A 3D Multi-Aperture Image Sensor Architecture

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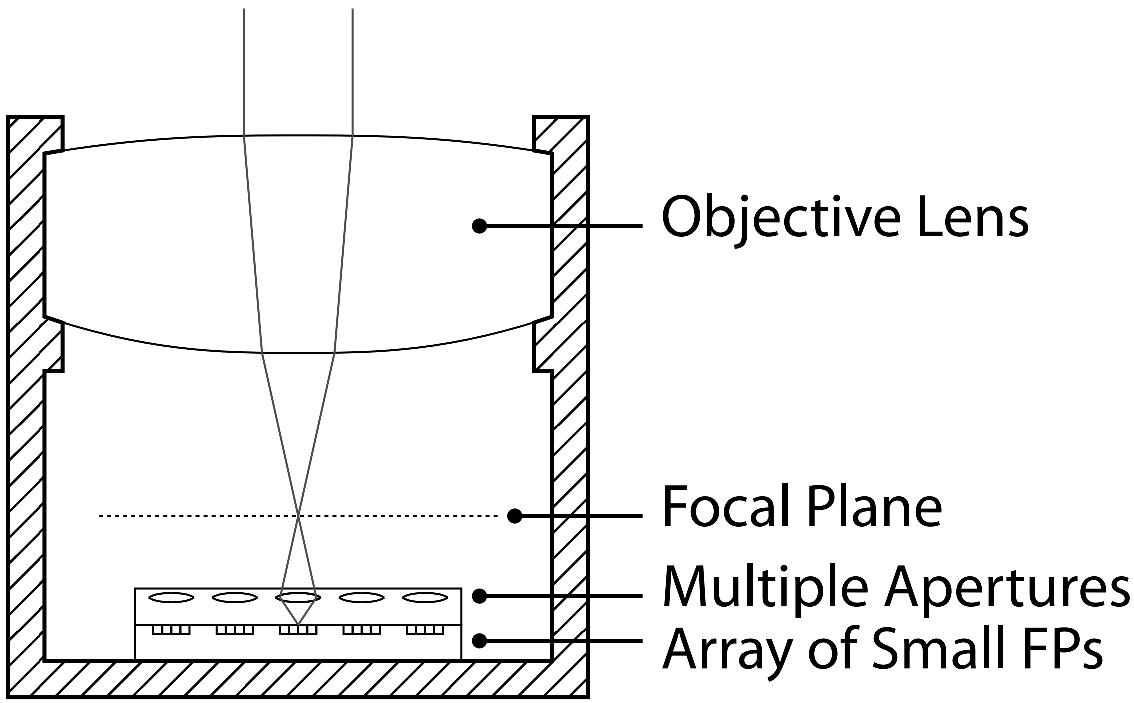
Outline

- Multi-Aperture system overview
- Sensor architecture and operation
- Image extraction
- Calculation of depth and resolution
- Sensor and System parameters
- Circuit Implementation

Multi-Aperture System

- **Scene focused via objective lens above detector plane**
- **Re-imaged via local optics onto disjoint arrays**
- **Arrays have overlapping fields of view**
- **Image is formed using digital signal processing**

