Optical Flow Estimation Using High Frame Rate Sequences

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Programmable Digital Camera Project

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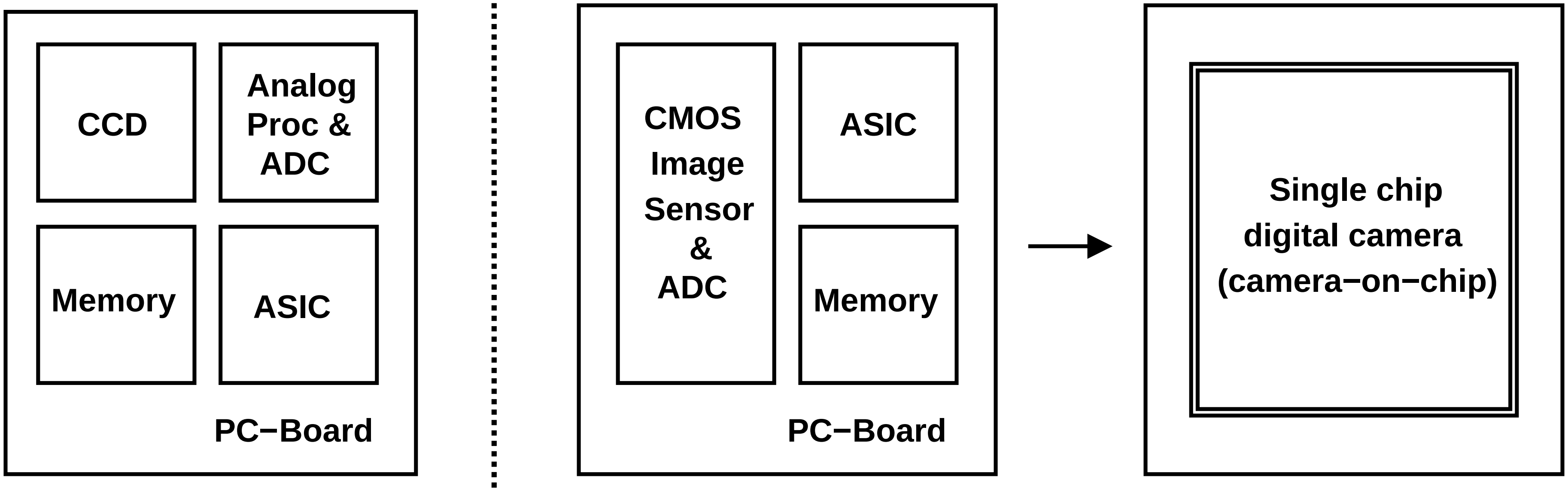
Digital Imaging System Implementation



- CMOS image sensor:
  - Integration of camera functions with sensor on same chip
  - Low power consumption
  - High frame rate imaging

High Speed CMOS Image Sensor Examples

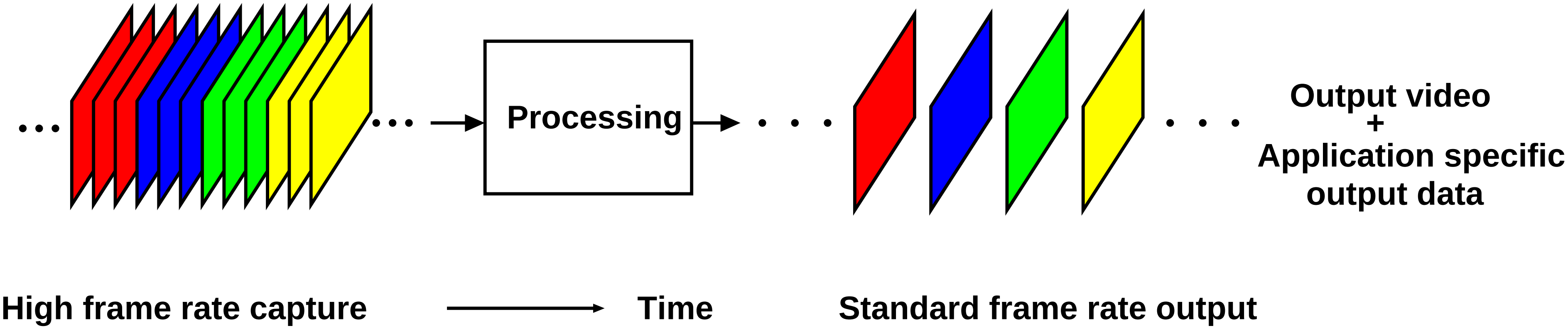
- **Fossum** *et al.* **(VLSI symposium 1999):**
  - **1024×1024 array with 500 fps**
  - **APS with 10μm×10μm pixel size**
- **Stevanovic** *et al.* **(ISSCC 2000):**
  - **256×256 array with 1024 fps**
  - **APS with 30μm×30μm pixel size**
- **Kleinfelder** *et al.* **(ISSCC 2001):**
  - **352×288 array with 10,000 fps**
  - **DPS with 9.4μm×9.4μm pixel size**
  - **ADC on each pixel**

