

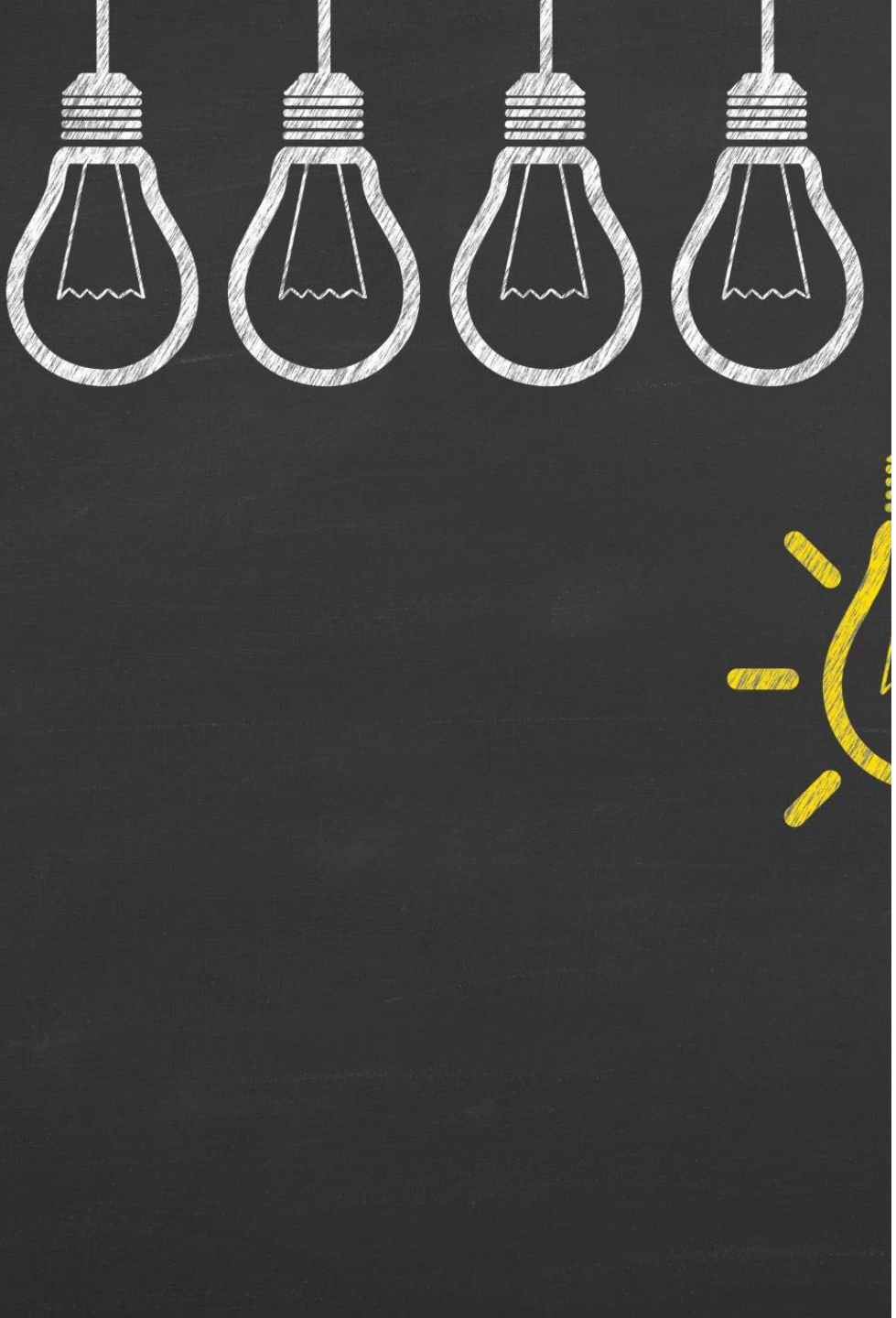
Displays with Integrated Microcamera Arrays for Image Capture and Sensing

Paper 54-2

May 2021

David Slobodin

IdeaFarm



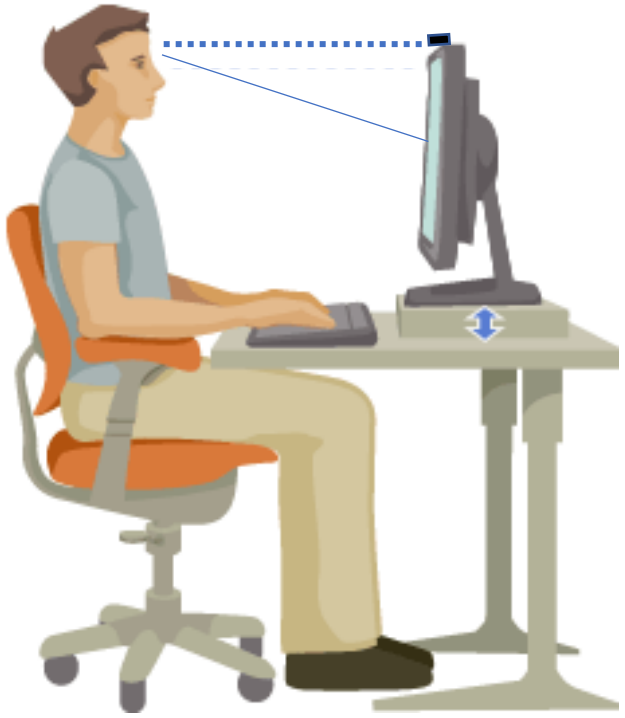
Displays with Integrated Microcamera Arrays for Image Capture and Sensing

1. Motivation and background
2. Implementation and modeling results
3. New functionality
4. Conclusions and future work

Motivation and Background

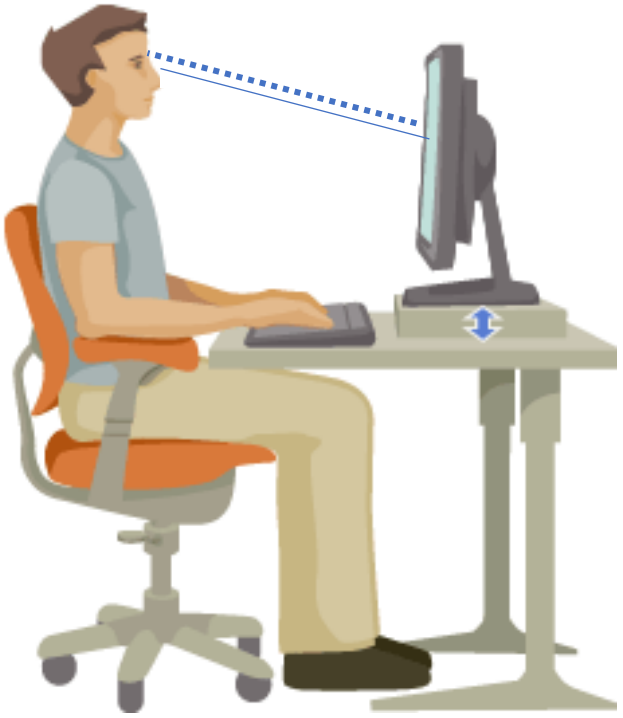
The Gaze Parallax Problem

Camera is center top of the monitor



Conventional desktop videoconferencing where camera axis is not coincident with viewing direction – poor eye contact

Camera is in the display



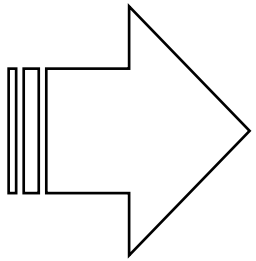
Display with embedded cameras enables effective camera axis to coincide with viewing direction – good eye contact

Maximize Display Area

Front-facing camera cut out or bezel

Mobile Phone

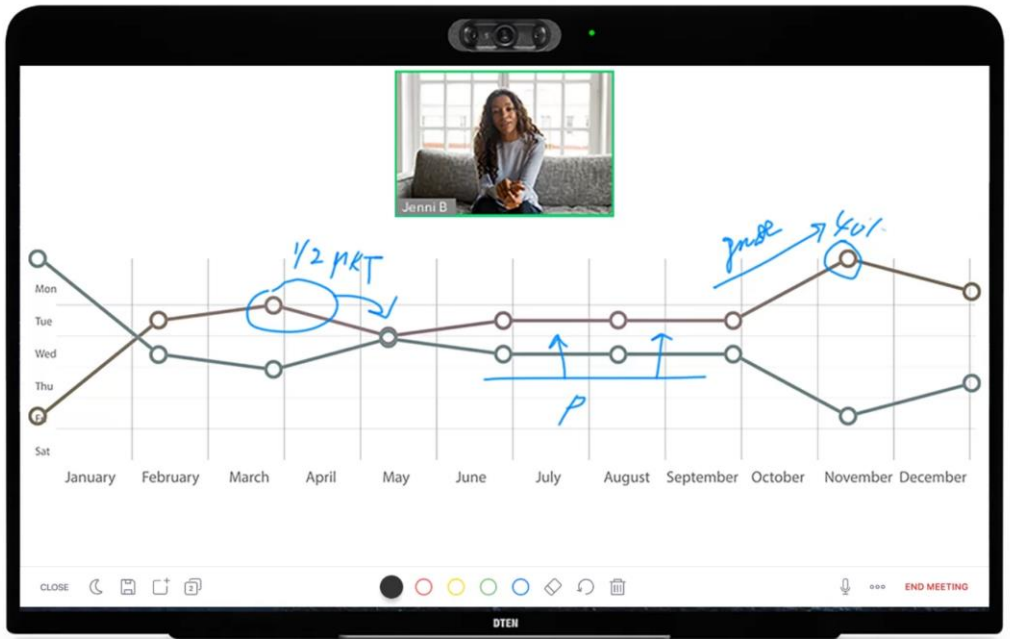


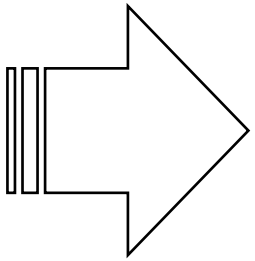


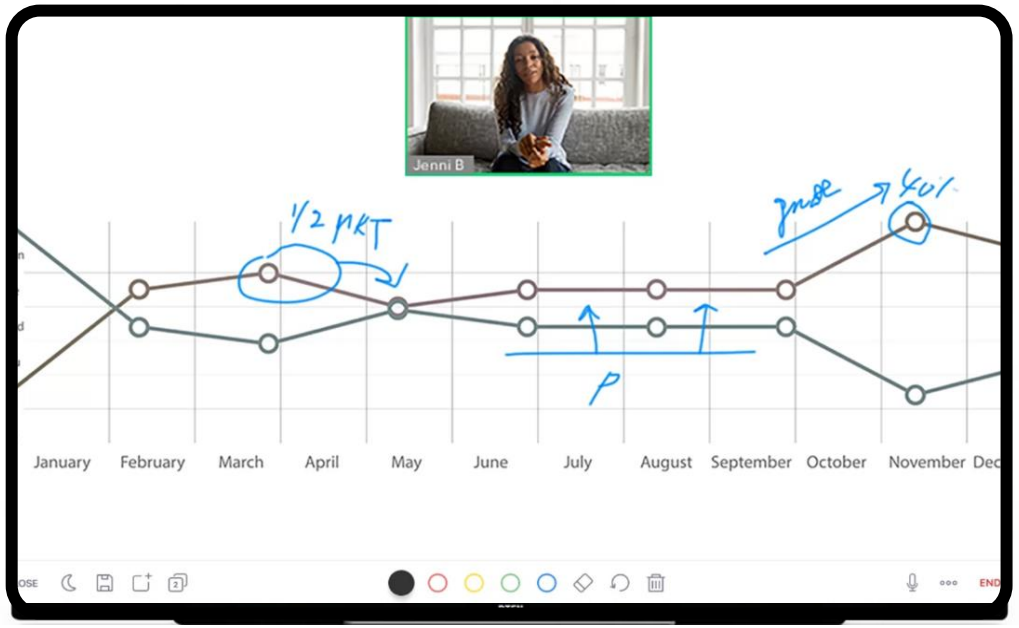


Maximize Display Area

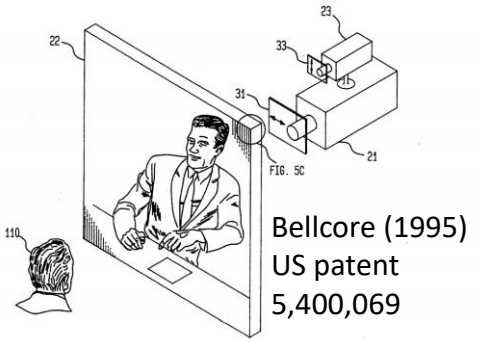








Prior Work



Bellcore (1995)
US patent
5,400,069



Buxton W. et. al , “Interfaces for Multiparty Videoconferences” (1997)

