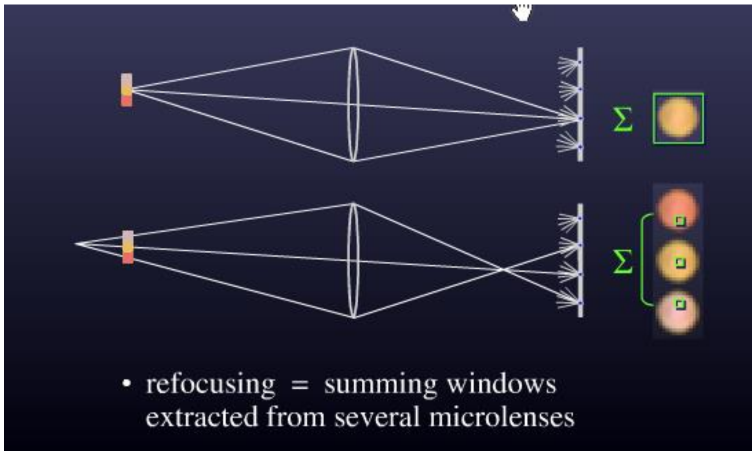
Focal Plane Coding (contd.)

- Spatio-angular sampling using a microlens array: Plenoptic camera [Ng 2005]; Focused plenoptic camera [Lumsdaine 2009], [Georgiev 2010]
  - Differences in focusing the main lens image and the microlenses → differences in reconstruction and render resolution

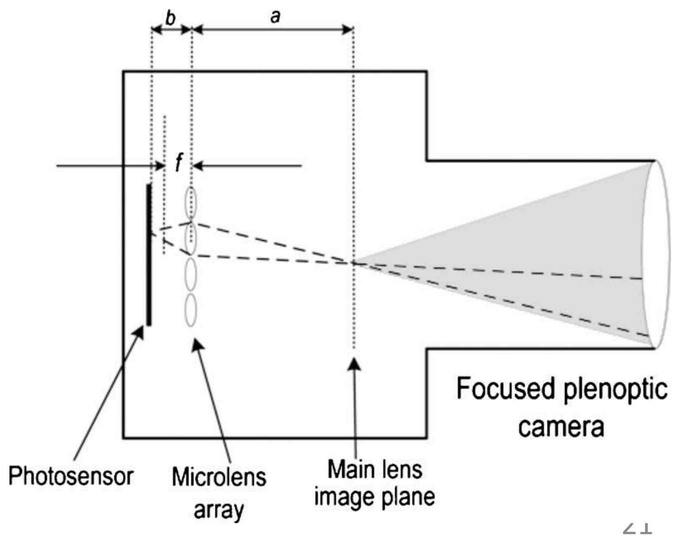
[Ng 2005]



- For example, in plenoptic camera [Ng 2005]
  - Image: integrate within microlens sub-images
  - Refocusing the image:



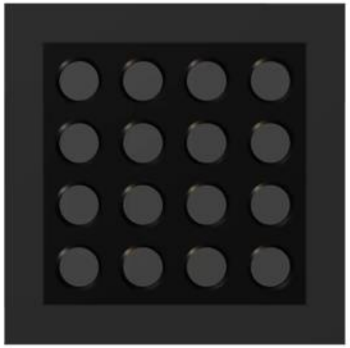
[Georgiev 2010]



Camera clusters – Virtualized Reality [Rander 1997]

- A Gantry (or Dome) is built to house cameras at different points of view
- The cameras capture multiple points of view
- Synthesize intermediate views from positions on the gantry, or from points inside the convex hull of the gantry

PI Computational Array Camera (PiCam)



Venkataraman, K., Lelescu, D., Duparré, J., McMahon, A., Molina, G., Chatterjee, P., Mullis, R., Nayar, S. (2008). PiCam: an ultra-thin high performance monolithic camera array. In *ACM Trans. Graph. 32(6):166*.

What can an array camera do?

- Features
  - Small form factor (very thin, e.g., 3.5mm) computational camera
  - Restore higher resolution imagery from low-resolution input – super-resolution (SR) – a balanced angular vs. spatial resolution (in 4D)
  - Virtual viewpoint (whether native res., or further super-resolved)
  - Dynamic focus; post-capture refocus/synthetic aperture; re-lighting, etc.
  - Natively co-located (RGBZ) depth map
    - Consumer depth-driven applications, depending on design
  - Video from an LF camera, can use depth features for applications
- The balancing of strengths in the multi-feature "star-graph" is part of design constraints. Some trade-offs have to be made (no free lunch)
- Camera instantiations can be built, with different combination of features and trade-offs.

Building computational cameras: stepping stones

- Computational camera design typically more complex than traditional camera
- Level 1: proof of concept design/simulations, more limited, controlled-condition testing
- Level 2: physical emulation or build, and more extensive testing, but not "consumer-grade", e.g.,
  - small number of cameras built, may use manual or per-image/class tuning
  - manufacturing tolerances
- Level 3: full-fledged camera module, meant for field operation, e.g.,
  - large numbers of cameras built, extensive testing
  - robustness is paramount, manufacturing tolerances
  - stable adaptive tuning to practically uncontrolled imaging conditions
  - (self-diagnosis/correction in the field)

Building computational cameras (contd.)