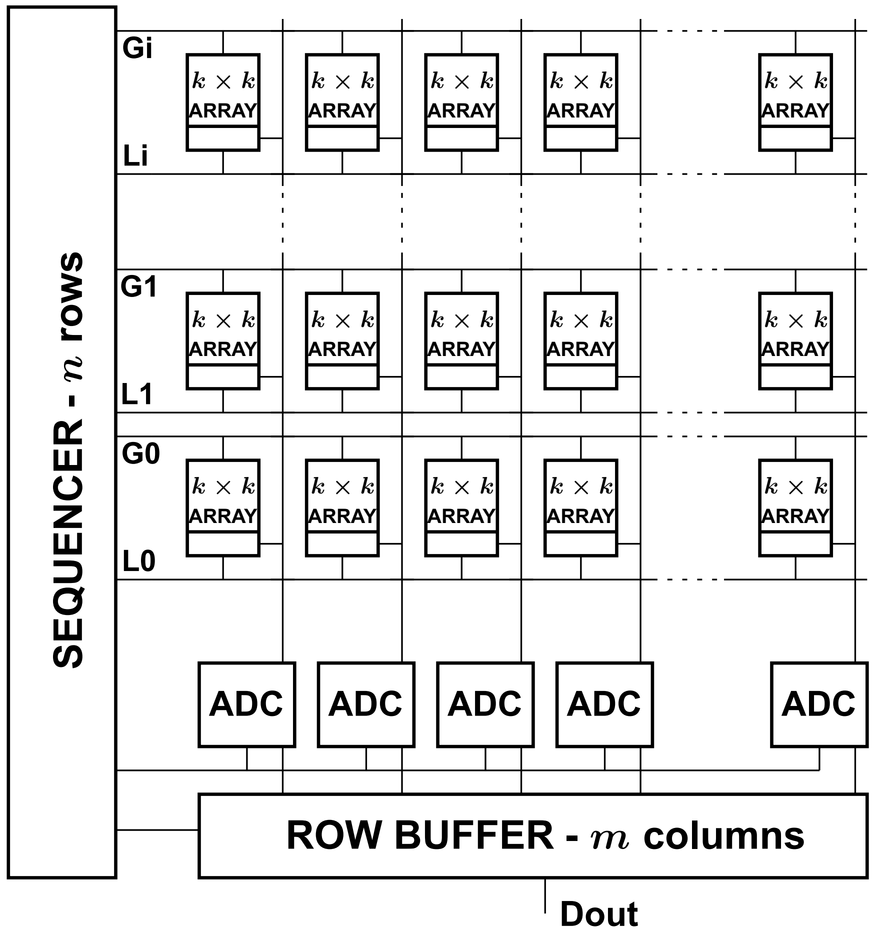


Why Multi-Aperture Imaging

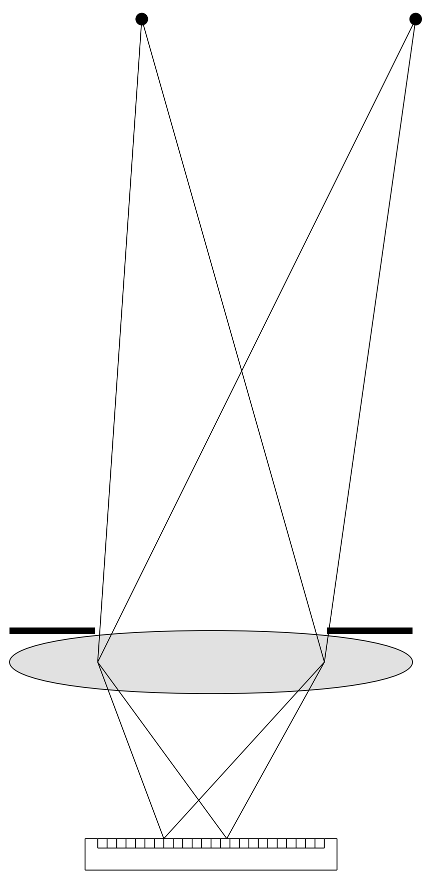
- Capture depth information
- Reduce requirements of objective lens (cheaper optics)
- Achieve better color separation (less crosstalk)
- Redundant data allows for manufacturing defect correction
- Facilitate new circuit design architectures
- Benefit from pixel scaling

Architecture

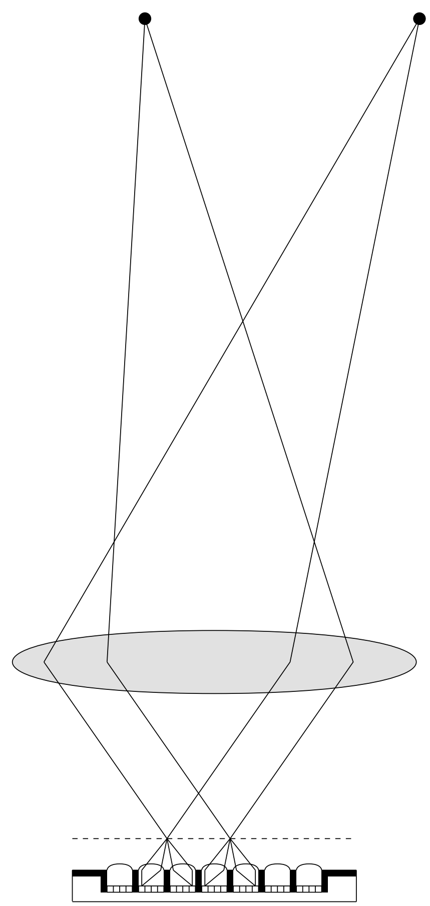
- **The sensor contains an $m \times n$ array of $k \times k$ pixel groups**