Regenbrecht H. et. al, “Eye-to-Eye Contact for Life-Sized Videoconferencing” (2014)

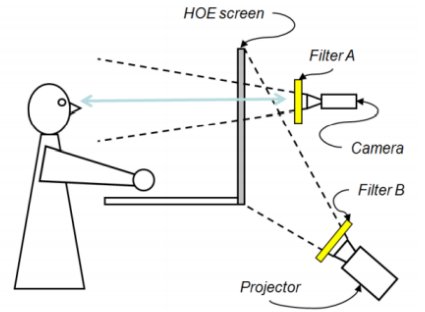
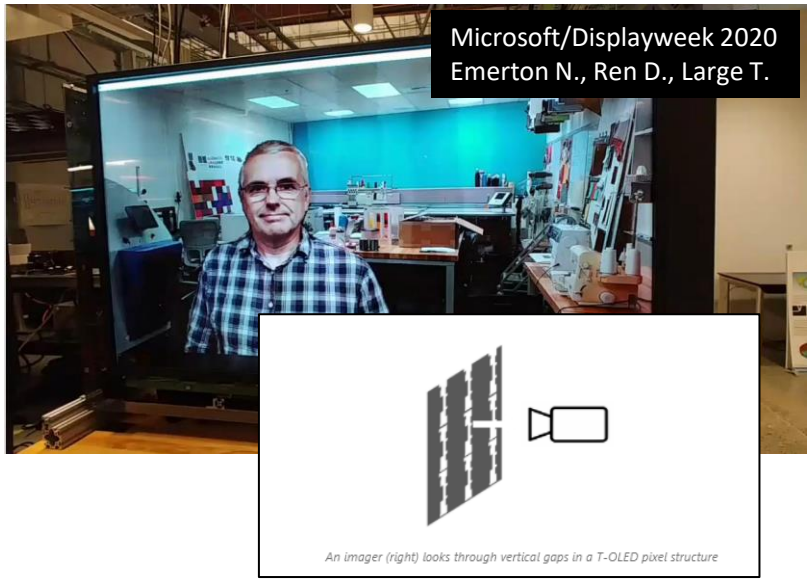


Figure 2. Schematic of “i2i” approach. A Holographic Optical Element (HOE) is used to separate the camera view from the projected video conferencing image. Additional polarization filters are added in the light path.

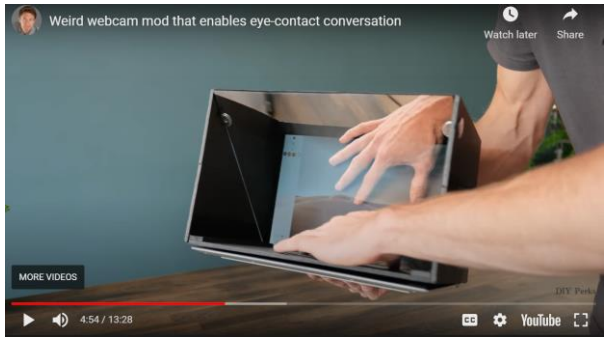


Oppo (2020)



Microsoft/Displayweek 2020
Emerton N., Ren D., Large T.

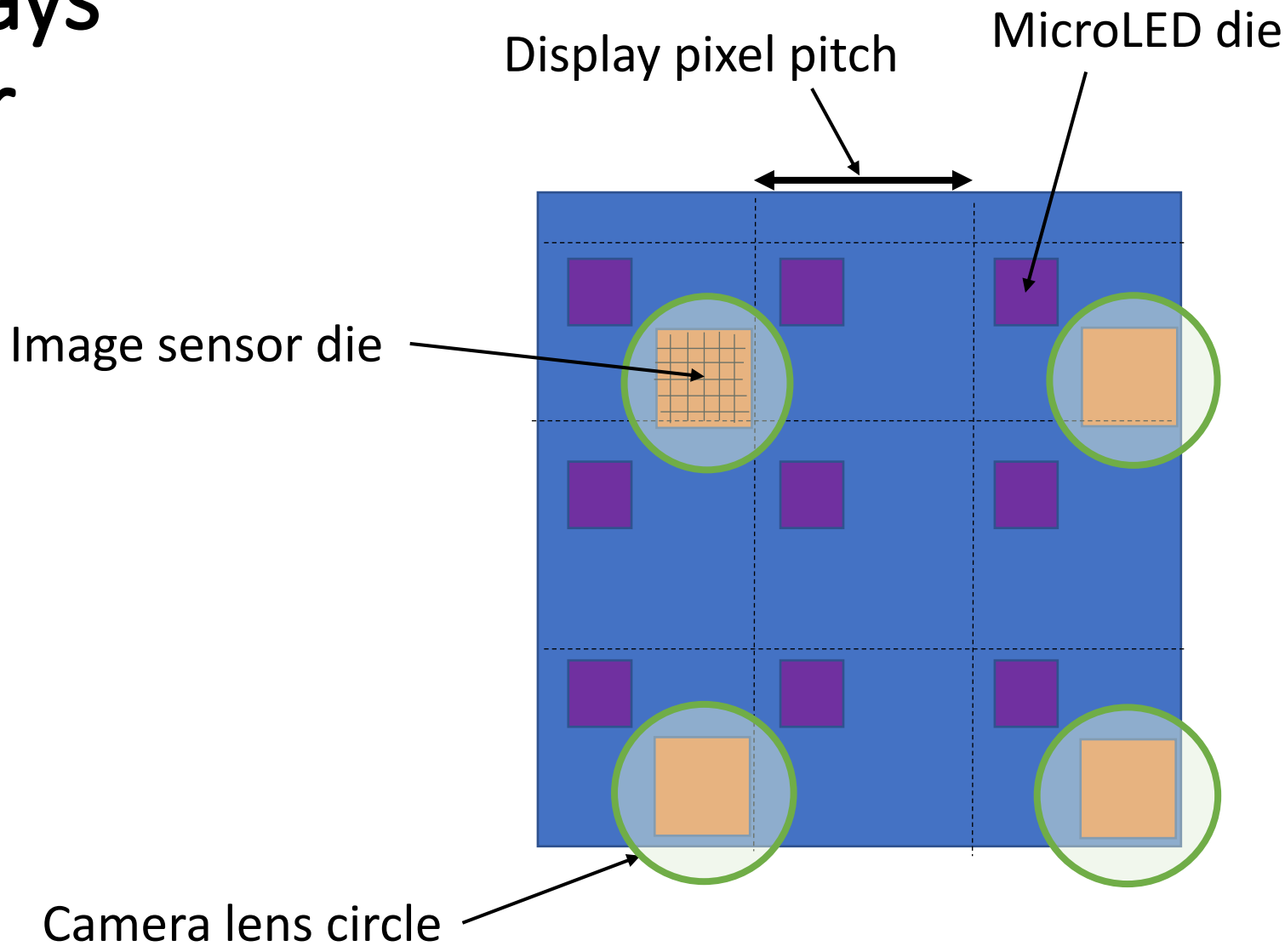
An imager (right) looks through vertical gaps in a T-OLED pixel structure



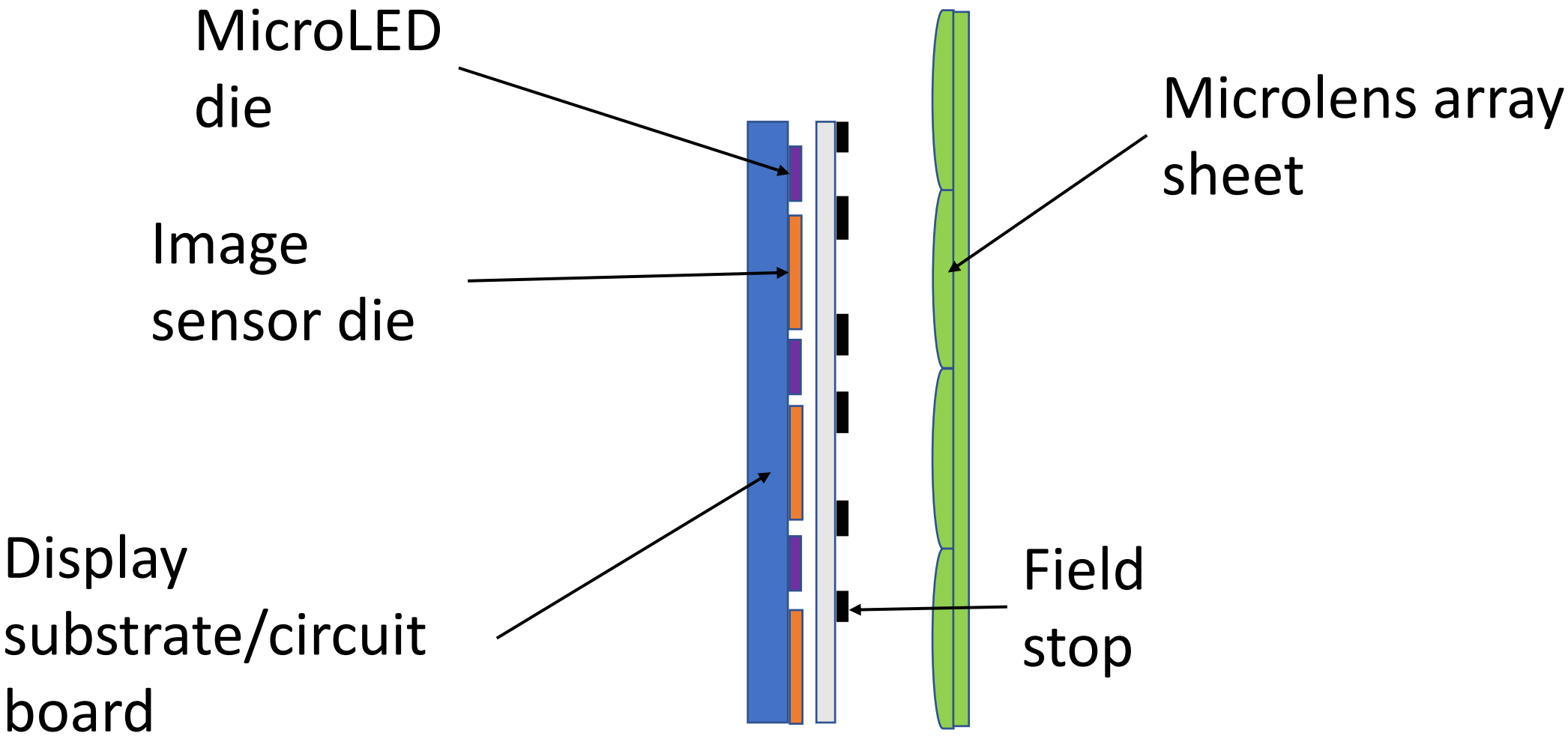
https://hackaday.com/2020/05/29/two-way-mirror-improves-video-conferencing/