- New HW challenges for an array camera, e.g.,
  - Performance and tolerances of components
  - New composite metrics, and tolerances for the array
  - Alignment techniques

- Critical to design jointly the Encoder (acquisition HW) and Decoder (digital processing)
  - Approach/algorithms/assumptions that will function within design constraints, and achieve desired functionality

  - Develop solutions from classes of advanced statistical signal processing approaches (esp. able to account for modeling/characterization uncertainties)

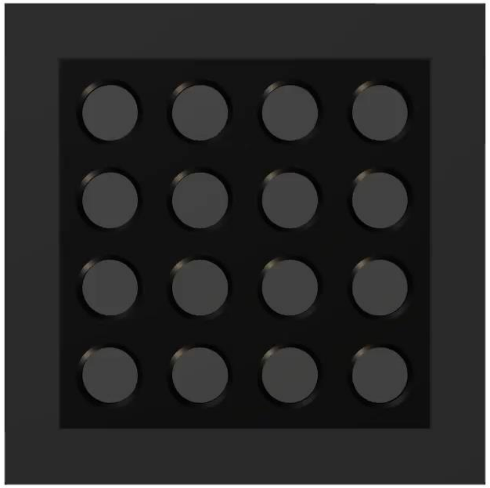
What does the array camera "encode"?

- Geometry and intensity information in 4D (u,v,s,t):
  - Depth information (disparity, in image space)
    - Decode: Geometric registration and parallax detection
  - High frequency information above sensor Nyquist (if so designed) in the form of phase-offset aliased input data → super-resolution decoding
    - Can be used (even at varying strength) to complement other features, e.g., refocus, virtual view, etc.
  - Dynamic range information (exposure bracketing in array)
    - For "single shot" HDR
    - Decode: HDR reconstruction

Sample considerations for PiCam design

- PiCam HW (“encoder”): Optics, sensors (and module integration)
- PiCam SW (“decoder”) Core processing
  - Parallax detection
  - Super-resolution
- PiCam SW applications

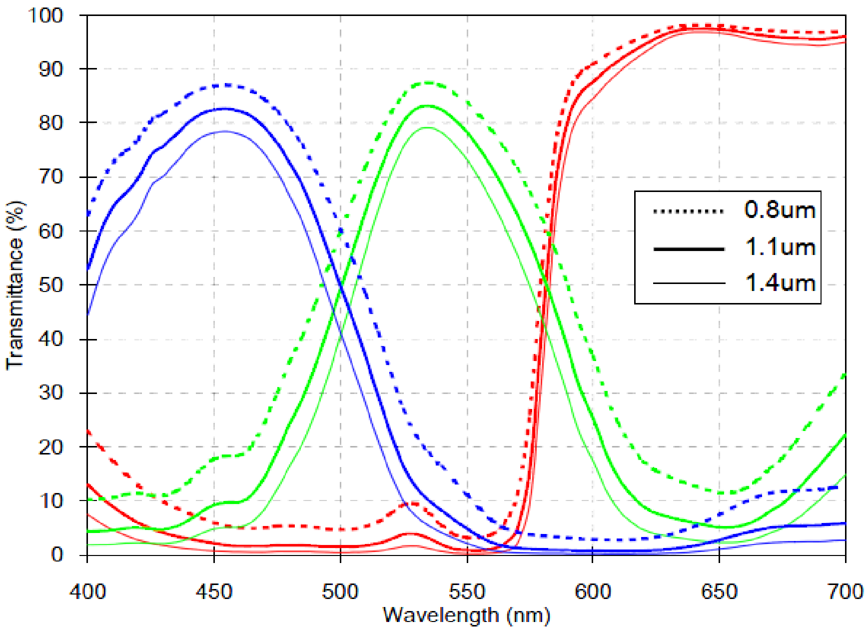
Encoder: Camera module structure



Encoder: Sample design considerations:Optics

- Each channel can be designed for a narrower spectral band
  - Small bandwidth – less achromatization needed, or better performance with the same effort
  - Separated color channels – each channel can be focused properly
- Small optical format reduces aberrations and influence of form errors