Traditional vs Multi-Aperture



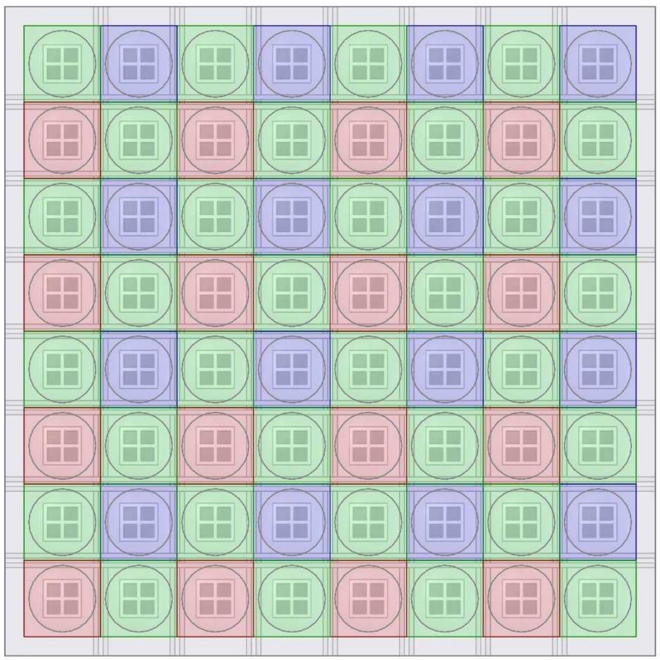
Traditional optical configuration

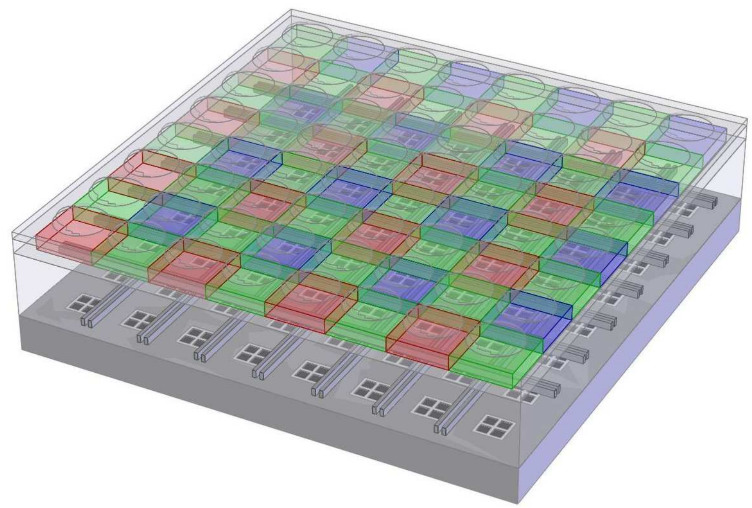


Multi-aperture optical configuration

Local Optics

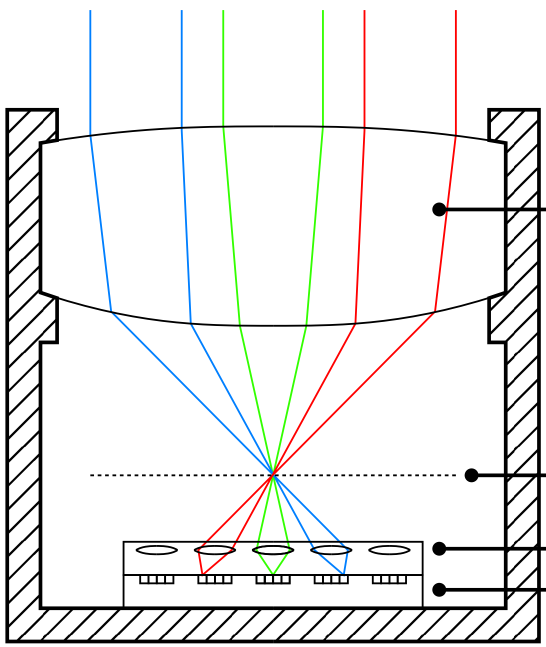
- **Local optics and Color Filter Array (CFA) can be built with CMOS Image Sensor (CIS) process**