Motivation

- Exploit high speed imaging capability to improve still and standard video rate imaging applications
  - Dynamic range enhancement
  - Motion blur-free capture
  - Optical flow estimation
  - Video stabilization
  - Super-resolution

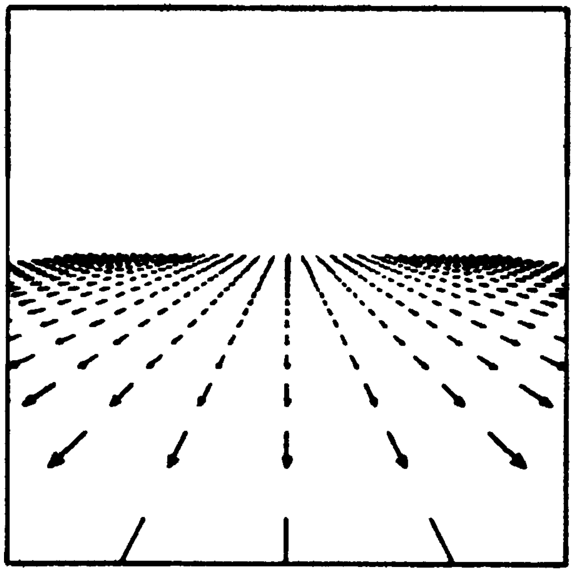
Integration of capture and processing on same chip makes system implementation feasible

Multiple Capture for Video/Data Enhancement

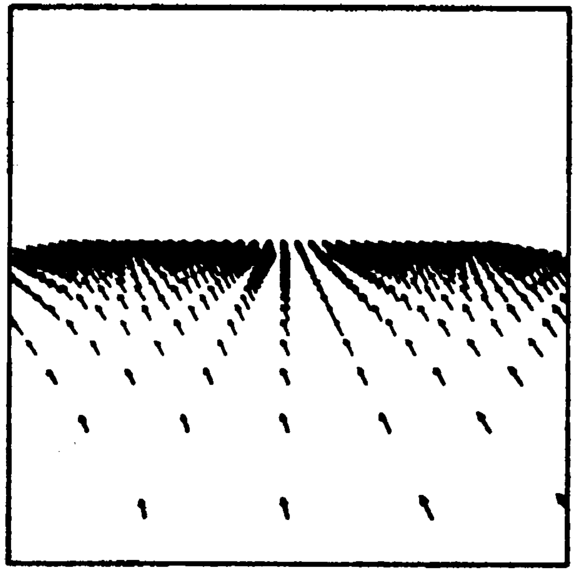


- Operate the sensor at high frame rate
- Process high frame rate data on-chip
- Output video with any application specific data at standard frame rate

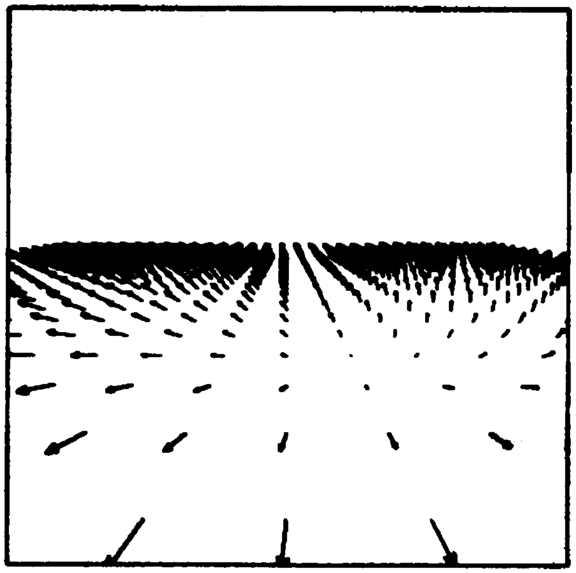
Optical Flow Estimation (OFE)