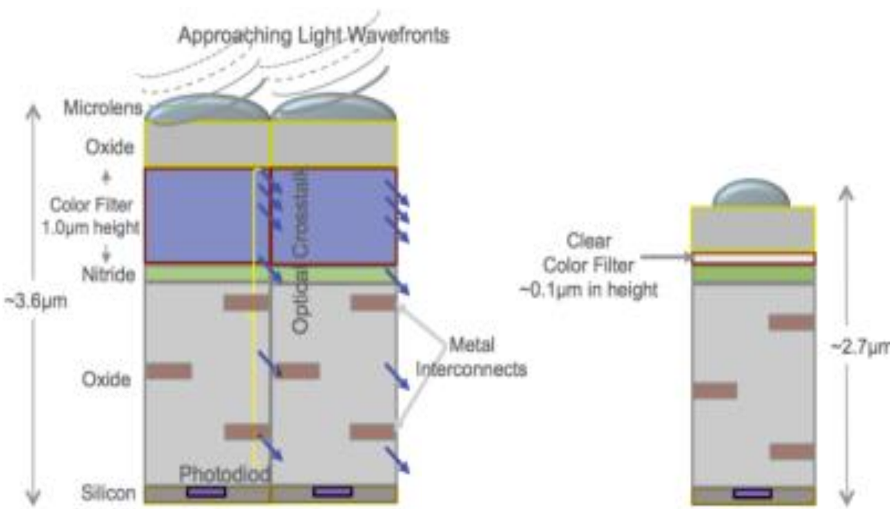
FUJIFILM CFA

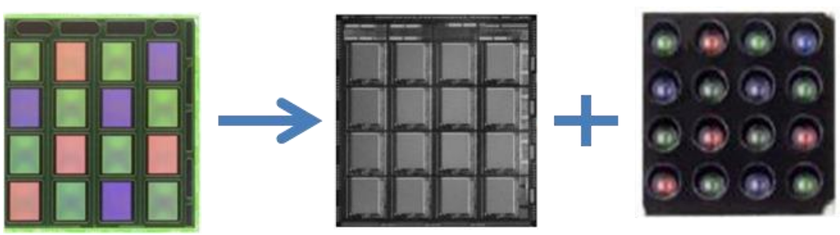


Example: monolithic lens array

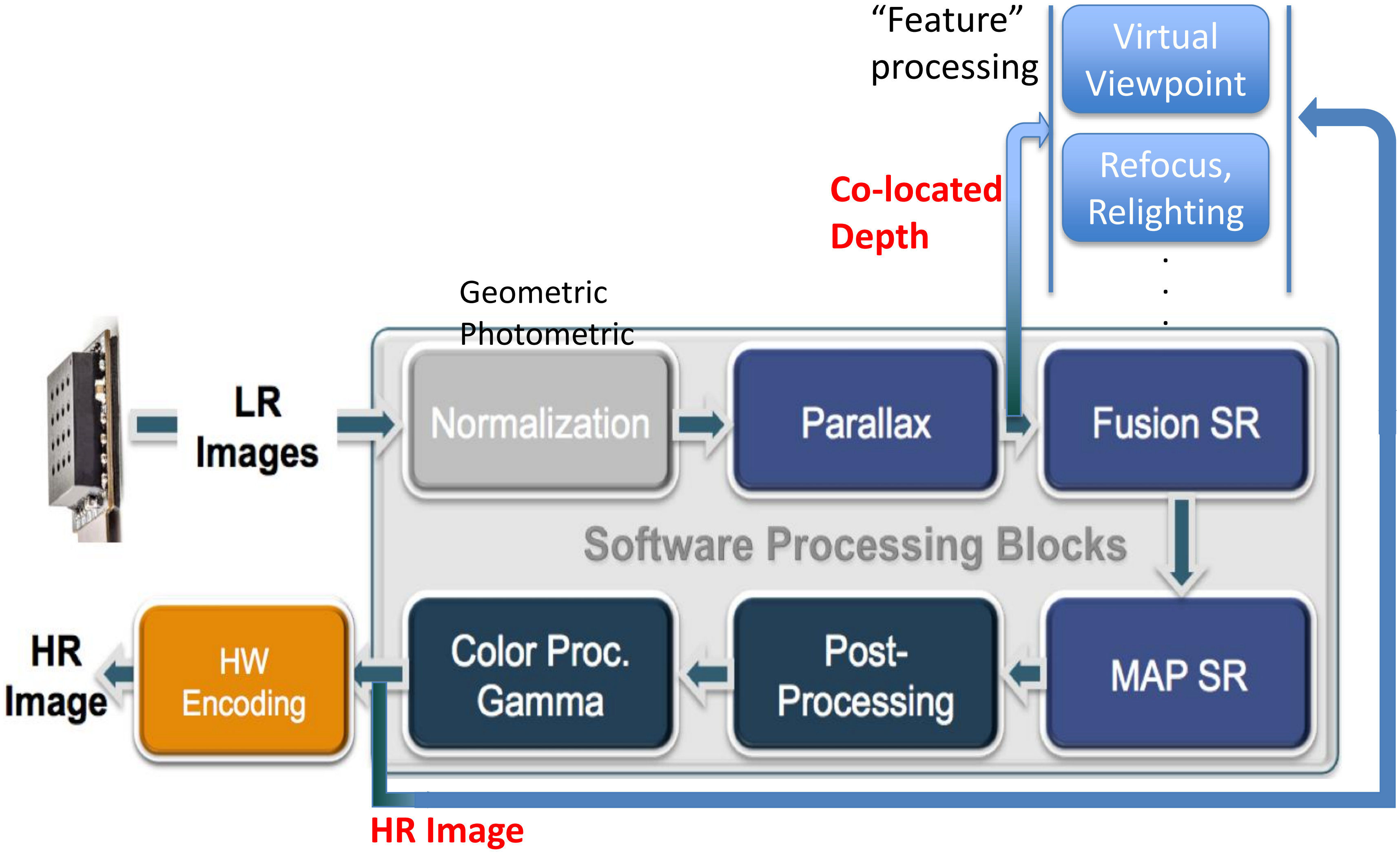
Encoder: Sensor Design

- In the case of a Bayer-pattern, the CFA is deposited on the pixels.
- Once each focal plane is monochrome the filter can be moved from sensor to the lens !
- Benefits:
  - Cheaper lithography & material
  - Reduced pixel stack height → increased pixel MTF (less crosstalk)