Implementation and Modeling Results

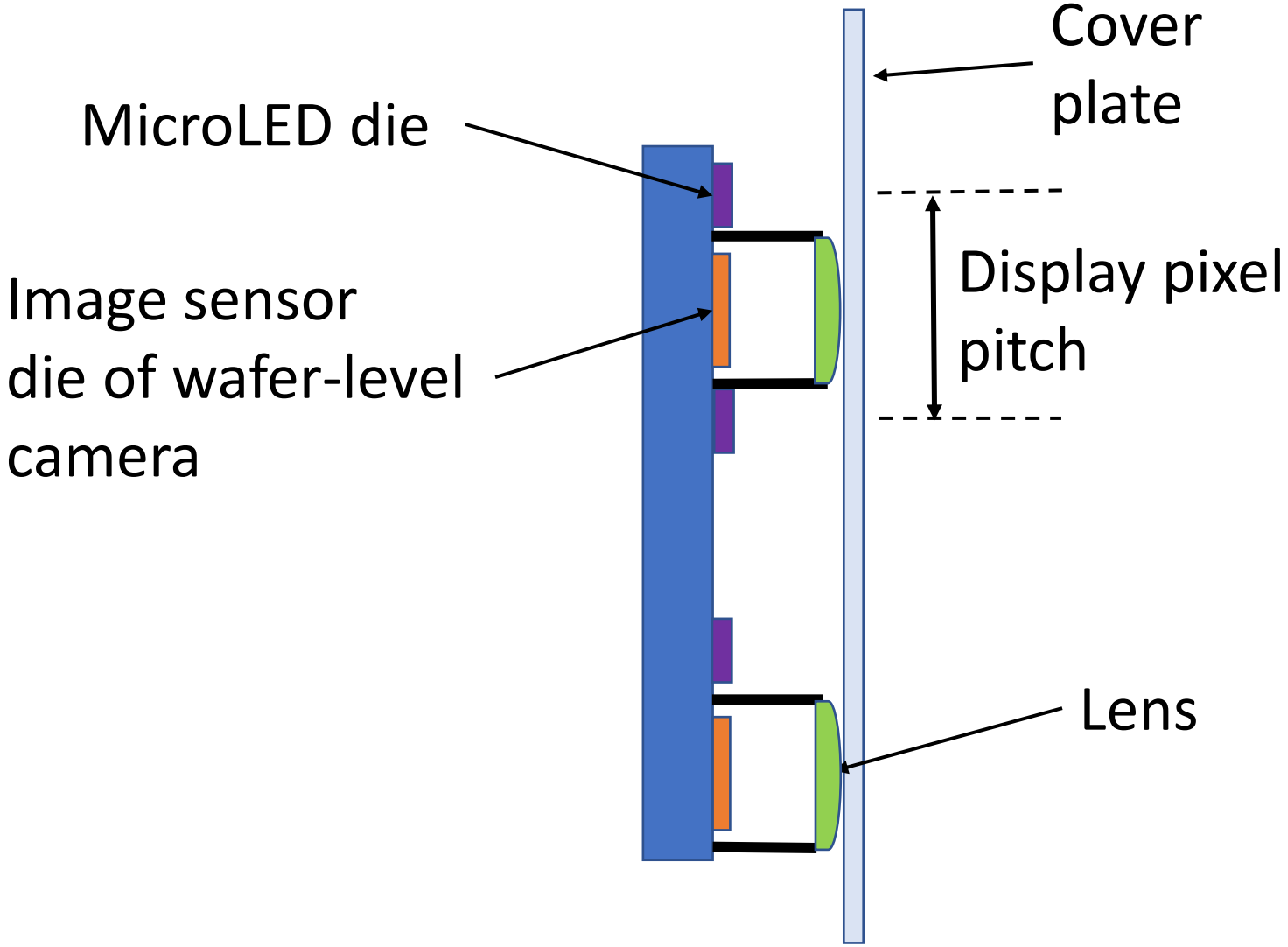
MicroLED Displays Afford Room for Cameras



Microlens Array Implementation

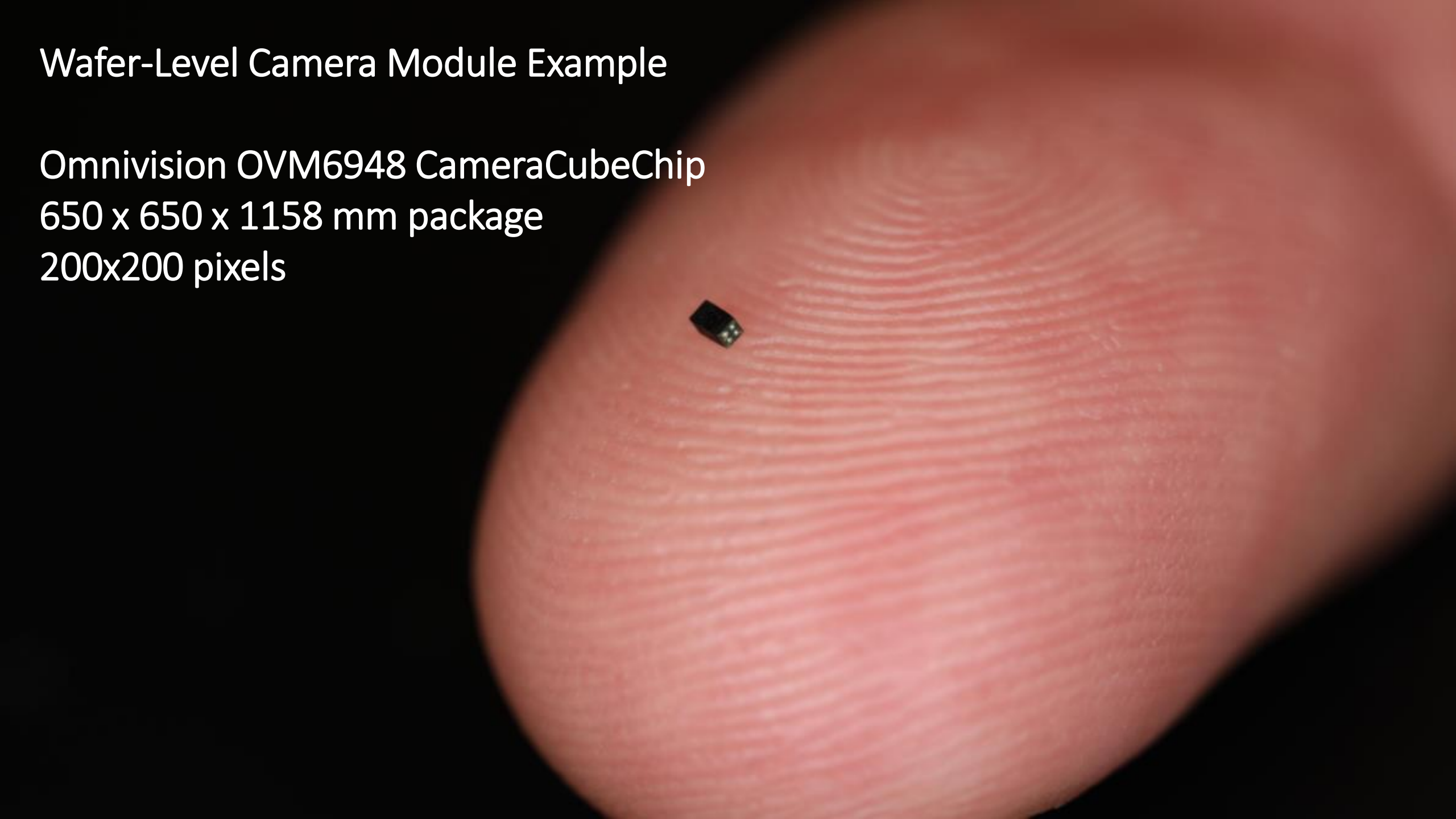


Wafer-Level Camera Implementation



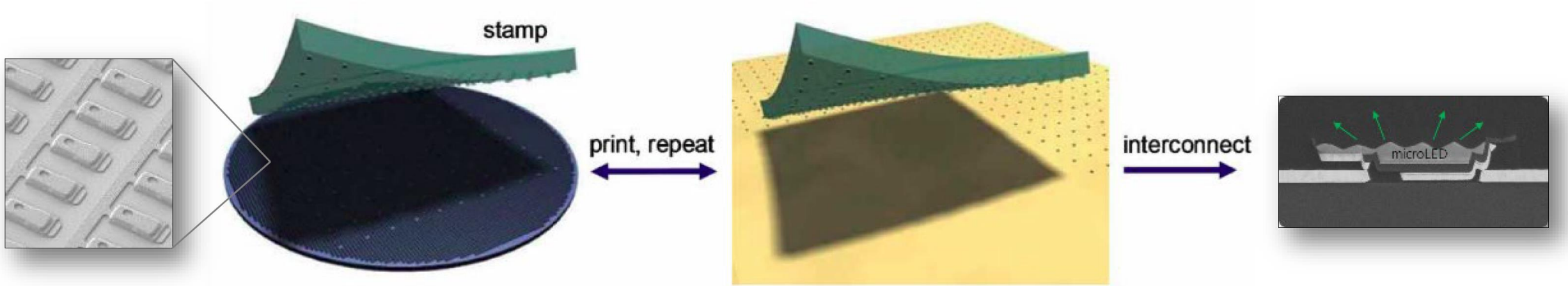
Wafer-Level Camera Module Example

Omnivision OVM6948 CameraCubeChip
650 x 650 x 1158 mm package
200x200 pixels



XDC's mass transfer solution: micro transfer-printing

1. Form undercut microdevices (LEDs, ICs, etc.), anchored at endpoints
2. Mass transfer to the target (display) substrate with a patterned elastomer stamp
3. Form interconnections to complete functional systems



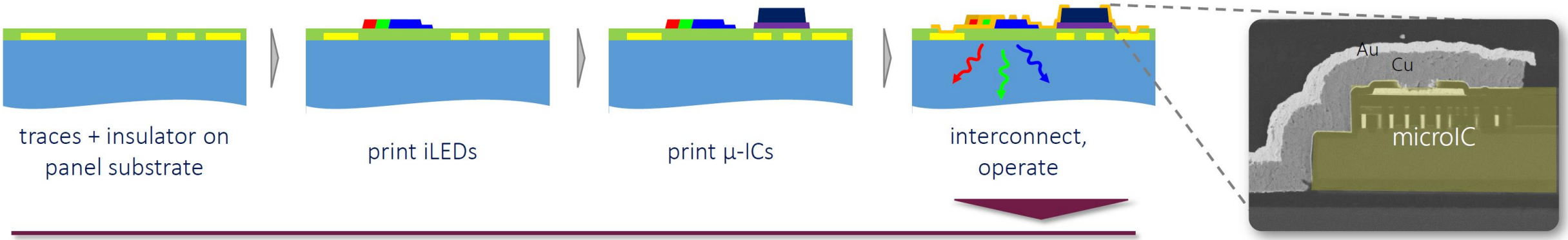
A ***source*** wafer provides the micro-devices

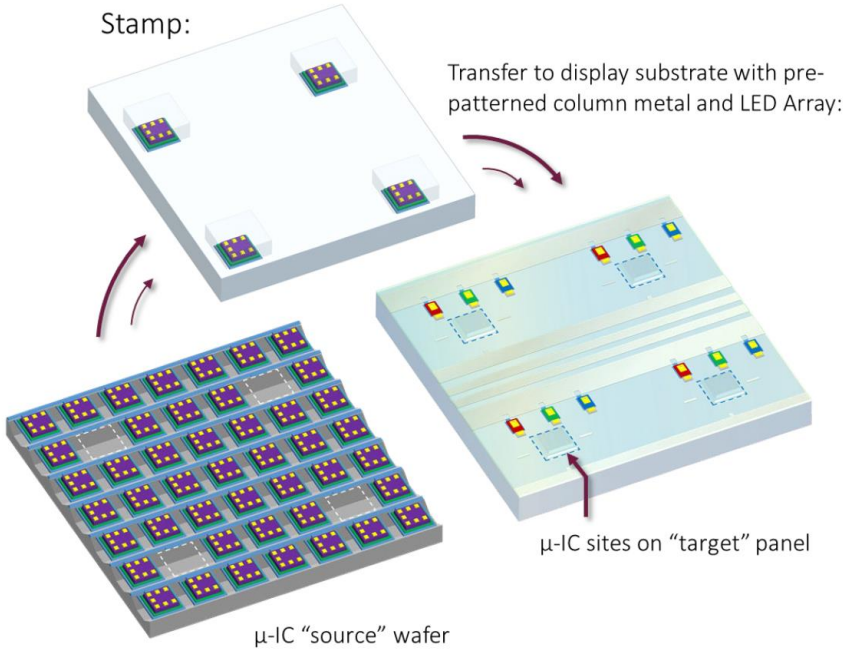
The micro-devices are assembled onto a ***target*** substrate