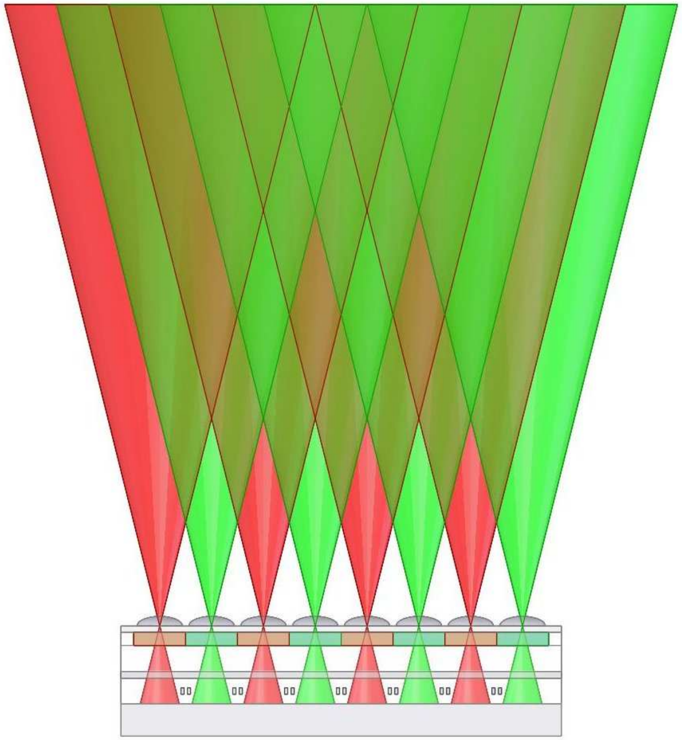
Multi-Aperture Color System

- **Spectral separation by aperture**
- **No color contamination from neighboring pixels**
- **Facilitates the use of large dielectric stack height which allows high logic density**



Projected Color Channels

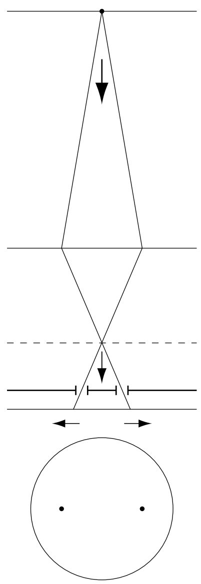
- **Color channels only overlap in the space above the detector**



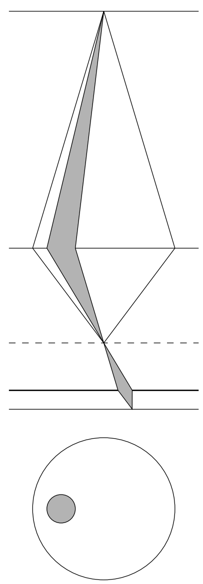
2D and 3D Image Extraction

- **Depth information is obtained from the disparity between apertures.**
- **Object movement translates to lateral displacement between corresponding points imaged by disjoint arrays.**
- **Solving the correspondence problem is eased by using several local apertures.**
- **The 2D image is formed by solving for the local correspondence and integrating the result across the sensor.**