Decoder: High-level core- and derived- functions



"Decoding" depth:
Parallax detection & regularization

- First level: joint (multi-camera) parallax detection, multi-channel (e.g., RGB)
  - Spatial arrangement of Color Filters (cameras) very important (occlusion handling)

- Second level: refinement through a "visibility processing" reasoning
  - Basically, verify validity of initial result by testing the obtained geometry against array constraints

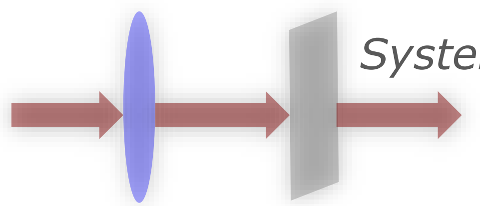
- Saves more geometry {u,v,s,t} information for the subsequent "uncertainty processing" (or hypothesis testing) in the MAP reconstruction

- For certain applications, a further depth –map regularization may be performed to fill in missing data.

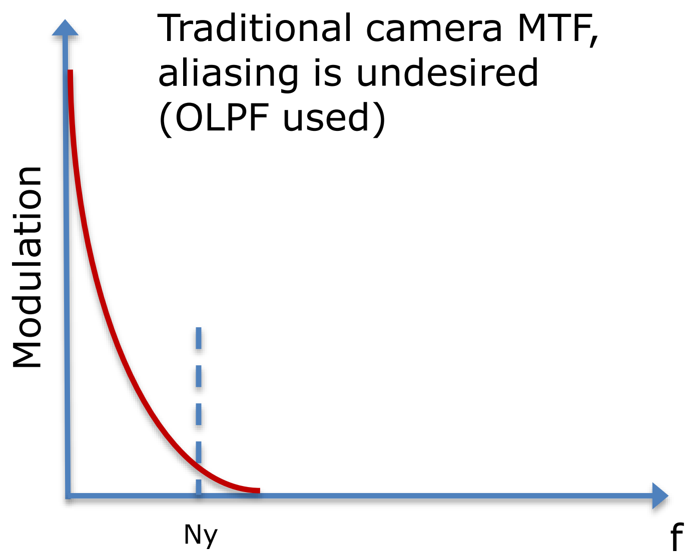
Example: Depth map (w/ confidence map)

Decoding: Recovering resolution

- The resolution is a function of multiple parameters, including
  - Optical Format of each camera in array
  - Number and arrangement of cameras
  - F/# (determines diffraction limit), aberrations, and resulting OTF of optics
  - Pixel size (sampling rate, aliasing)
  - Sensor MTF
  - Super resolution factor



$$System_{MTF} = Optics_{OTF} \times Sensor_{MTF}$$



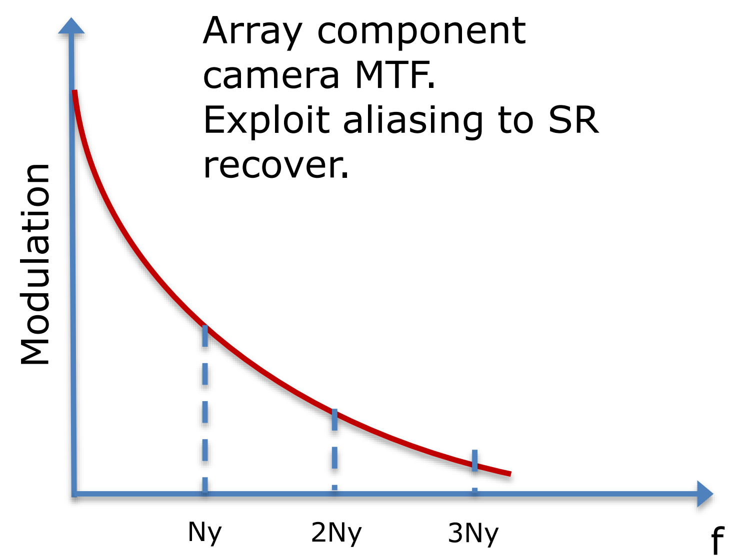
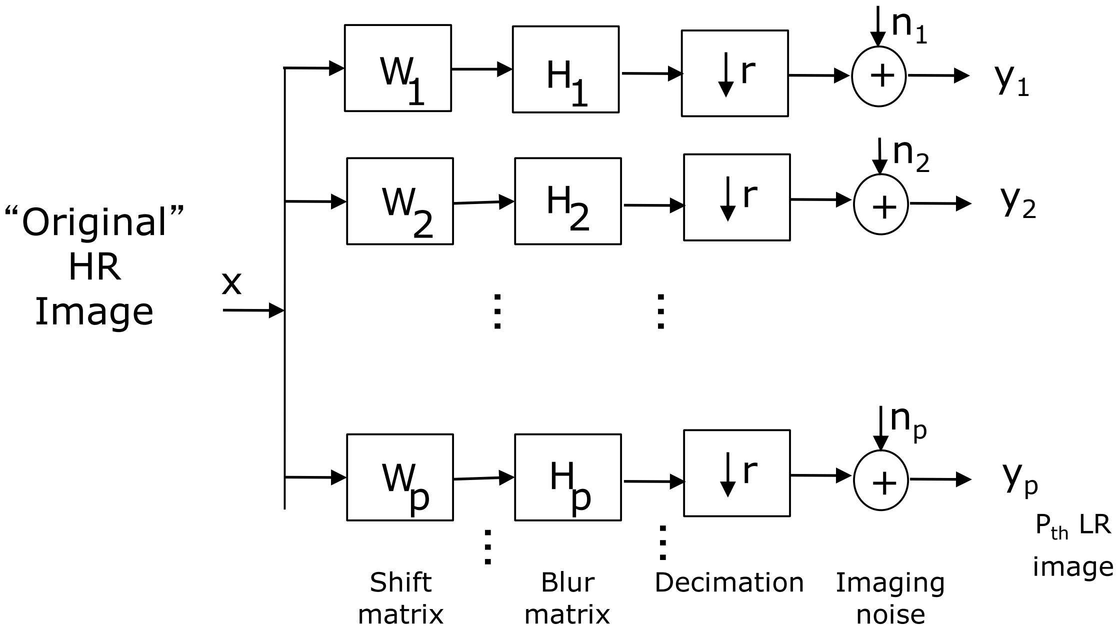