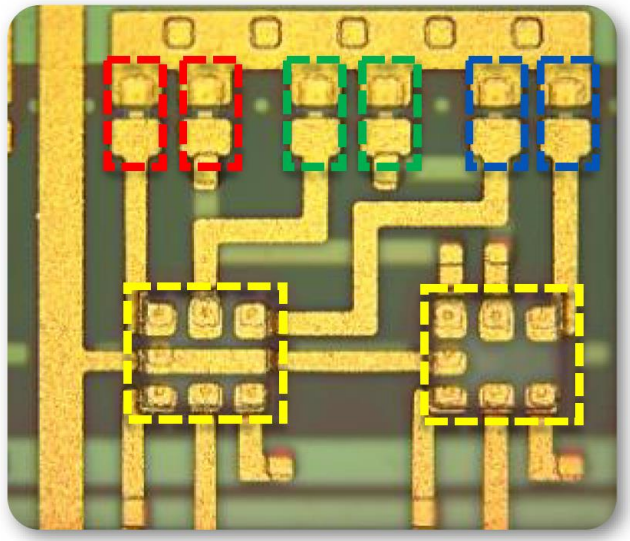
Courtesy of C. Bower, S. Bonafede, E. Radauscher, A. Pearson, B. Raymond, E. Vick, C. Verreen, T. Weeks, B. Krongard, M. A. Meitl, XDC

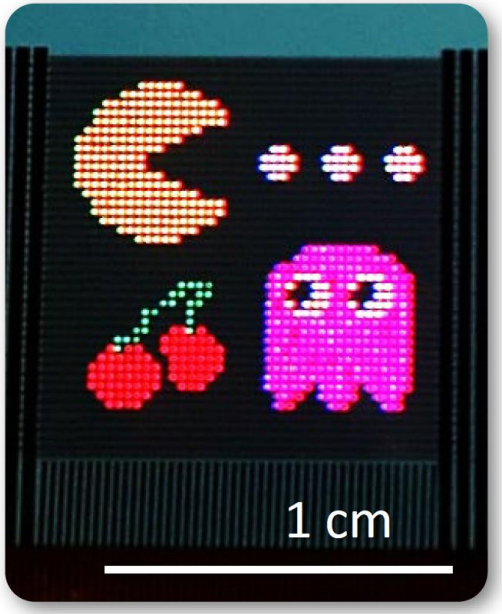
© X Display Company 2020

Printed microICs for digital active-matrix









Courtesy of C. Bower, S. Bonafede, E. Radauscher, A. Pearson, B. Raymond, E. Vick, C. Verreen, T. Weeks, B. Krongard, M. A. Meitl, XDC

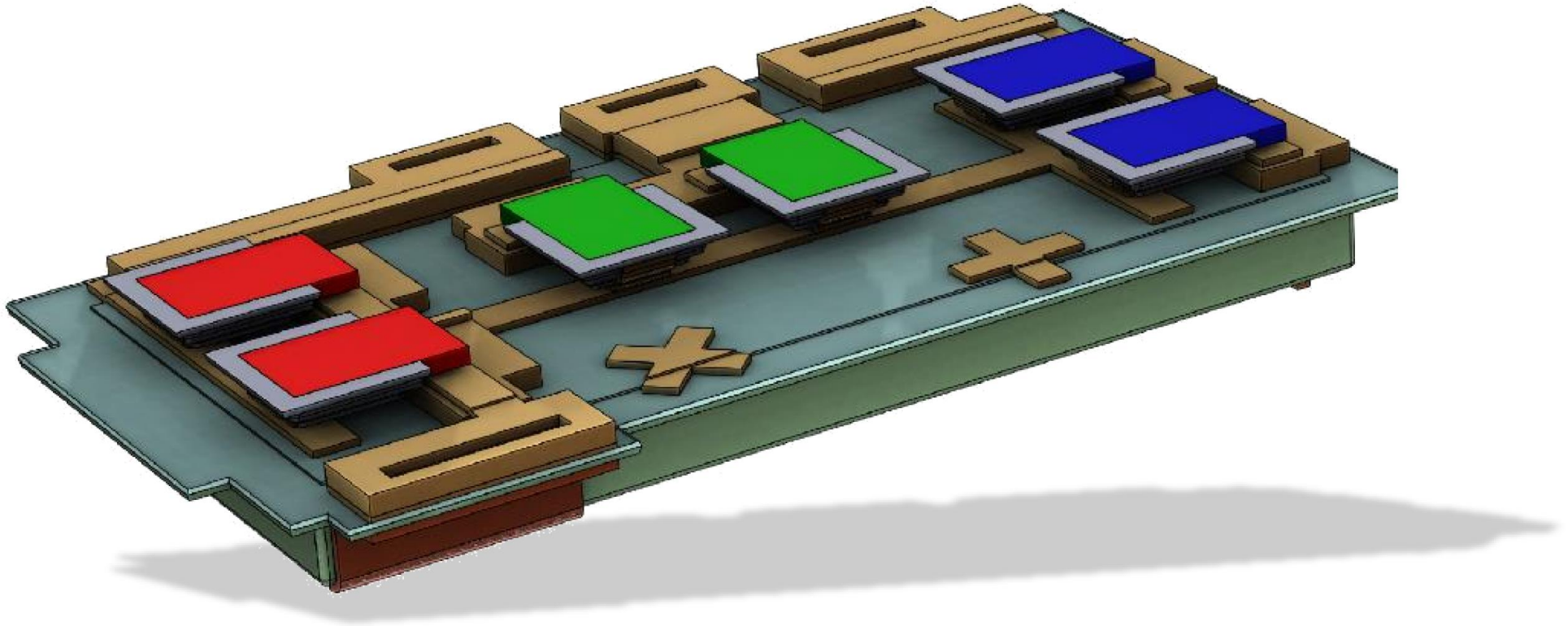
SID 2017 DIGEST

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A printable PixelEngine™ package

One micro transfer printable package that provides all active pixel components:

- pixel-level circuitry: pulse-width and/or –amplitude modulation.
- (redundant) set of flip-chip 8 x 15 µm^2 microLEDs
- pressure concentrators for electrical contact



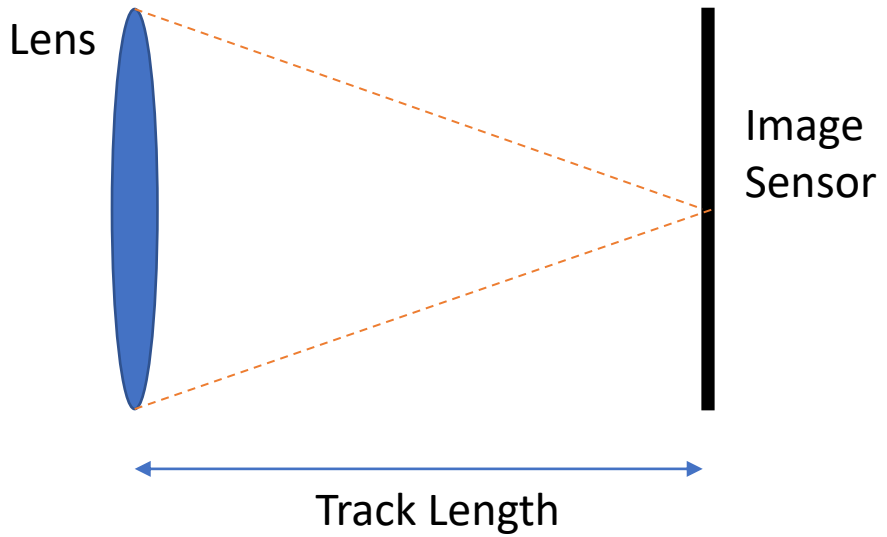
Courtesy of C. Bower, XDC

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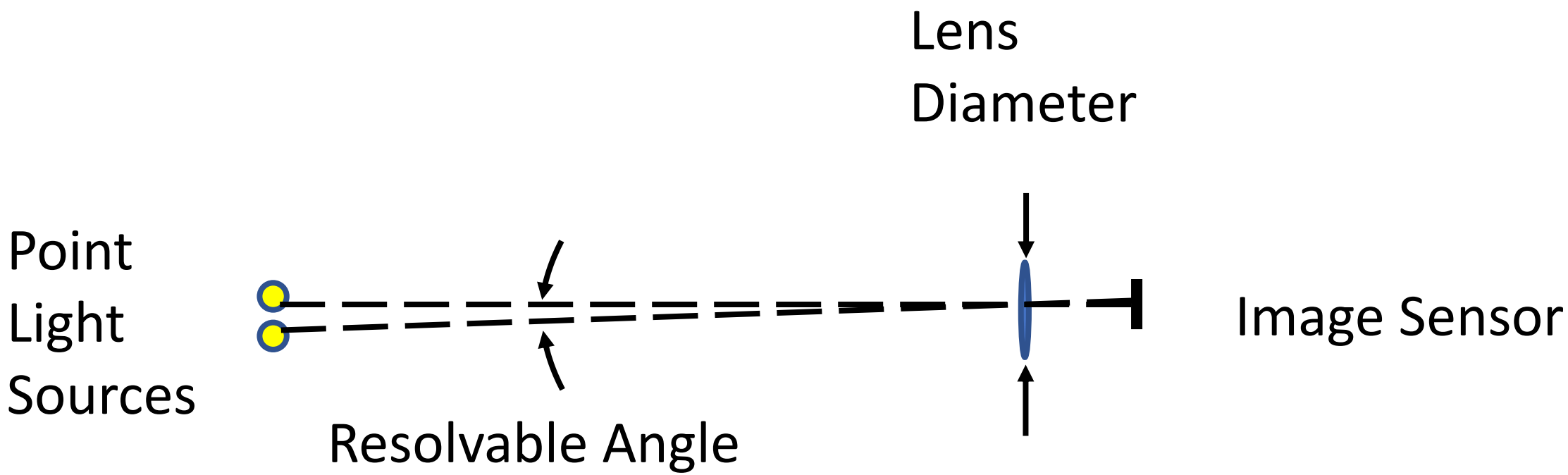
Display Device Thickness Consideration

Microcamera track length ~ f-number * lens diameter

Lower f-number microcamera lens for larger display pixel pitch devices



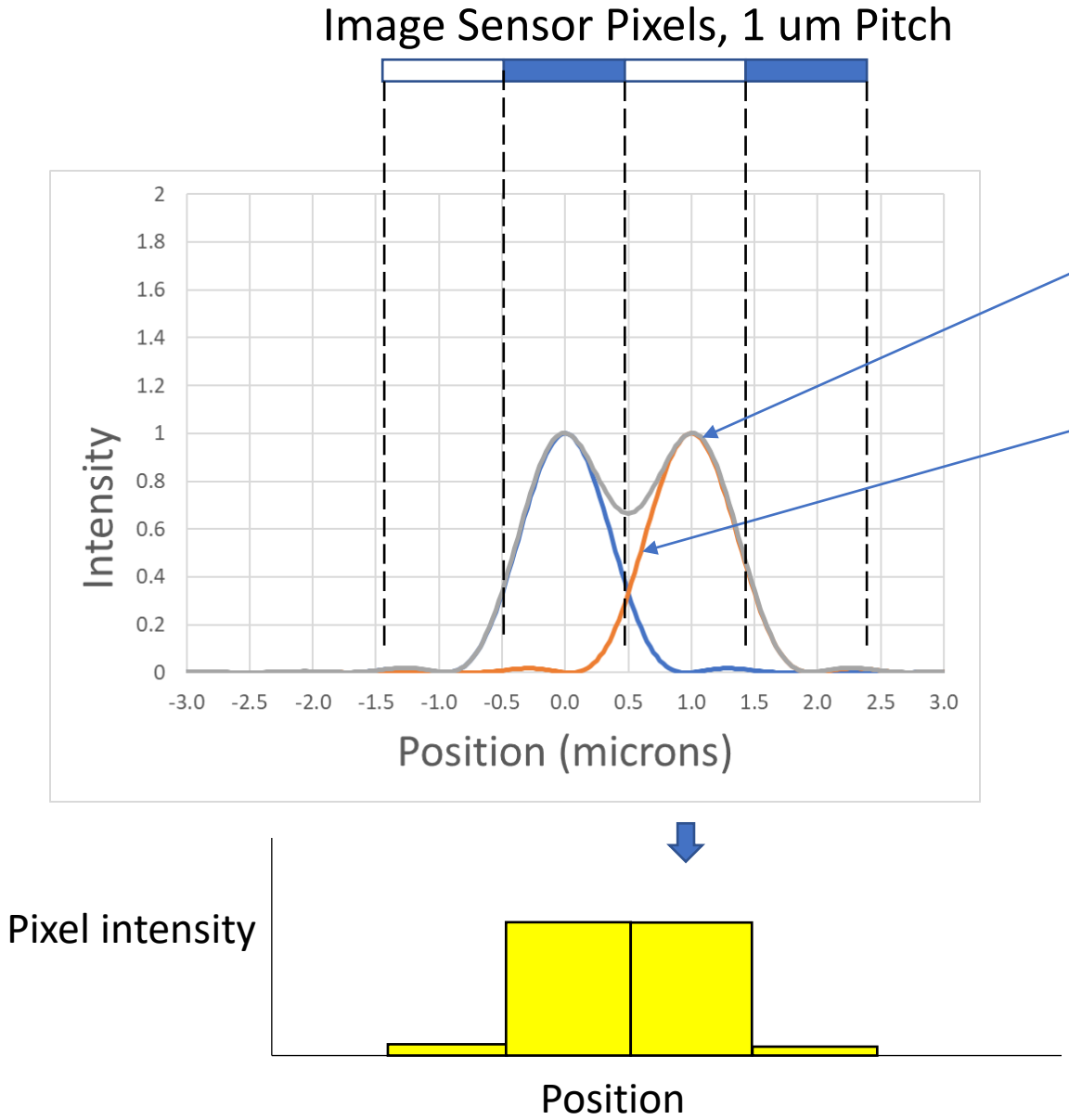
Microcamera Angular Resolution Modeling



Angular Resolution: “Macrocamera”