A



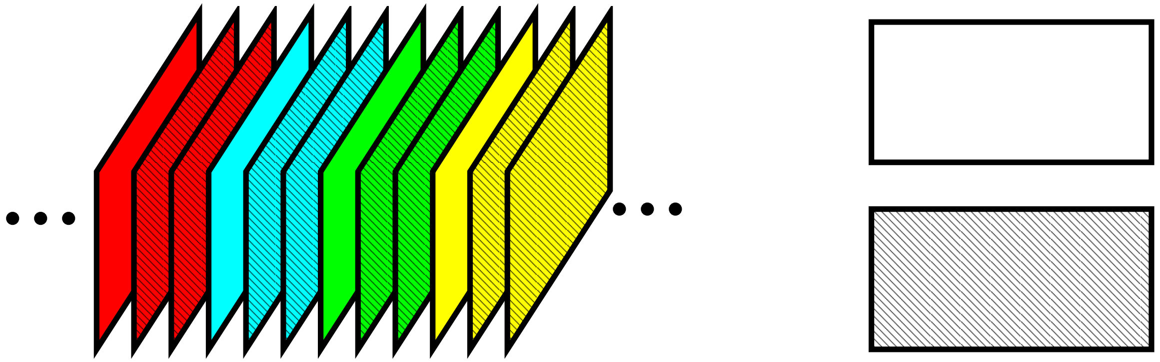
B



C

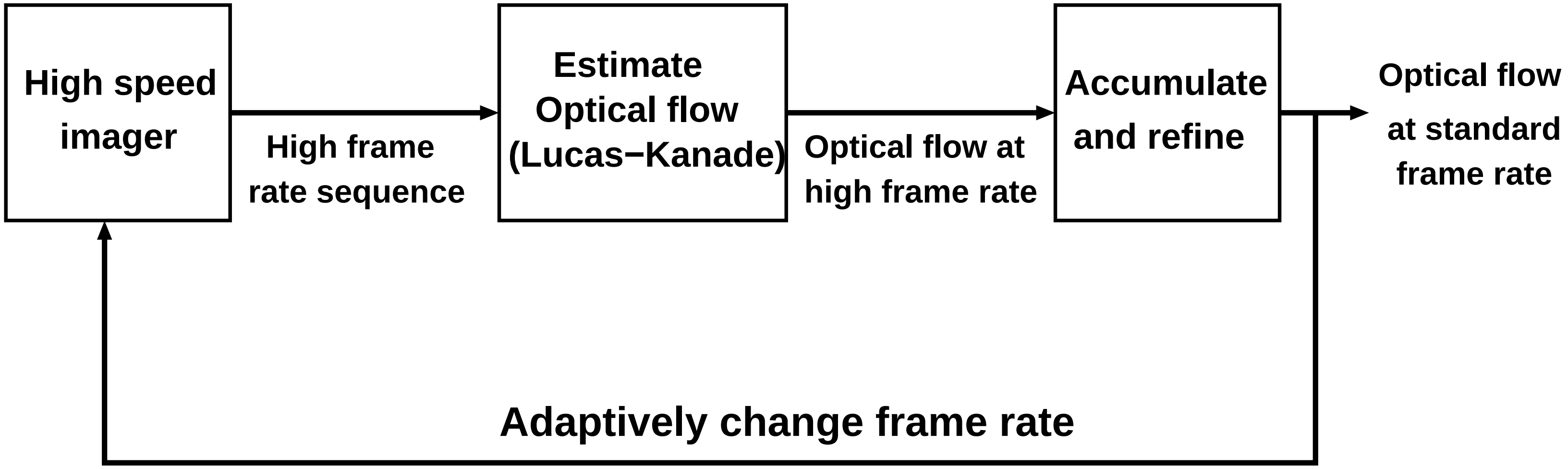
- Applications
  - 3D motion and structure estimation
  - Super-resolution
  - Image restoration
- Accuracy is of primary concern

Block Diagram of Our OFE Method



☐ Output frames

▨ Intermediate frames



High speed imager

High frame rate sequence

Estimate Optical flow (Lucas−Kanade)

Optical flow at high frame rate

Accumulate and refine

Optical flow at standard frame rate

Adaptively change frame rate

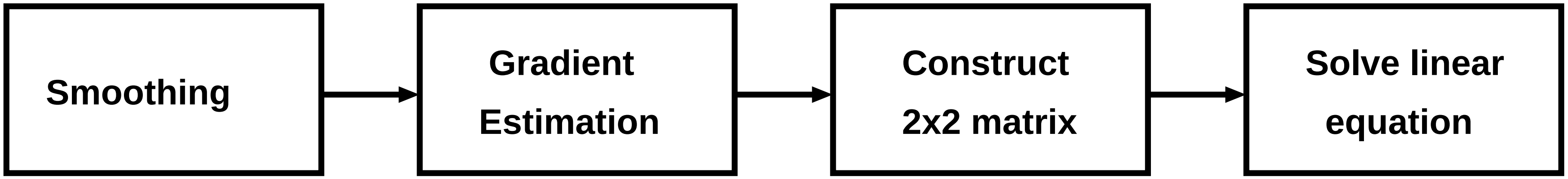
Effect of High Frame Rate on Optical Flow Estimation