Image reconstruction: modeling, and uncertainties



Observed "Degraded" LR images

recover

$$\Rightarrow \mathbf{y}_p = \mathbf{D}\mathbf{H}_p\mathbf{W}_p\mathbf{x} + \mathbf{n}_p$$

✓ ✓ ✓ ? ? ∿

- Important to model, characterize, or determine "degradations":
  - multiple blurs (e.g., optics, sensor)
  - geometry (e.g., scene-independent distortions, scene-dependent parallax)
  - Noise (both imaging, and impact of cumulative estimator noise)

- Trust (to some degree) but verify:
  - The processing design starts with built-in assumption of uncertainties → most appropriate statistical models adopted → toward robust functionalities

Decoding: Super-resolution reconstruction

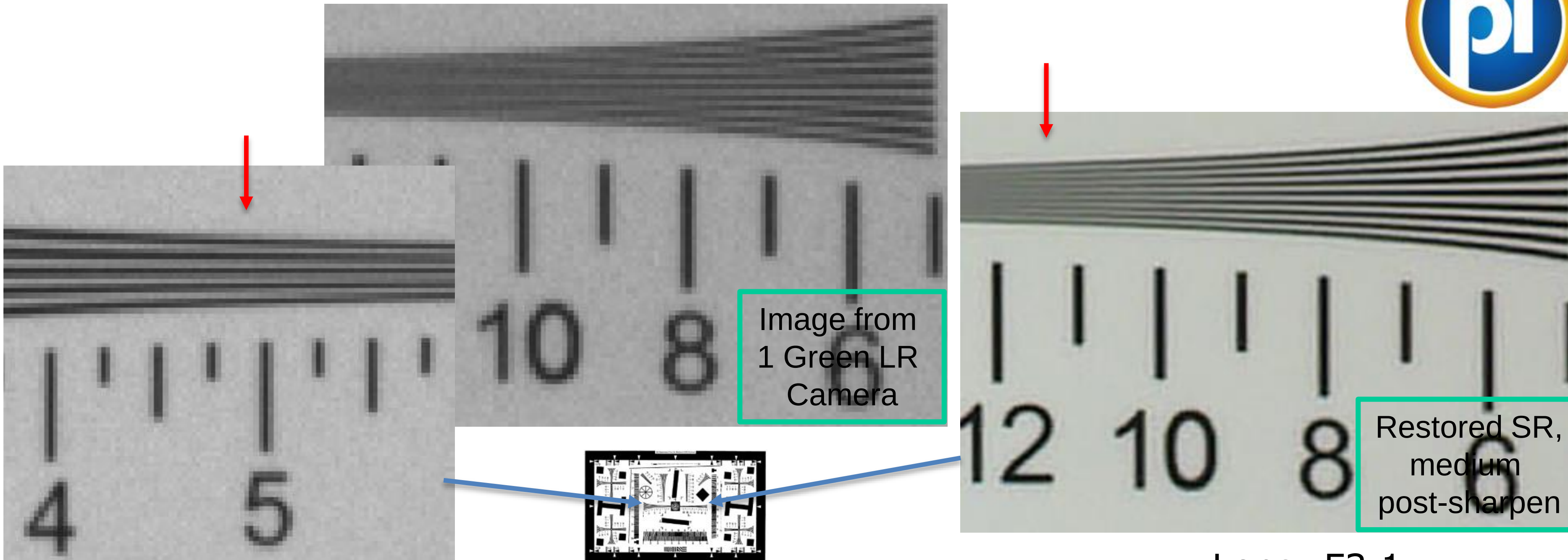
- Leverage Bayesian philosophy
  - No "turn-key" solution; needs dedicated derivations

- Probabilistic models incorporate general, and system-specific priors
  - Optics characteristics – e.g., PSFs, geometry
  - Sensor – e.g., MTF, Noise
  - Array geometry