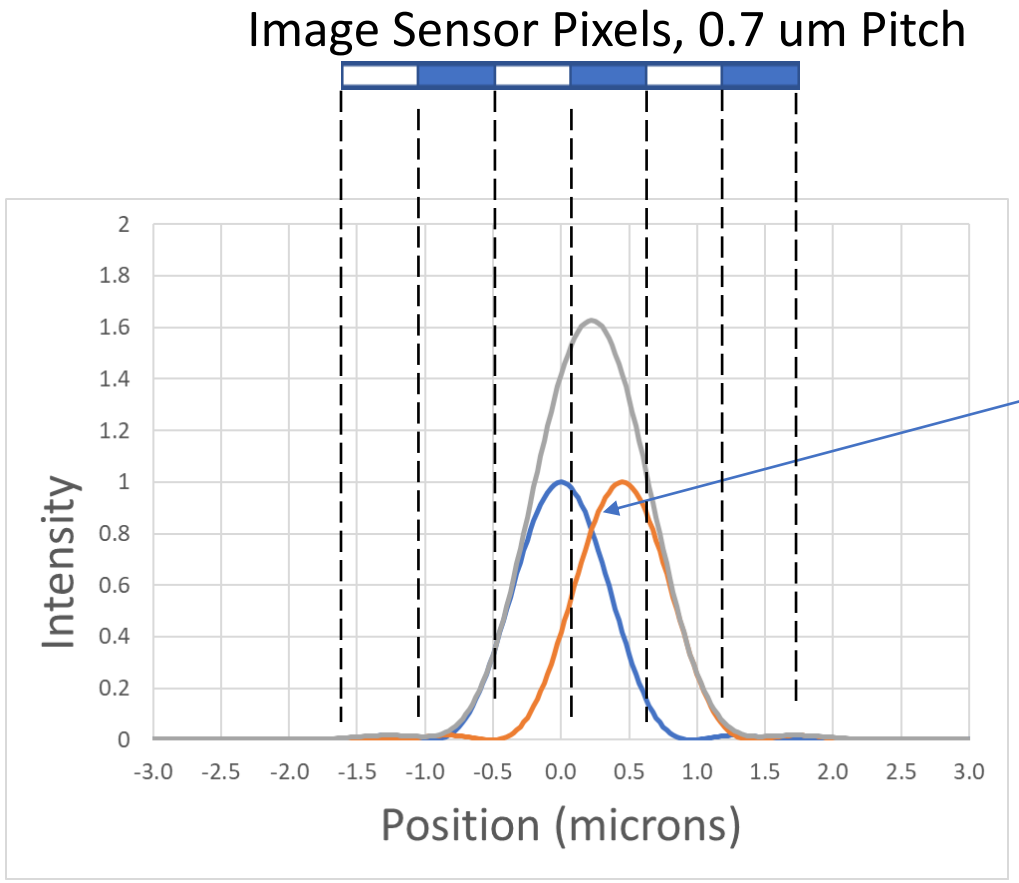
1000 micron diameter
f/1 Lens Camera

Point sources just resolvable by Rayleigh criterion

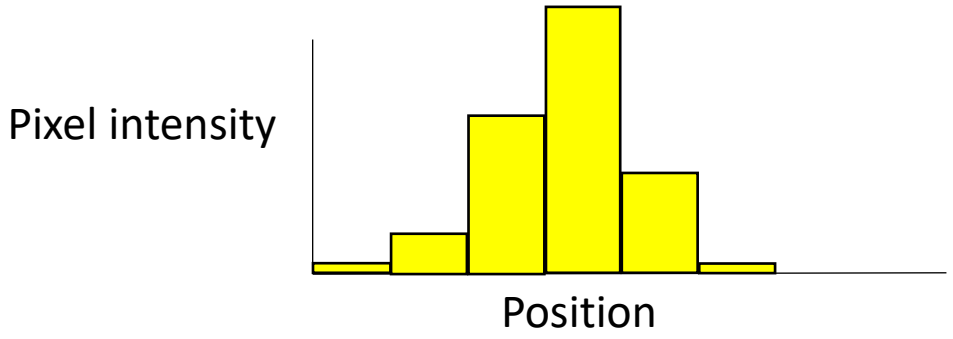


Angular Resolution: Microcamera

500 micron dia., f/1 Lens Camera



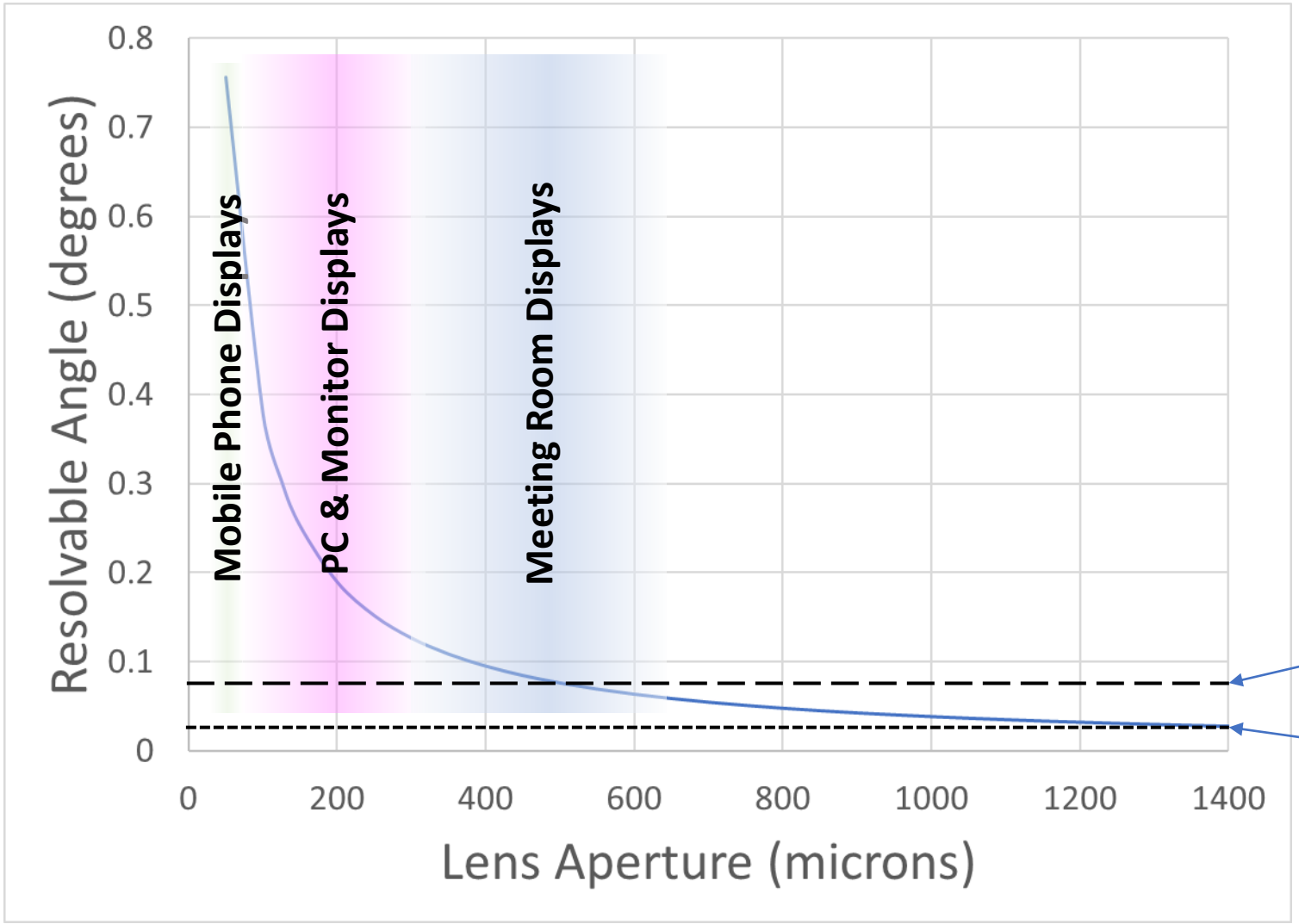
Point spread function (Airy disk) profile



Resolvable Angles for Different Display Applications

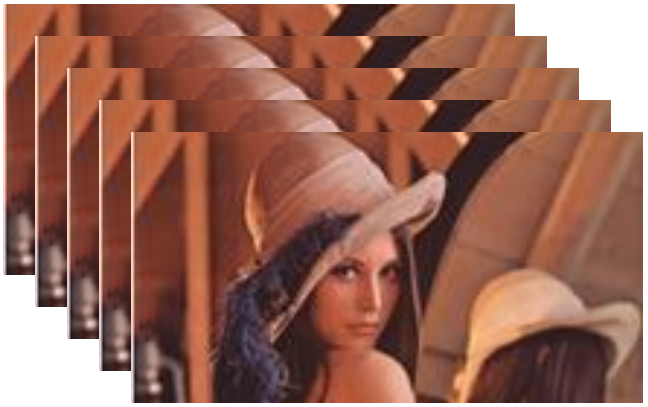
Model is geometry-based, with camera pixel size ~Airy disk core diameter

Resolvable angle depends on lens diameter, not lens f-number.