- **Advantages for gradient-based methods**
  - **Brightness constancy assumption, *i.e.***

    $$\frac{dI(x,y,t)}{dt} = \frac{\partial I}{\partial x}v_x + \frac{\partial I}{\partial y}v_y + \frac{\partial I}{\partial t} = 0$$

    becomes more valid with higher frame rate
  - **Less temporal aliasing**
  - **Temporal derivatives better estimated**
  - **Smaller kernel size needed**
- **Disadvantages**
  - **Lower SNR**

Lucas-Kanade OFE Method



Smoothing

Gradient Estimation

Construct 2x2 matrix

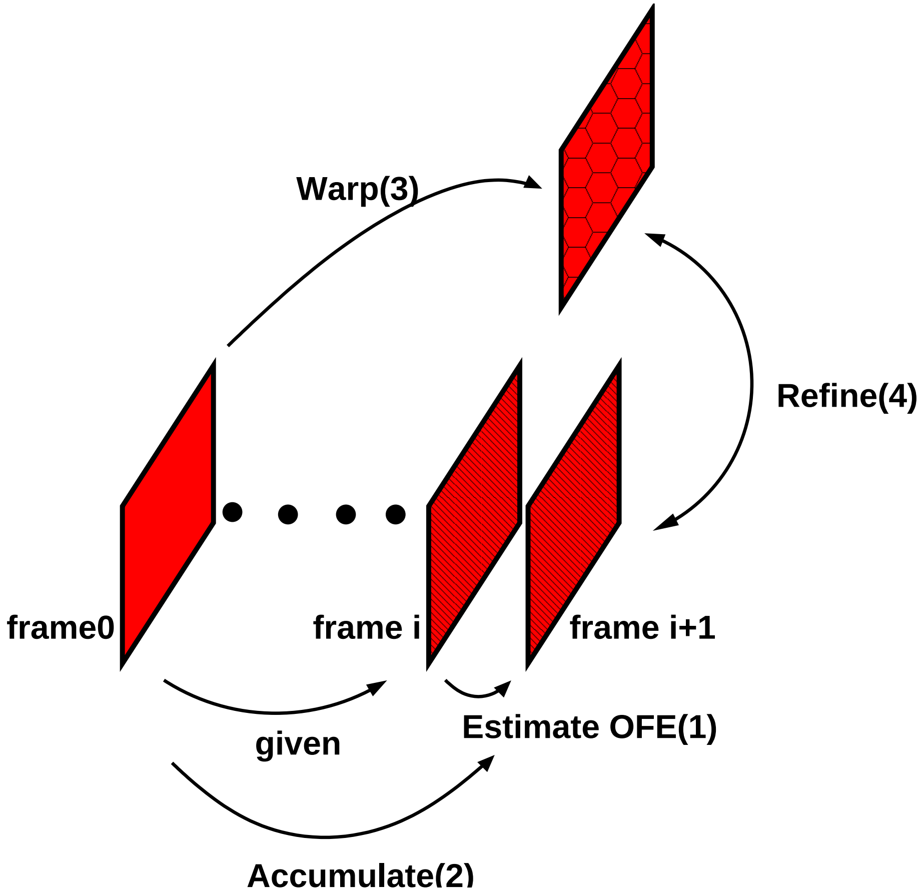
Solve linear equation

$$\begin{bmatrix} \sum wI_x^2 & \sum wI_xI_y \\ \sum wI_xI_y & \sum wI_y^2 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix} = - \begin{bmatrix} \sum wI_xI_t \\ \sum wI_yI_t \end{bmatrix}$$

- I_x,I_y and I_t are partial derivatives computed using 5-tap filters
- $w(x, y)$ puts more weight to the center of neighborhood (5×5)