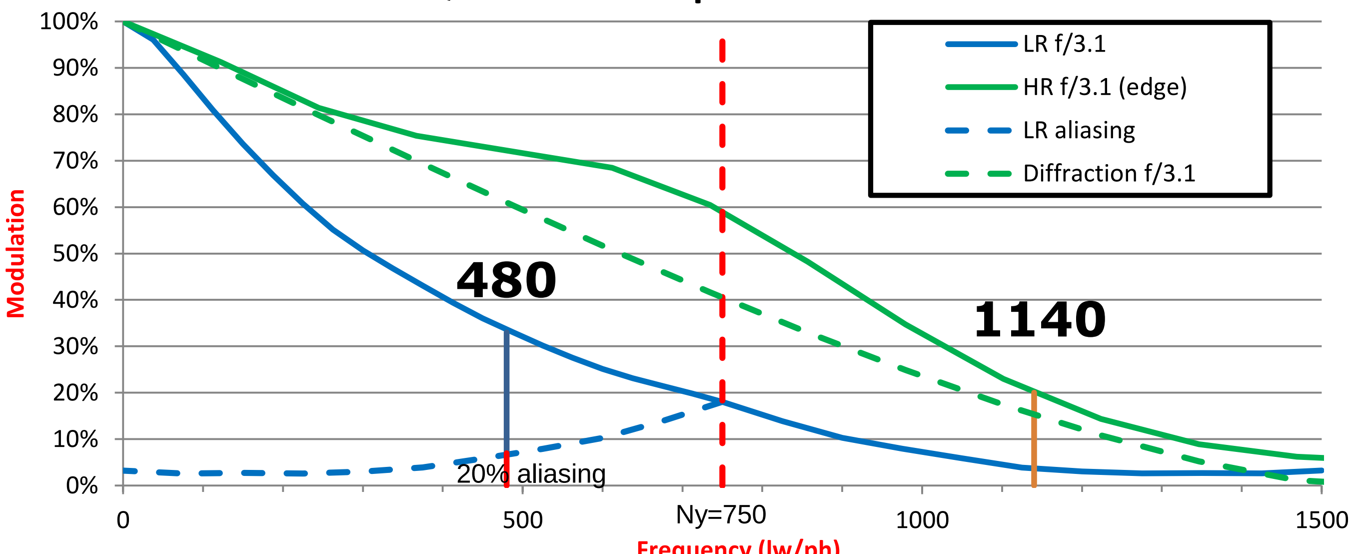
- A MAP (maximum a-posteriori) restoration approach provides a powerful unified framework for processing
  - Addresses uncertainty from prior stages (e.g., parallax, normalization)
  - Stabilizes solution

- Cross-channel fusion of Red/Blue channels, along with selective transfer of weighted MAP-gradients from Green
  - Could optimally be done "inside the loop", but more expensive

“Decoder”: The Super-resolution reconstruction (contd.)



Quantitative super-resolution – ISO 12233 chart



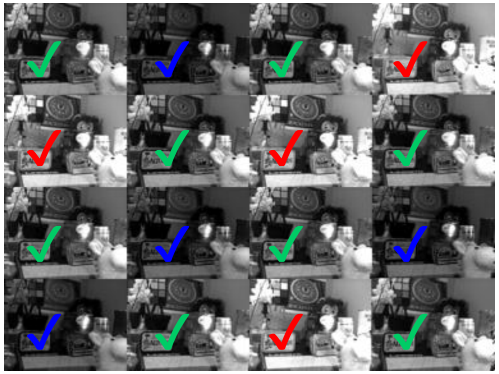
Lens: F3.1
Array: 16 cams
1000x750 each
1.75µ pixels

By this aliasing measure (*percent aliasing* & *visual*):
SR Factor
1140/480=2.4

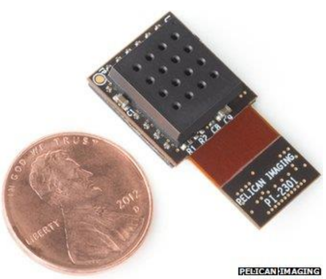
Other measures are possible, as long as applied consistently