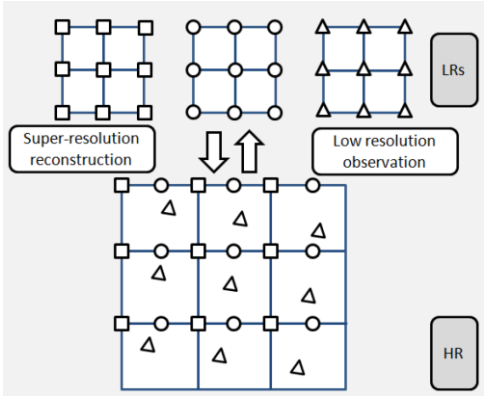


Multi-Image Super-Resolution (MISR)

Construct a high-resolution image from multiple low-resolution images taken from different viewpoints

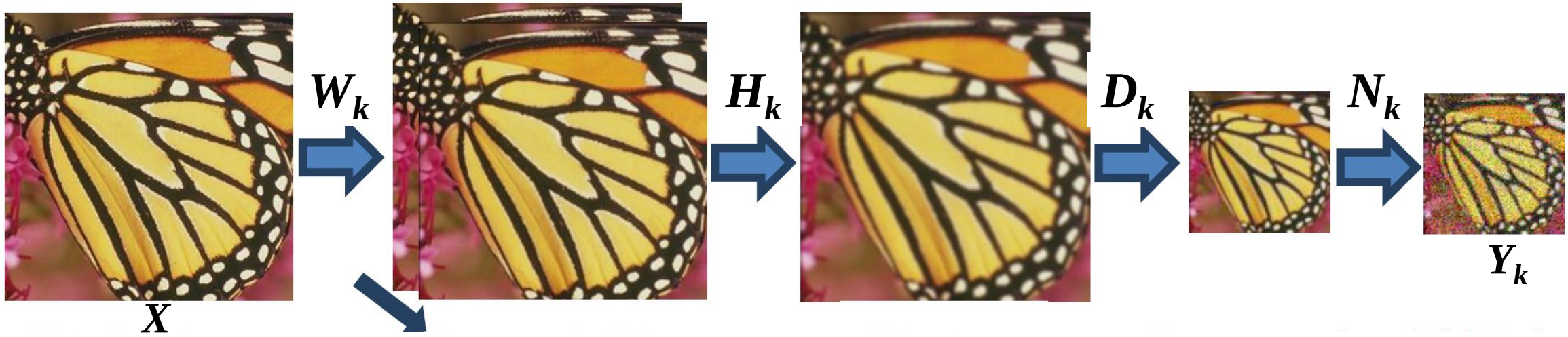






Reference: Yang J., Huang T., “Image super-resolution: Historical overview and future challenges”, **Super-Resolution Imaging**, Chapter 1 (2011)

Imaging Model



$$Y_k = D_k H_k W_k X + N_k,\ k = 1,2,\ldots M,$$

Where:

Yk = kth Low Resolution (LR) microcamera image

X = High Resolution (HR) image (virtual camera)

D_k = decimation matrix

H_k = blurring operator

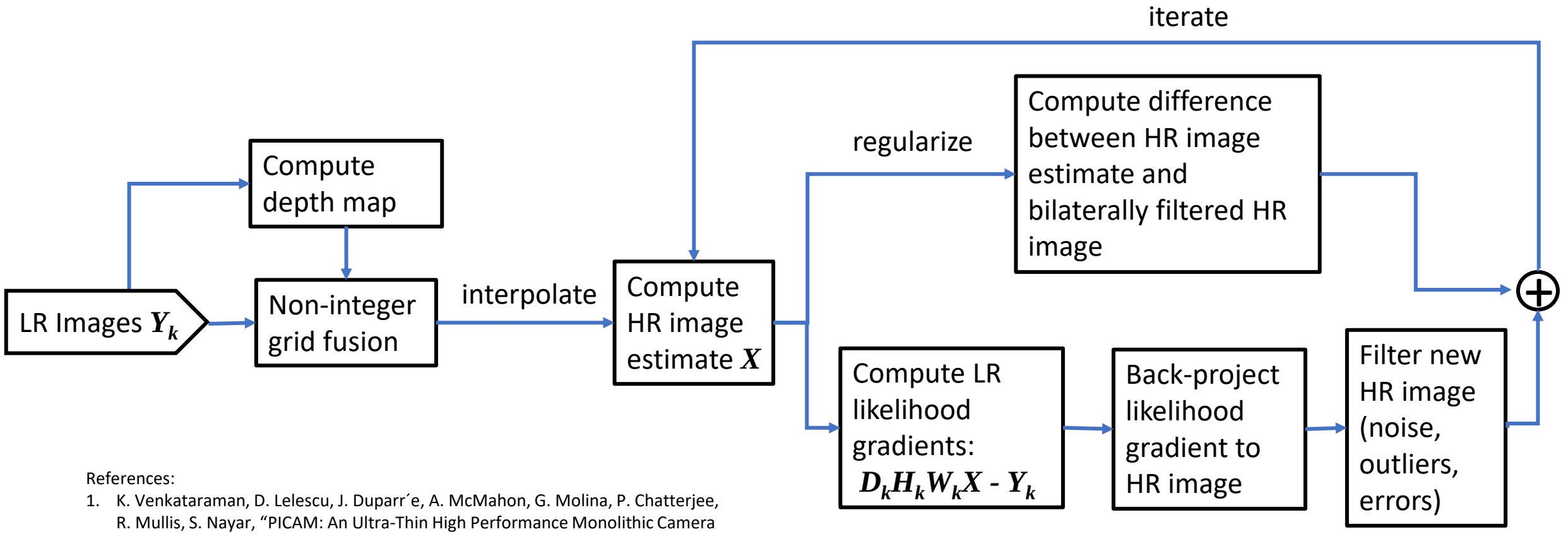
W_k = geometric distortion/parallax shift matrix of Y_k

N_k = noise in Y_k

Reference: L. Wang, Z. Lin, X. Deng, W. An, "A Multi-frame image super-resolution with fast upscaling technique", arXiv e-prints, (2017)

Multi-Image Superresolution High Resolution Image Reconstruction Process

(Maximum-a-Posteriori (MAP) approach example)

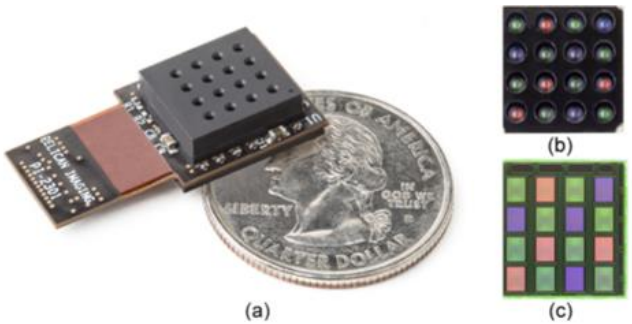


References:

1. K. Venkataraman, D. Lelescu, J. Duparr´e, A. McMahon, G. Molina, P. Chatterjee, R. Mullis, S. Nayar, “PICAM: An Ultra-Thin High Performance Monolithic Camera Array”, ACM Transactions on Graphics, Vol. 32, No. 6, Article 166, (2013)
2. L. Wang, Z. Lin, X. Deng, W. An, “Multi-frame image super-resolution with fast upscaling technique”, arXiv e-prints, (2017)

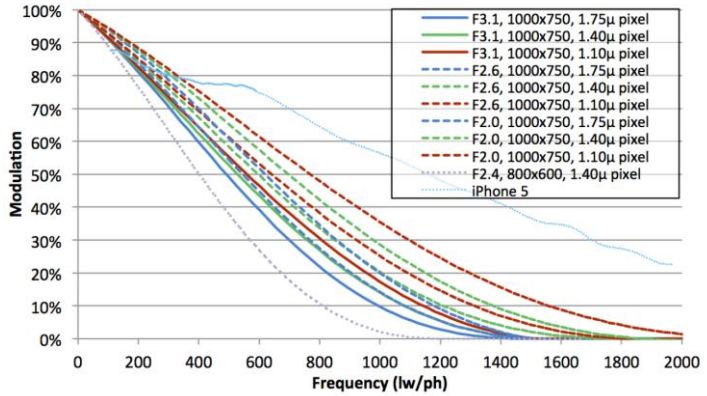
Previous Microcamera Array/MISR Work Showed Promise

PICAM (2013)

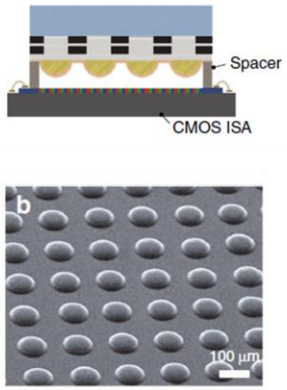


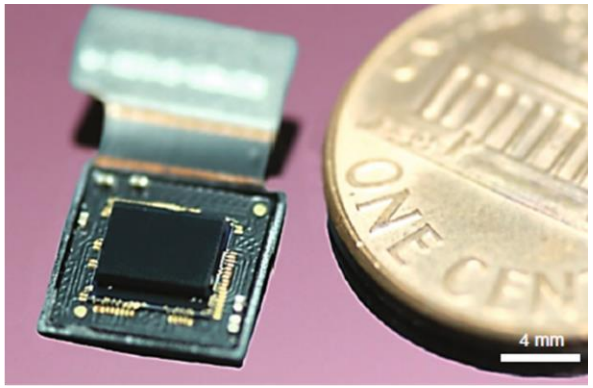
(a) The PiCam module (b) lens array (c) sensor array

4x4 camera array
CMOS sensor, 1.75 μm pixel
645 μm, f/3.1 lenses
~2500 μm camera pitch
1000x750 pixels per camera
Monochrome cameras
Reconstructed image: 3200x2400

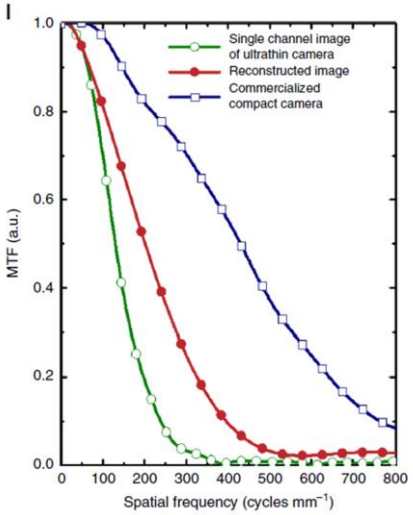


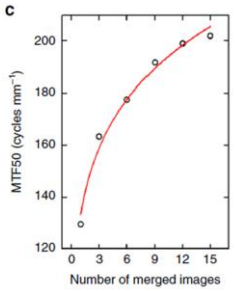
KAIST (2020)





3x5 camera array
CMOS sensor, 1.12 μm pixel
100 μm, f/5 singlet lenses
238 μm camera pitch
214x214 pixels per camera
Light baffles





References:
1. Kim K, Jang KW, Ryu JK, Jeong KH, "Biologically Inspired Ultrathin Arrayed Camera For High-Contrast and High-Resolution Imaging", Light: Science & Applications (2020)
2. K. Venkataraman, D. Lelescu, J. Duparr´e, A. McMahon, G. Molina, P. Chatterjee, R. Mullis, S. Nayar, "PICAM: An Ultra-Thin High Performance Monolithic Camera Array", ACM Transactions on Graphics, Vol. 32, No. 6, Article 166, (2013)

Relative Improvements of Display with Microcamera Array

Higher optical isolation for better SNR

Higher number of captured images

Monochrome cameras, no Bayer filter

Small lens size simplifies design, reduces aberrations at low-f-numbers

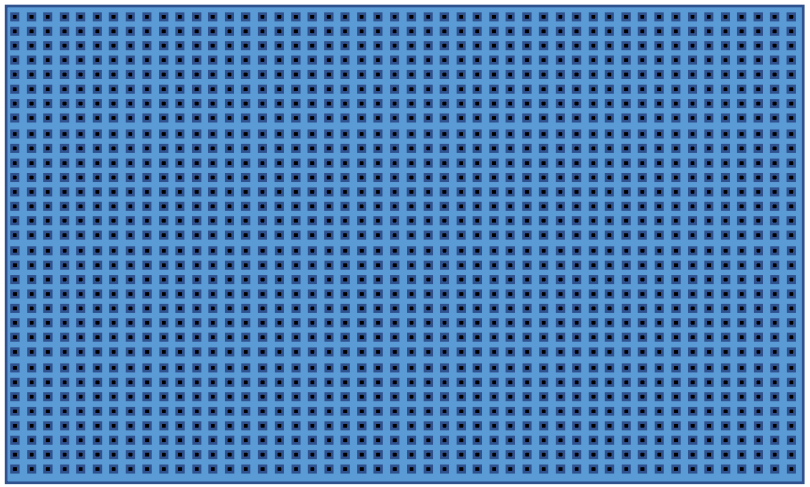
Small camera pitch: less than minimum feature size at typical viewing distance

Customized image sensor with appropriate chief ray angle correction and pixel size