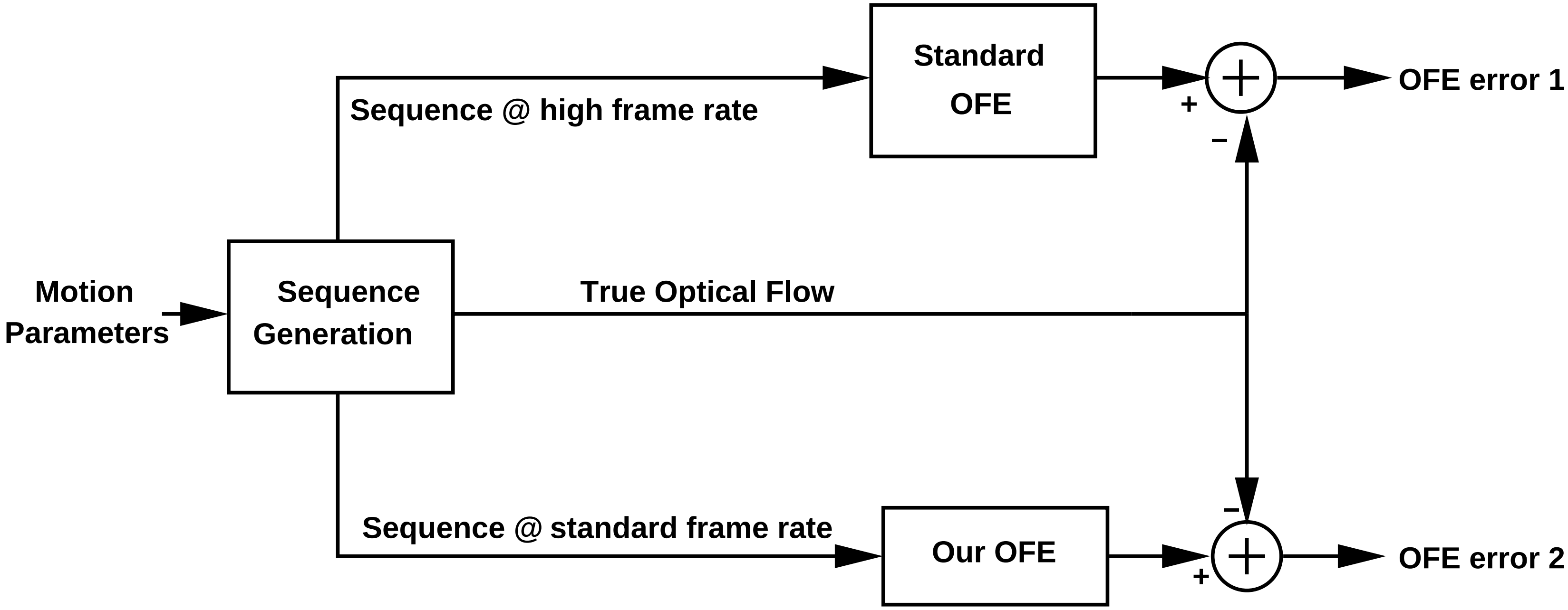
Accumulate and Refine

For $i = 0, \ldots, OV$:



OV is the temporal oversampling ratio

Experimental setup



- Displacement can be controlled and are known
- Motion blur and noise added
- Effect of frame rate on image quality included
- Standard OFE implemented by Barron *et. al*

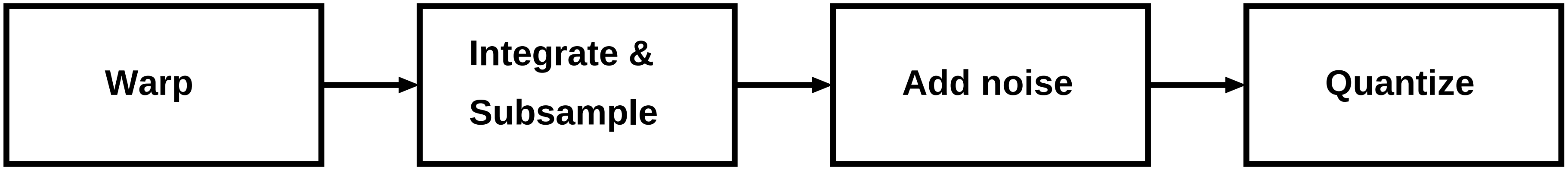
Video Sequence Model

- **The output charge from each pixel:**

$$Q(m,n) = \int_0^T \int_{ny_0}^{ny_0+Y} \int_{mx_0}^{mx_0+X} j(x,y,t)dxdydt + N(m,n)$$

  - **(m,n) is the pixel index**
  - **x_0 and y_0 are the pixel dimensions**
  - **X and Y are the photodiode dimensions**
  - **T is the exposure time**
  - **$j(x,y,t)$ A/cm^2 is the photocurrent density**
  - **$N(m,n)$ is the noise charge**
- **Pixel intensity, I, proportional to $Q(m,n)$**