“Decoder”: Reconstruction animation

COLOR RECONSTRUCTED



PiCam: More examples and applications



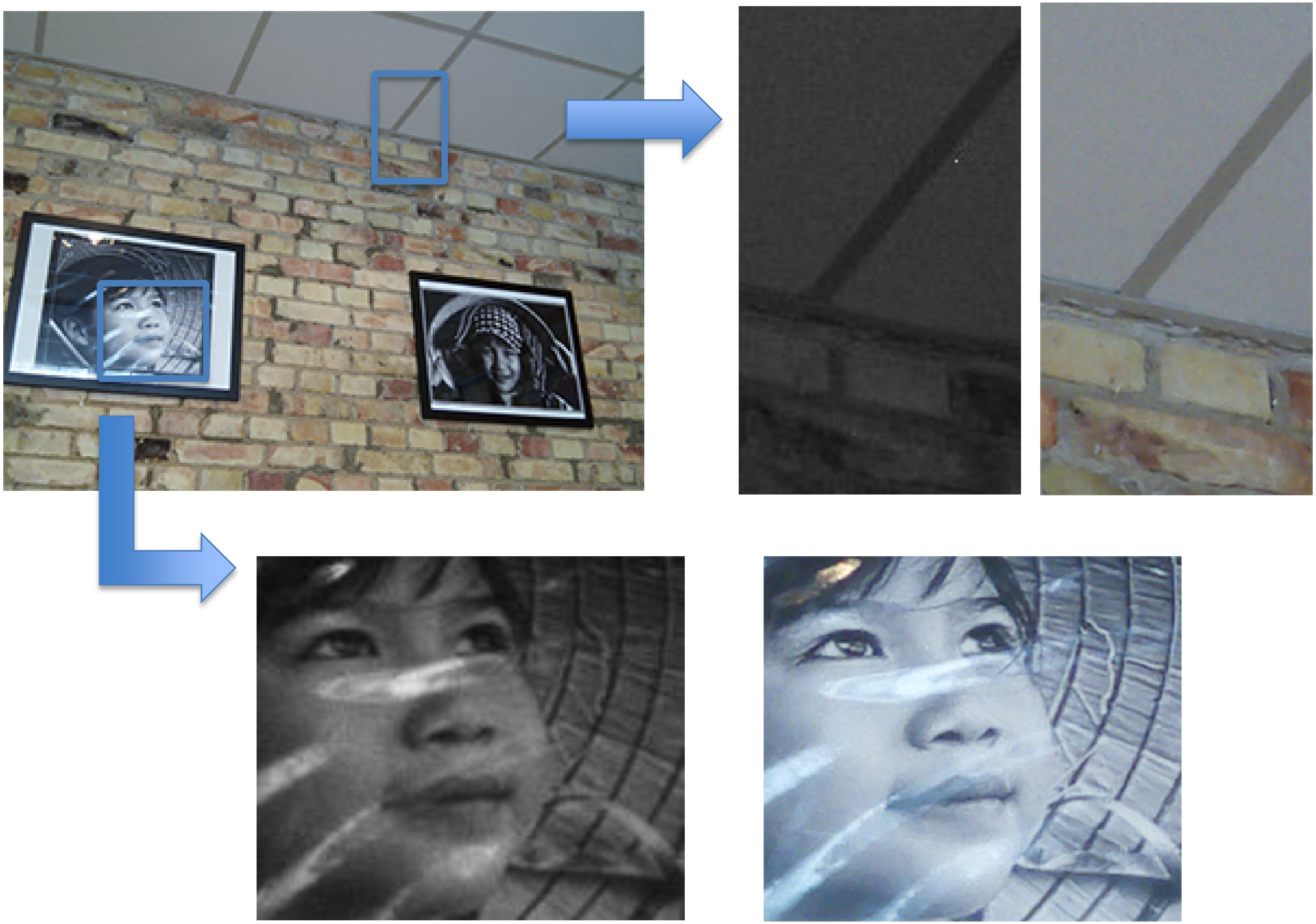
Reconstruction

Reconstruction

Single subarray low-res image

Super resolved image

Reconstruction (indoor, higher noise)

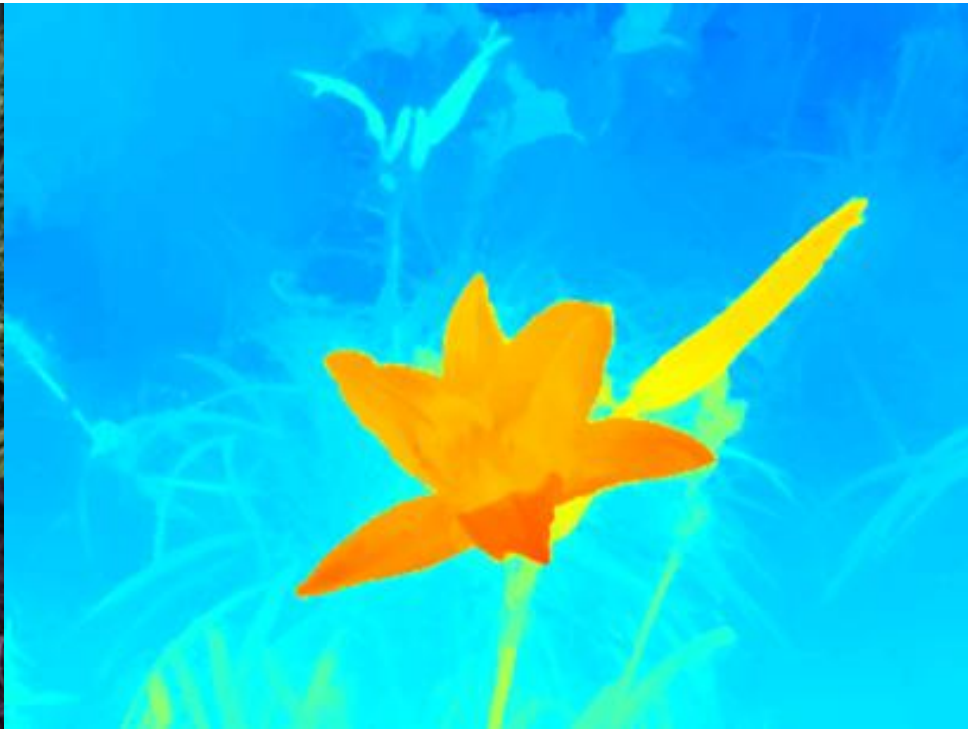


Reconstruction (far)

Reconstruction, DoF/resolution comparison

Depth map + regularization (outdoor depth)