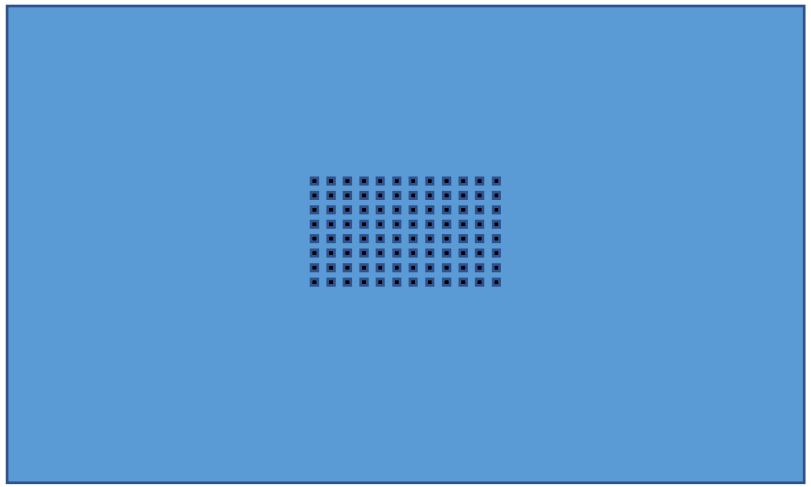
Better pre-calibration: point-spread, geometry, distortion and aberrations



Display Microcamera Configurations



Display with full microcamera coverage



Display with partial microcamera coverage

Microcameras may be distributed over entire or portion of display area

Subset (cluster) of microcameras adaptively selected for MISR high resolution image reconstruction, depending on need

Microcamera pitch may equal display pixel pitch (larger displays) or be multiples of display pixel pitch (smaller displays)

Careful design required to hide microcameras and avoid visual artifacts: ensure uniform reflectance of areas with and without microcameras

80 Inch 4K Display Example

Display Diagonal Size (inches)	Display Resolution	Display Pixel Pitch (mm)	MicroLED Dimension (mm)	Microcamera Image Sensor Dimension (mm)	Microcamera Lens Dimension (mm)
80	3820x2160	0.5	0.2	0.2	0.3

Microcamera Lens F-number	Approximate Microcamera Track Length (mm)	Image Sensor Pixel Pitch (μm)	Image Sensor Pixel Count	Resolved Spot Size at 2 m	MISR Enhancement Required (rel. to commercial FHD camera @ 120 degree HFOV)	Approximate Number of Cameras Per Active Array	Microcamera Pitch Within The Display (mm)
1.3	0.4	0.7	285 x 285	5.9	2.8	28	0.5

Electronics Block Diagram

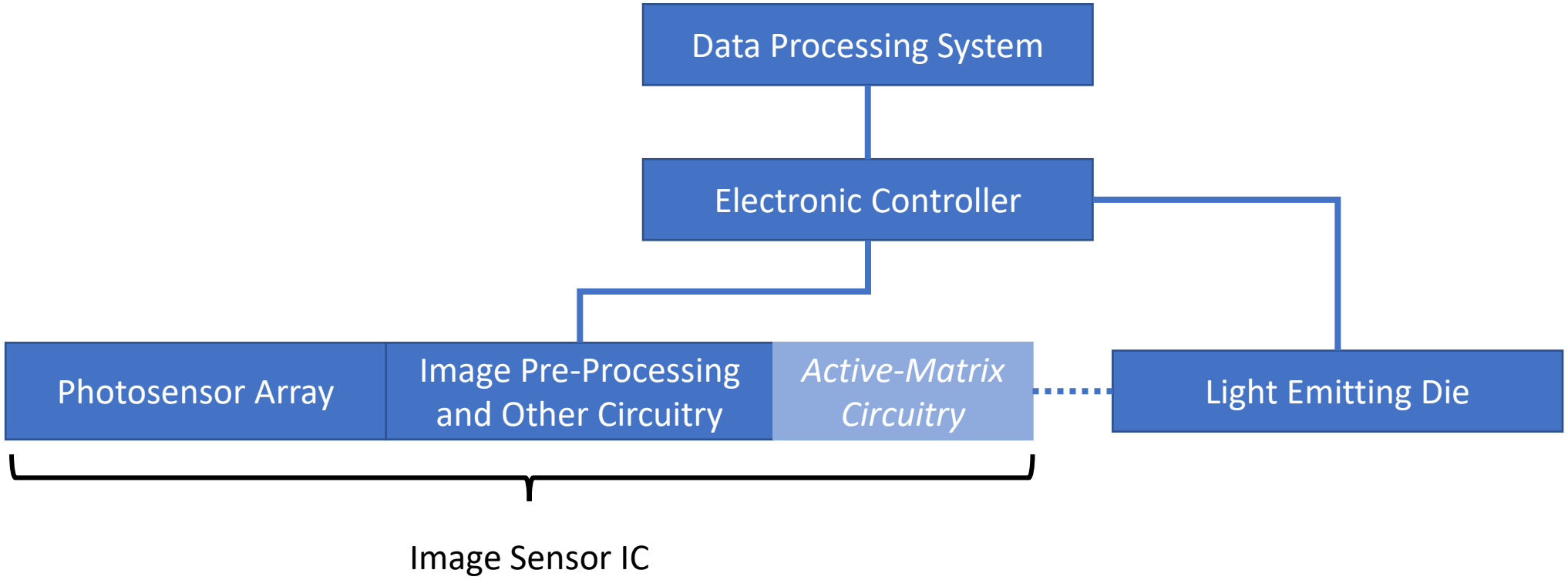
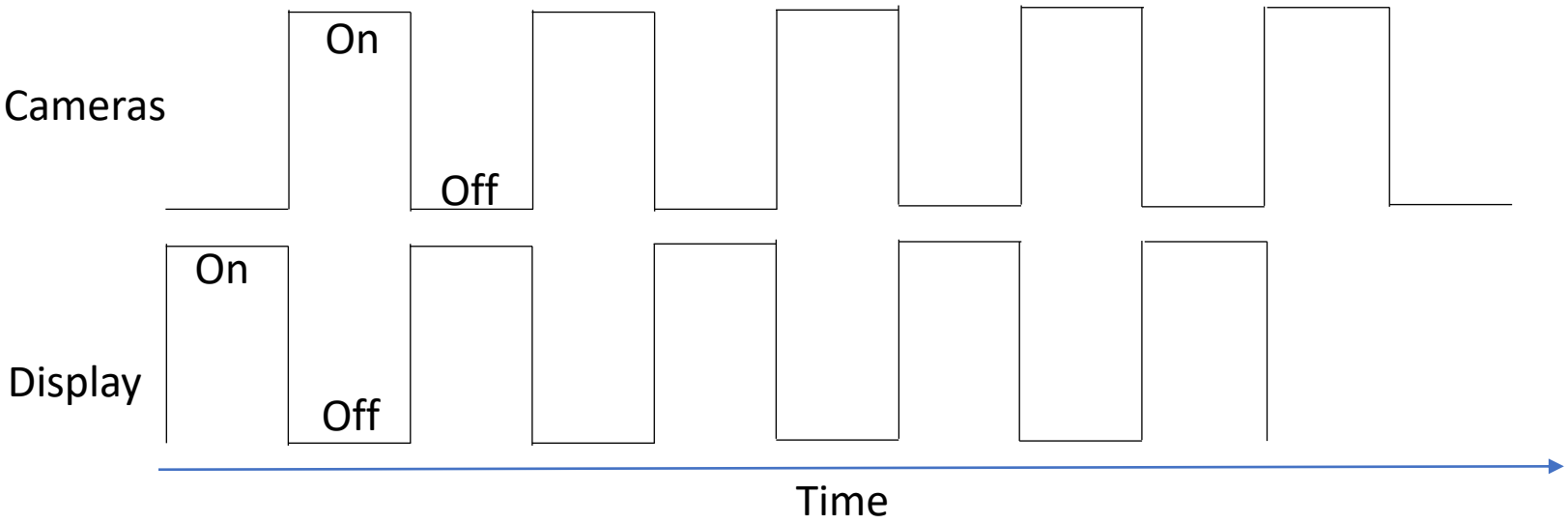


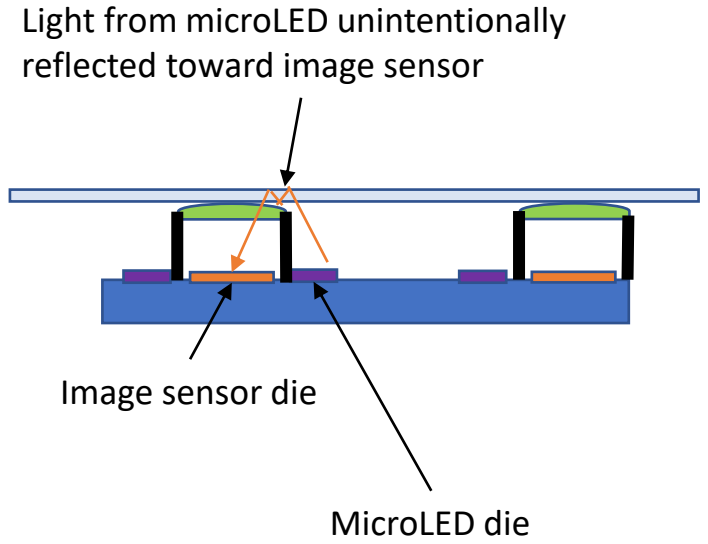
Image sensor IC pre-processing includes uniformity, gain, gamma, distortion, aberration corrections, etc.

Image sensor IC could include loss-less data compression to reduce data rate

Display active-matrix circuitry for the nearby microLEDs might also be included in image sensor IC

Display-Camera Duty Cycle To Eliminate Displayed Image Noise





Display light emitting devices are turned off when cameras are imaging

The duty cycle should be fast enough to avoid observable flicker

The full area of the display could be turned off or a subsection of the display could be turned off during image acquisition

Real-Time MISR Processing

Real-time MISR processing is a key challenge

- Target processing time <33 ms for live video capture

Older MISR research real-time only for low resolution

- 2007 example: Intel real-time MISR, 176x144 -> 352x288 resolution
- 2014 example: 5x5 array of 1600x1200 pixel cameras yielding a 3600 x 2700 image using PC running Matlab for 10 iteration reconstruction took 200 seconds

Path to achieve real-time:

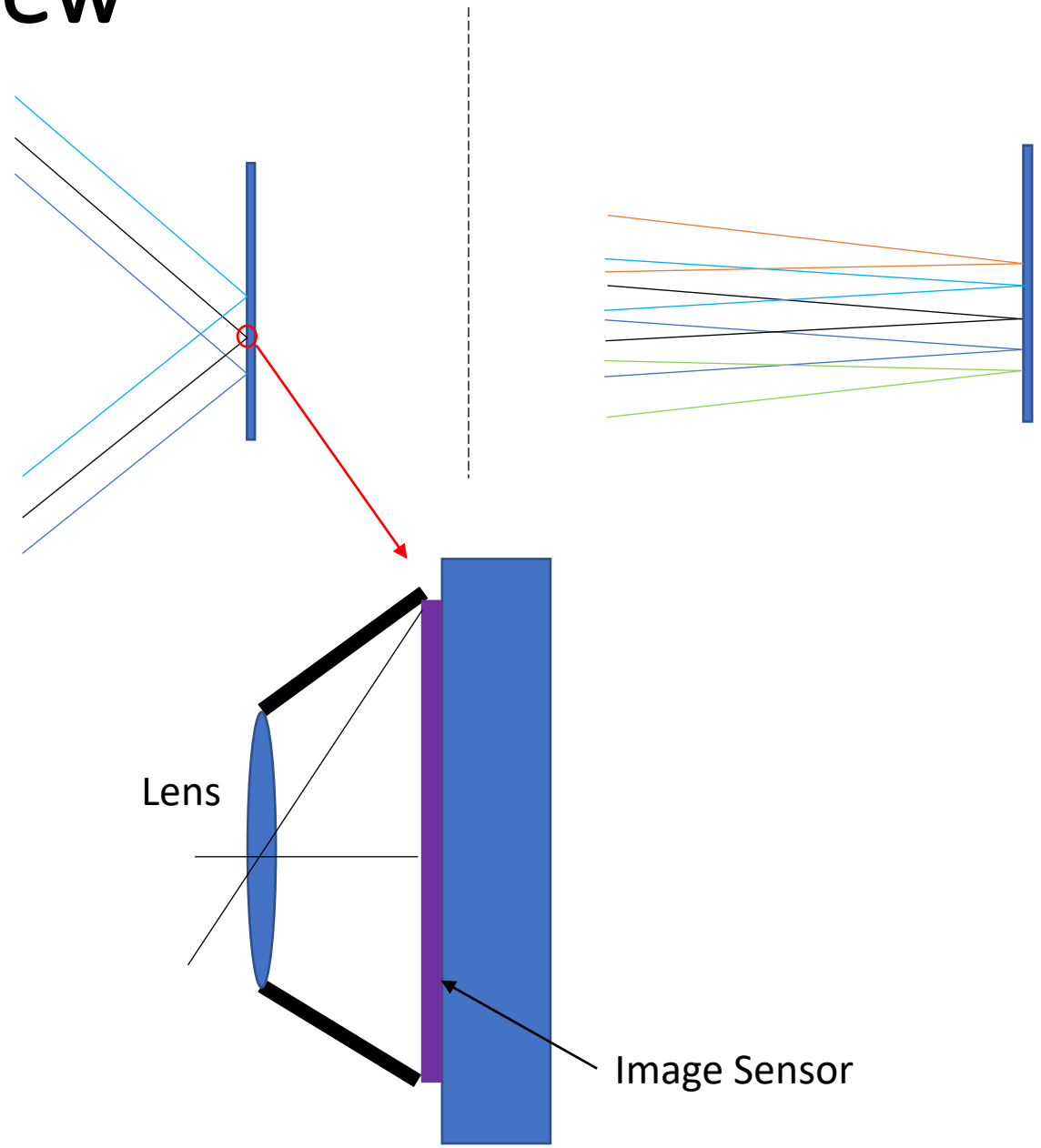
- Leverage pre-calibration and local pre-processing as much as possible
- Reduce number of iterations required
- Use non-iterative approach
- Apply parallel processing: GPU or multi-core processors