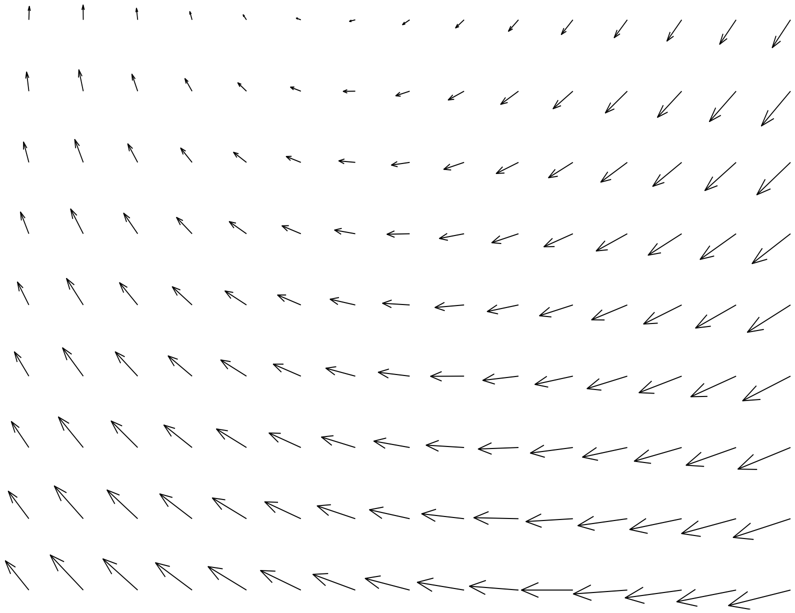
Synthetic Sequence Generation



1. Warp a high resolution (1312 × 2000) image using perspective warping
2. Integrate and subsample spatially (4 × 4) and temporally (10)
3. Add readout noise and shot noise according to the model
4. Quantize the sequence