Input Image

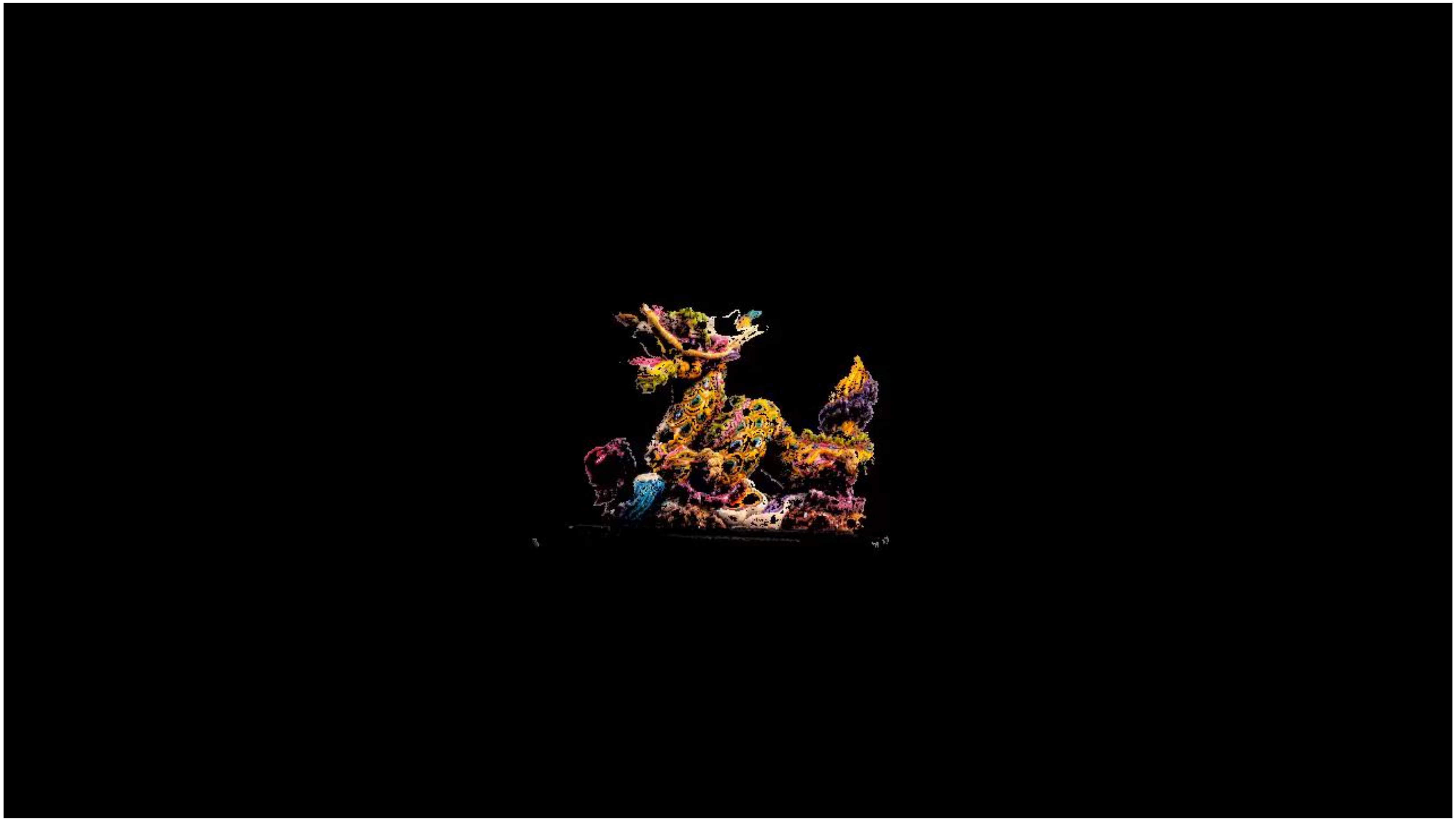


Regularized Depth

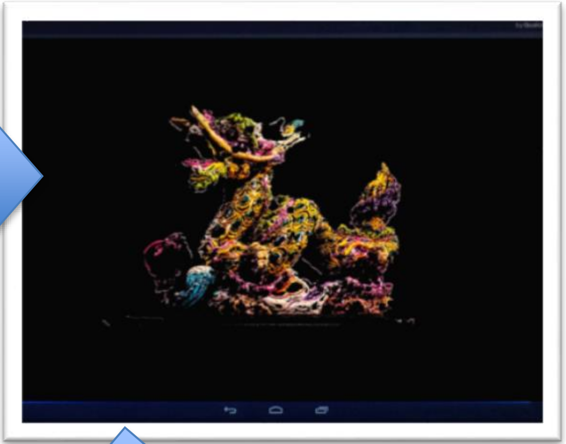
Applications: Refocus

Applications: Re-Lighting

Applications: Point clouds (capture at 10-15cm)



Future applications: Close object scan



Summary

- Computational cameras
  - Can provide set of unique/interesting/useful features
  - Ongoing efforts to bring them to consumer

- Array camera
  - Core functionalities:
    - Provides depth
    - Higher-resolution than that of individual component camera
  - Form factor adapted to application domain (including very thin, mobile form-factor camera)
  - With higher computational budgets, more (or increased quality) features could be offered in an even small form factor.

More information at
www.pelicanimaging.com

Thank you

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