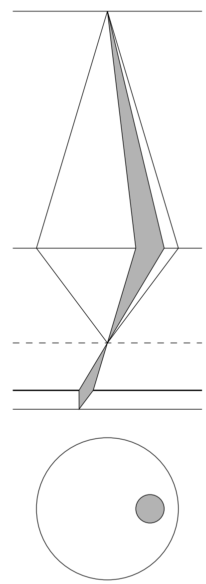
Virtual Aperture Views



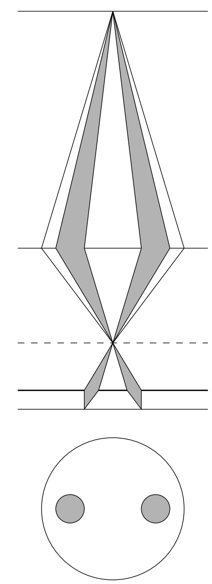
Chief rays for a pair of apertures



Left virtual objective aperture



Right virtual objective aperture



Virtual apertures for stereo view

Depth Calculations

- By the geometry of the local optics and focal plane,

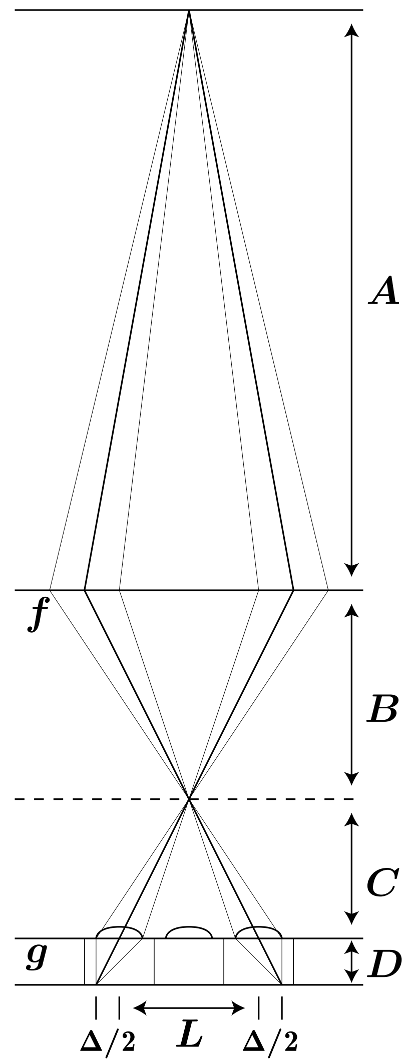
$$C/L = D_0/\Delta$$

- Using the lens law for A as a function of B and making the substitution $B = E - C = B_0 + C_0 - C$,

$$A = \left(\frac{1}{f} - \frac{1}{B}\right)^{-1} = \left(\frac{1}{f} - \frac{1}{B_0 + C_0 - C}\right)^{-1}$$

- Solving for A in terms of Δ with $M = B/A$ and $N = D/C$ gives the depth equation,

$$A = \left[\frac{1}{f} - \frac{1}{(M_0 + 1)f + D_0/N_0 - D_0 L/\Delta}\right]^{-1}$$



Depth Resolution Decreases with Distance

- **The amount of depth information available falls off with the square of the object distance.**
  - **Solving for a measured displacement gives,**

$$\Delta = \frac{D_0 L}{(M_0 - M)f + D_0/N_0}.$$

  - **As M decreases, Δ rapidly approaches its limit of $D_0 L/(M_0 f + D_0/N_0)$.**
  - **The rate of change in Δ with A,**

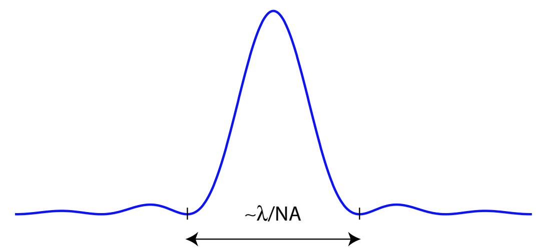
$$\partial\Delta/\partial A \approx -\frac{f^2}{A^2}\frac{DL}{C^2} \longrightarrow \partial\Delta/\partial A \approx -M^2 N^2 \frac{L}{D}.$$

Spatial Resolution and Pixel Size

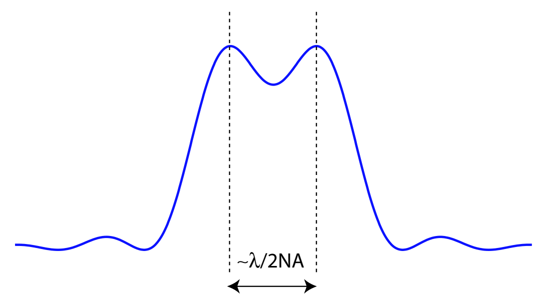
- **Spatial resolution is limited to the total number of pixels mnk^2.**
- **In order to achieve redundancy, the local magnification factor is set to $N < 1$.**
  - **Spatial resolution is reduced by $1/N^2$.**
  - **The total recoverable resolution is $\approx mnk^2N^2$**
- **Example: A 16×16 array of 0.5μm pixels with a magnification factor of $N_0 = 1/4$ produces a maximum resolution 16 times greater than the aperture count and 16 times lower than the pixel count.**