Example Original Scene and Optical Flow

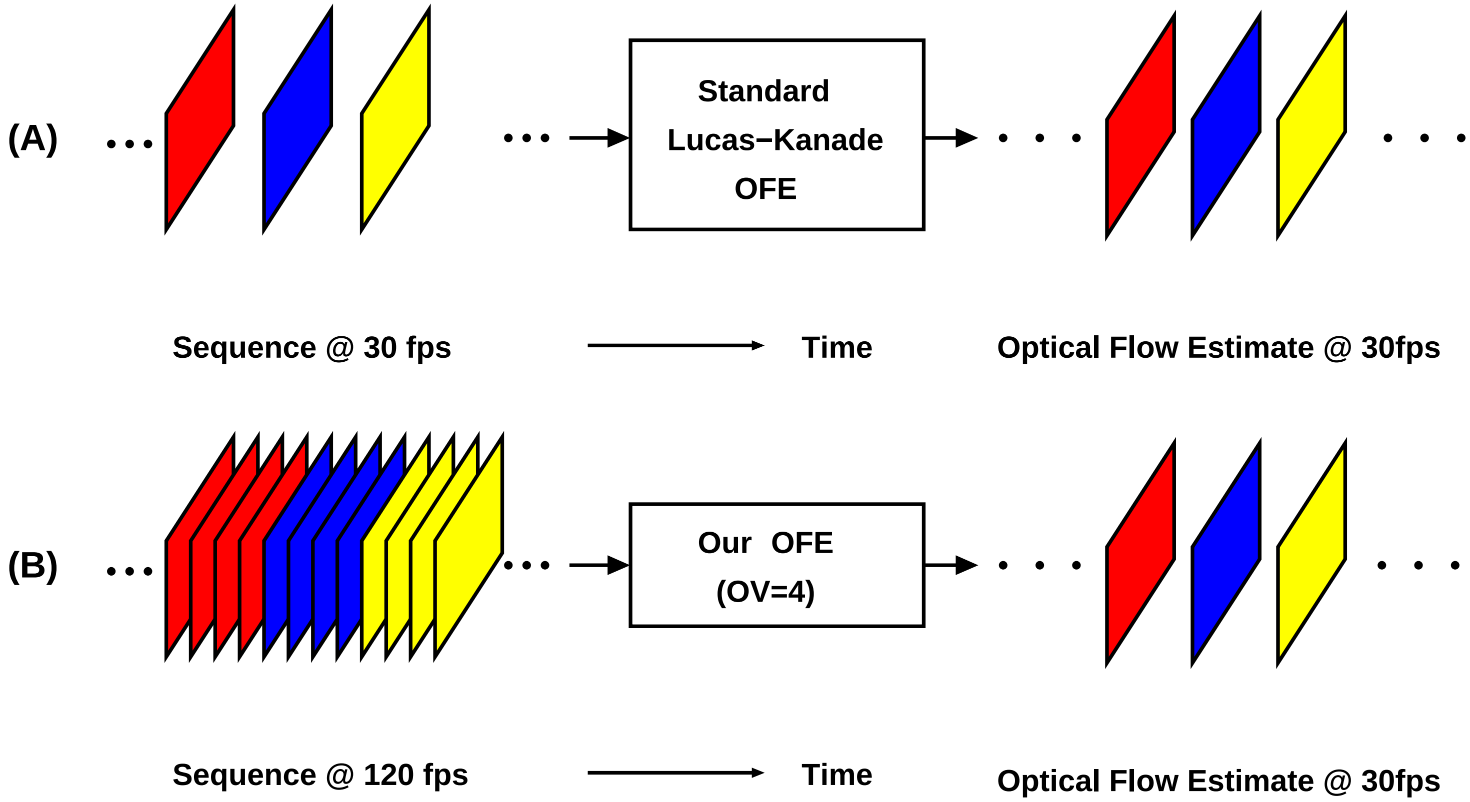
Original scene



Optical flow

Experiment I

Compare standard Lucas-Kanade OFE and our OFE



Displacement < 4 pixels/frame at standard frame rate

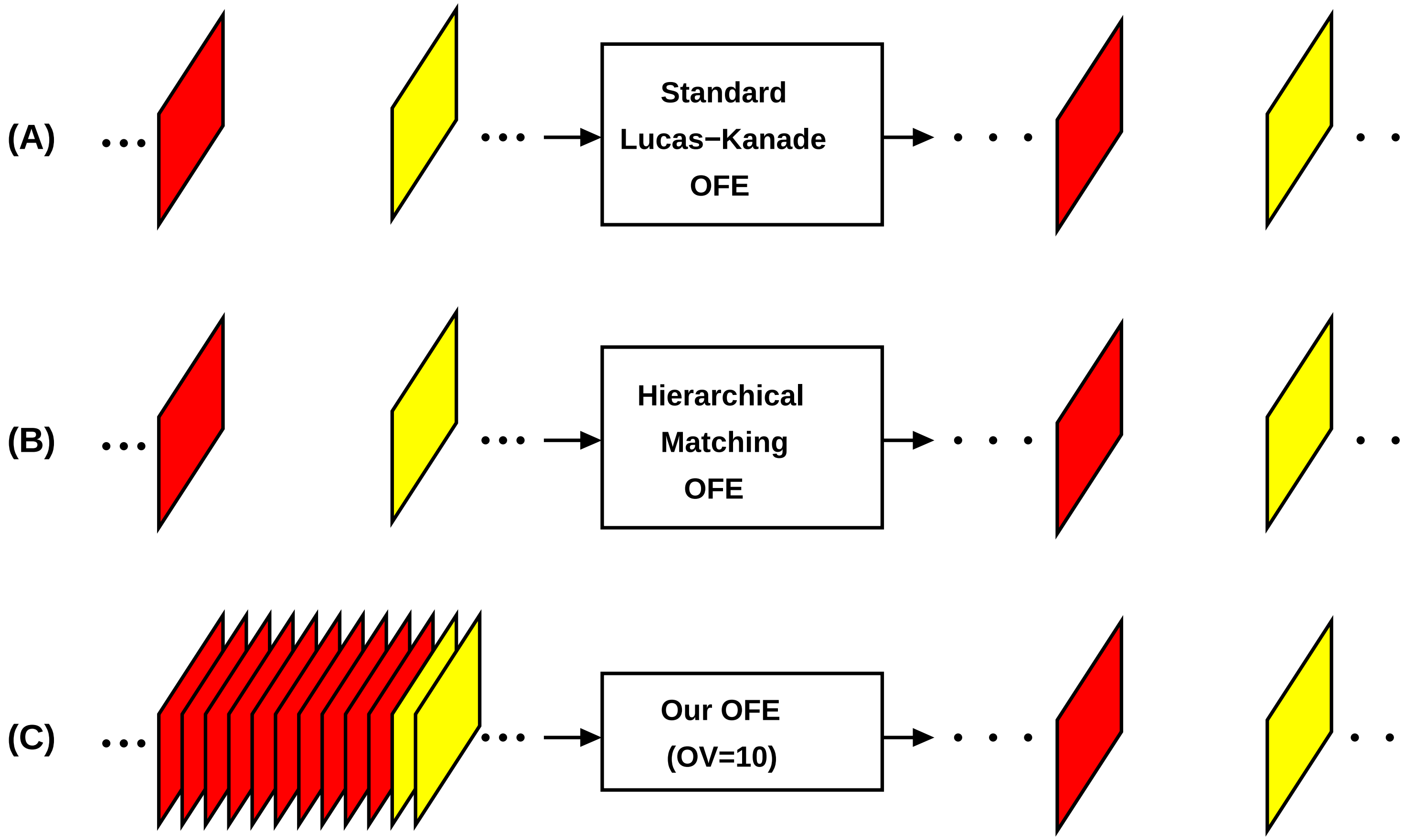
Result I

Scene	Lucas−Kanade method (A)		Our method (B)	
	Angular error	Density	Angular error	Density
1	4.43°	55.0%	3.43°	55.7%
2	3.94°	53.0%	2.91°	53.4%
3	4.56°	53.5%	2.67°	53.4%