1. Carles Santacana, G., Downing, J., and Harvey, A., "Super-resolution imaging using a camera array", Optics Letters, 39 (7). pp. 1889-1892. (2014)
2. Krylov et. al. "Video Super-resolution with Fast Deconvolution", Pattern Recognition and Image Analysis, 19(3) (2009)
3. L. Wang, Z. Lin, X. Deng, W. An, "Multi-frame image super-resolution with fast upscaling technique", arXiv e-prints, (2017)
4. Akgun T., Gevrekci M., "Accelerating Super-Resolution Reconstruction Using GPU by CUDA", Advances in Computational Science, Engineering and Information Technology pp 47-58 (2013)
5. Intel Whitepaper, "Video Image Reconstruction and Enhancement" (2007), https://www.intel.com/content/dam/www/public/us/en/documents/technology-briefs/intel-labs-image-reconstruction-brief.pdf

Field of View

Each camera samples full FOV angle

Fields overlap considerably



Each camera samples small angle

Progressively decentered lenses required toward edge of camera cluster to image at higher field angles

Summary

Feasible to invisibly integrate microcameras within a thin microLED display

Proper design can address display light noise, thickness, field-of-view, resolution and cost goals

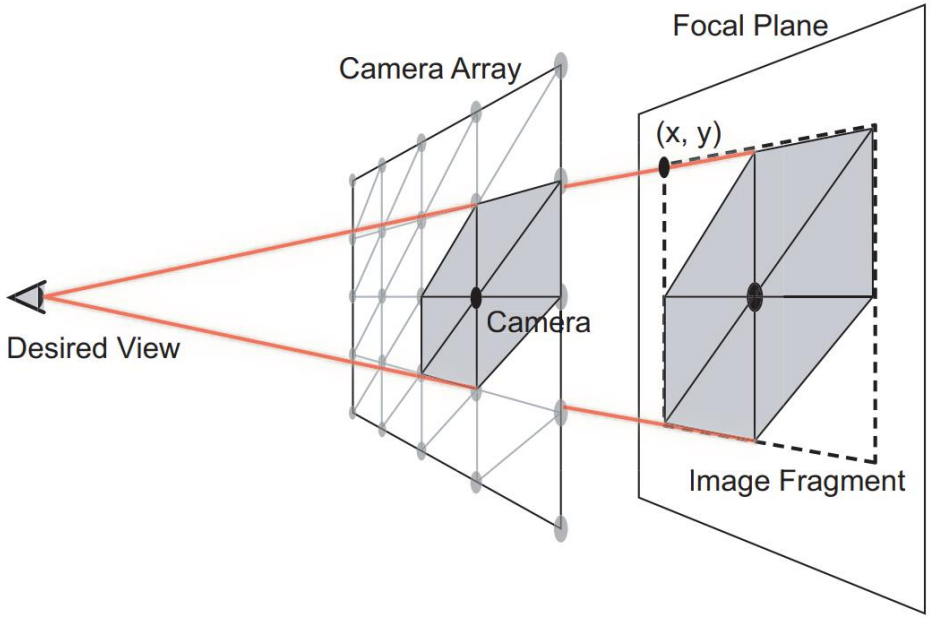
MISR can be successfully applied to overcome microcamera angular resolution/diffraction limit issues

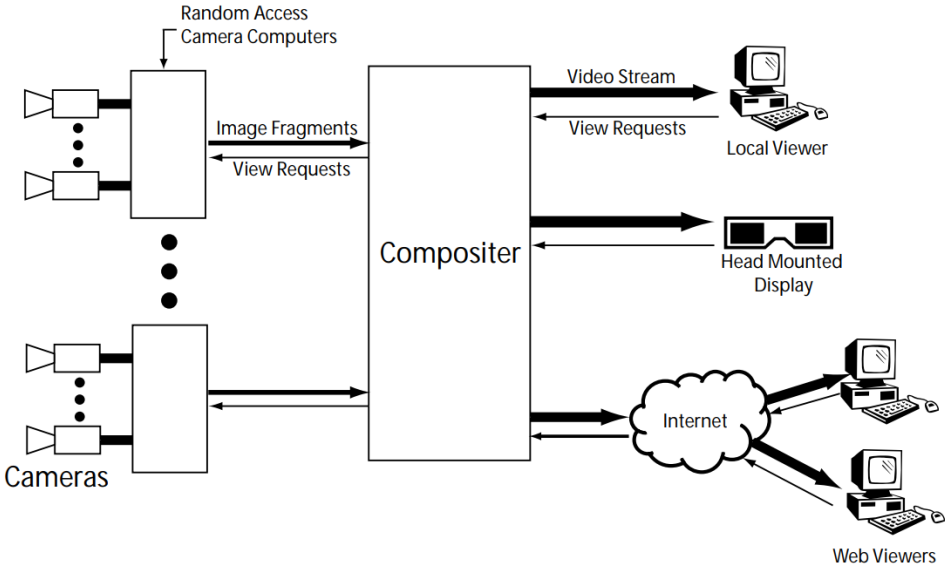
Real-time MISR represents a challenge, but is expected to be feasible

New Functionality


Microsoft Teams
Chat
Teams
Meetings
Calling
Files
Feedback
Get Apps
Call with Joshua, Babak, Sarah, and Danielle
02:01
Joshua Vanburen
Babak Shammas
Share your desktop
Share an app
Screen #1
Microsoft Teams
Northwind Presentation
July Promotion
2017_Marketing

Plenoptic Camera Mode





Camera arrays naturally capture light fields

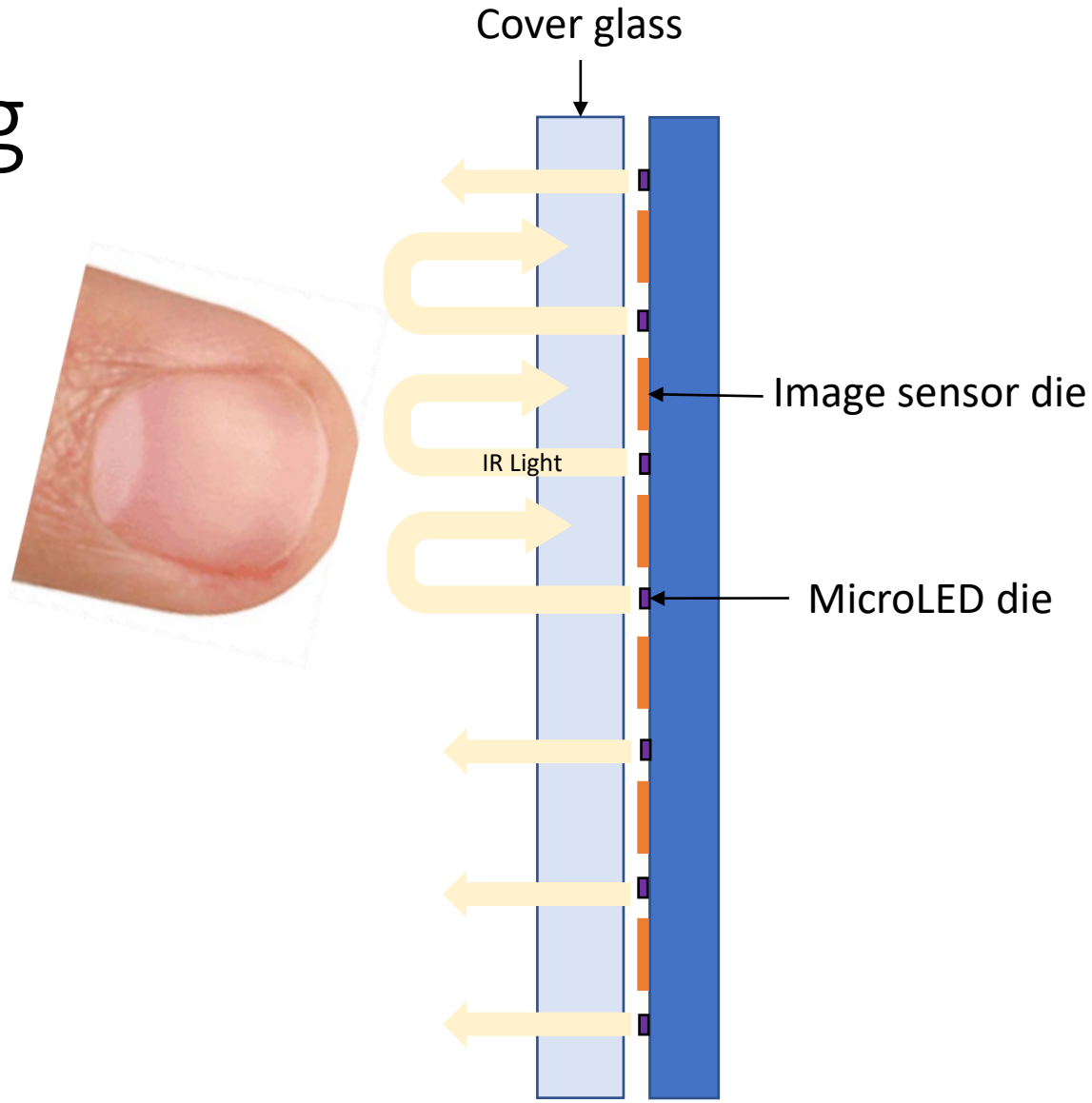
- Full light field from one or multiple viewpoints
- Stereo pair(s) from one or multiple viewpoints
- Room depth map/room intelligence

References:

1. Yang, J., Everett, M., Buehler, C., and McMillan, L. (2002). ***A real-time distributed light field camera***. In Eurographics Workshop on Rendering (2002)
2. Wilburn, B., Joshi, N., Vaish, V., Talvala, E., Antunez, E., Barth, A., Adams, A., Levoy, M., Horowitz, M., "High Performance Imaging Using Large Camera Arrays", *ACM Transactions on Graphics* (Proc. SIGGRAPH), Vol. 24, No. 3, pp. 765–776 (2005)

Touch and Hover Sensing

- Operating mode switches from image capture to sensing when objects come within a certain “hover” distance from the display
- Modulated IR microLEDs turned on to illuminate objects
- Reflected IR captured by cameras, using IR LED modulation to enhance SNR
- Cameras may operate in full or partial pixel-binning mode with more widely spaced cameras used for positional sensing or dedicated IR sensors can be used instead



Reference: [Microsoft PixelSense - Wikipedia]

Conclusions and Future Work

Conclusions and Future Work

MicroLED displays afford integrated image capture not previously possible with other display technologies

Promising approach to eliminate gaze parallax and maximize display area in thin form factor

Valuable and interesting new functionality is also enabled

Future development:

- Prototypes/demos
- Display architectures and fabrication (electronics architecture, signal routing, etc.)
- Real-time MISR image reconstruction
- Synthetic aperture approaches for small pixel pitch displays

Thank You!