Spot Size Comparison

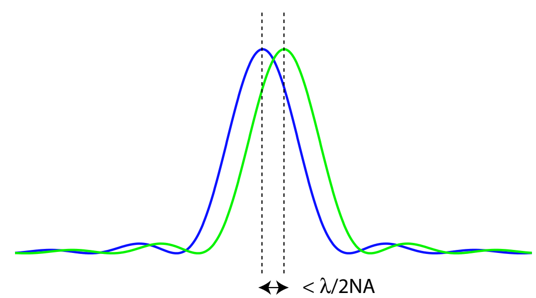
- The minimum spot size for a diffraction limited system is approximately λ/NA.



- The minimum useful pixel pitch is half the spot size using Rayleigh criterion.

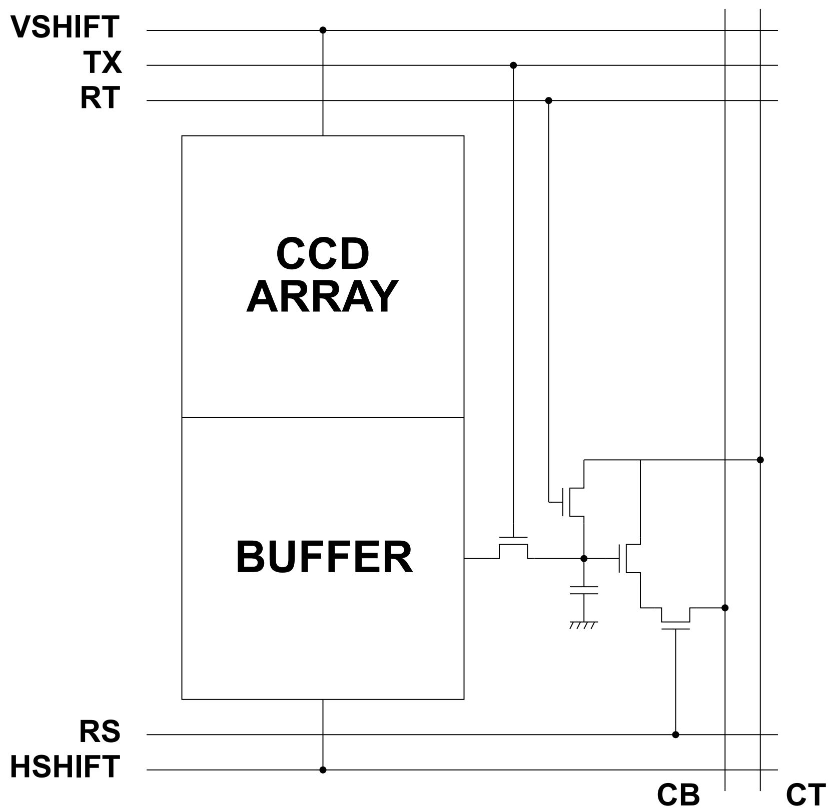


- Disparity from a Multi-Aperture system gives displacement which can be smaller than diffraction limit.



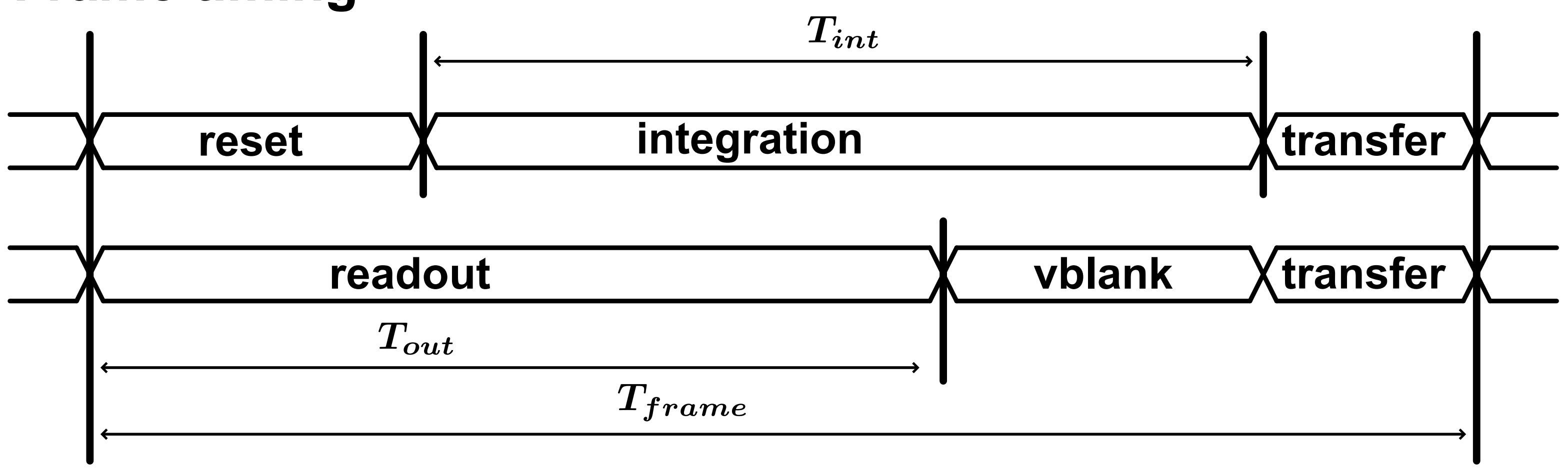
Pixel Structure

- **Single aperture array with local readout**
- **Architecture enables global exposure**

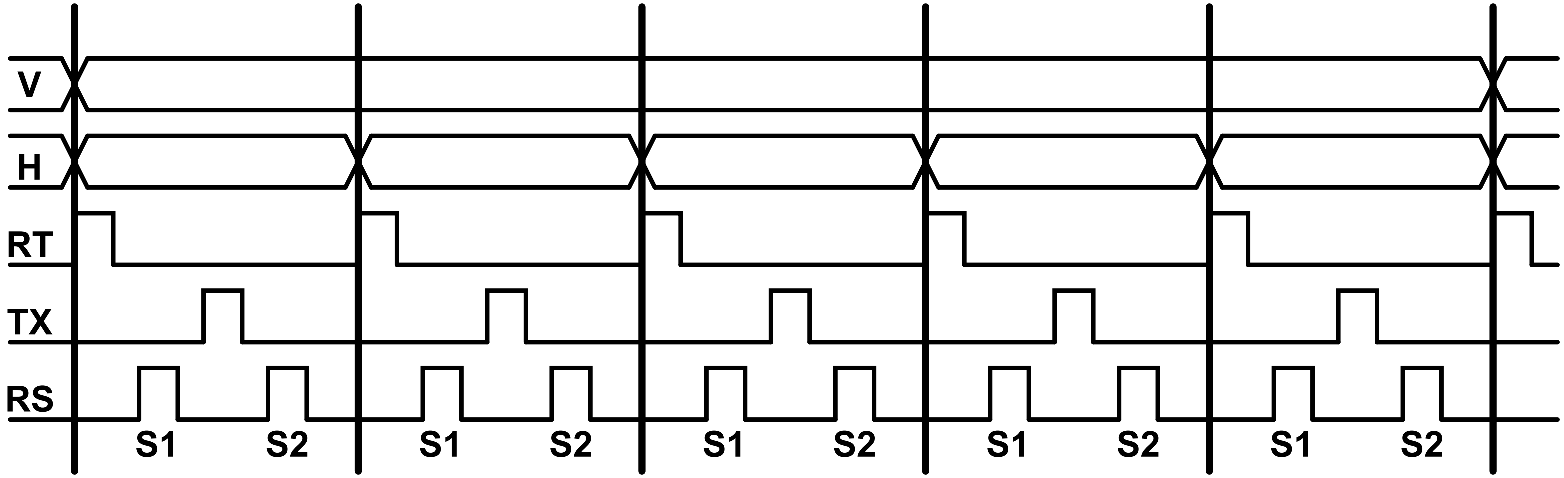


Capture and Readout Sequence

- **Frame timing**



- **Row timing**



Conclusion

- Depth map is extracted by solving the correspondence problem between multiple views of the same points in the primary focal plane.
- The spatial resolution of the system is shown to be greater than the aperture count itself and governed by the magnification of the local optics and pixel size.
- The amount of depth resolution available increases with decreasing pixel size while the 2D spatial resolution remains limited.
- The sensor architecture may be useful in improving the performance of color imaging by employing a per-aperture color filter.