- Higher accuracy achieved with our method
- More difference when brightness constancy does not hold
- Temporal filters
  - Our method: 2-tap
  - Lucas-Kanade method: 5-tap

Experiment II

Investigate accuracy gain for large displacements



Displacement $<$ 10 pixels/frame at standard frame rate

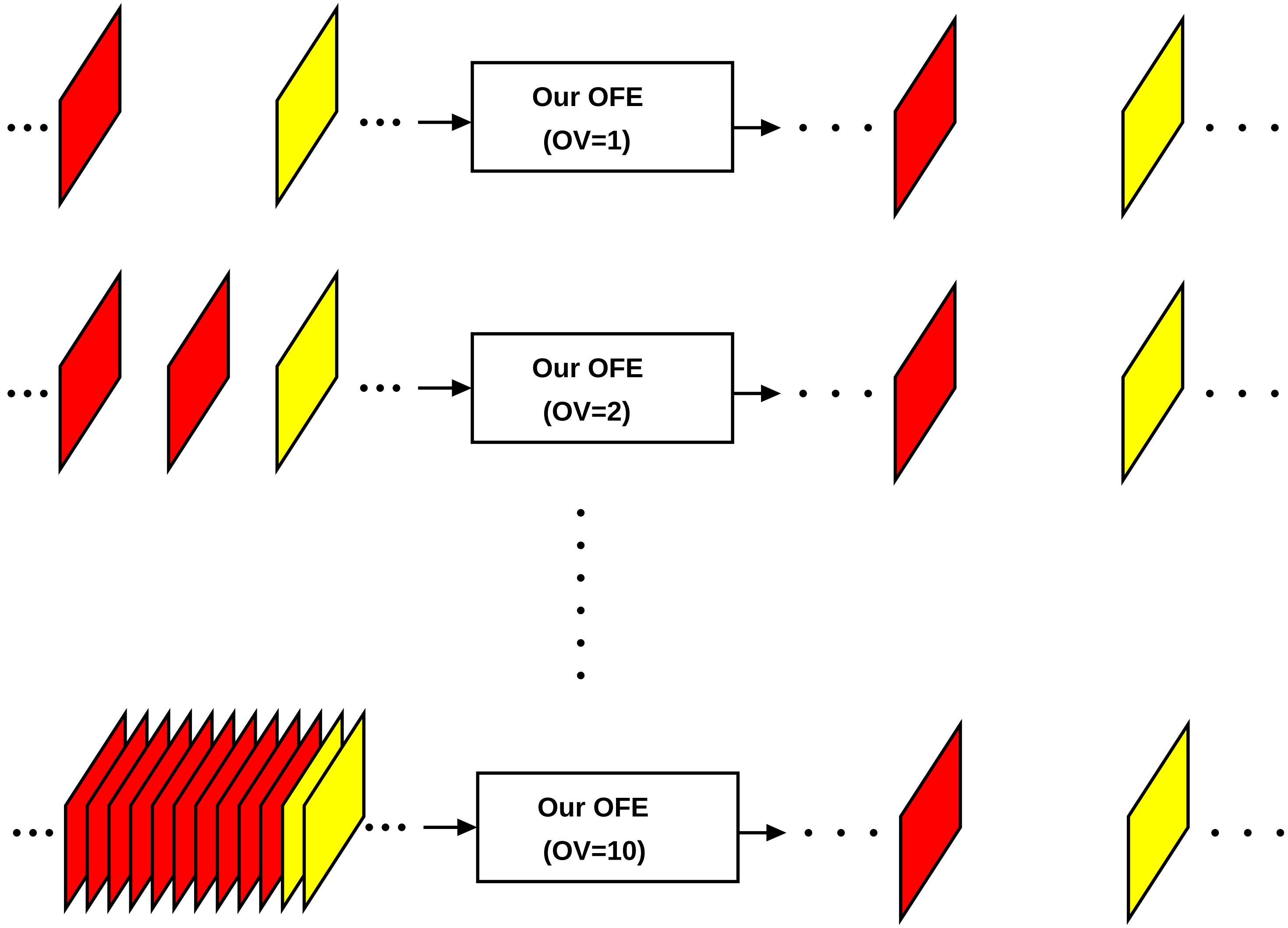
Result II

	Angular error	Density
Lucas−Kanade method	9.18°	50.81%
Hierarchical matching method	4.72°	100%
Our method (OV=10)	1.82°	50.84%

- Standard Lucas-Kanade method deteriorates for large displacements
- Hierarchical matching method has 100% density but lower accuracy
- Our method works well for both small and large displacements

Experiment III

Investigate the effect of varying OV on accuracy

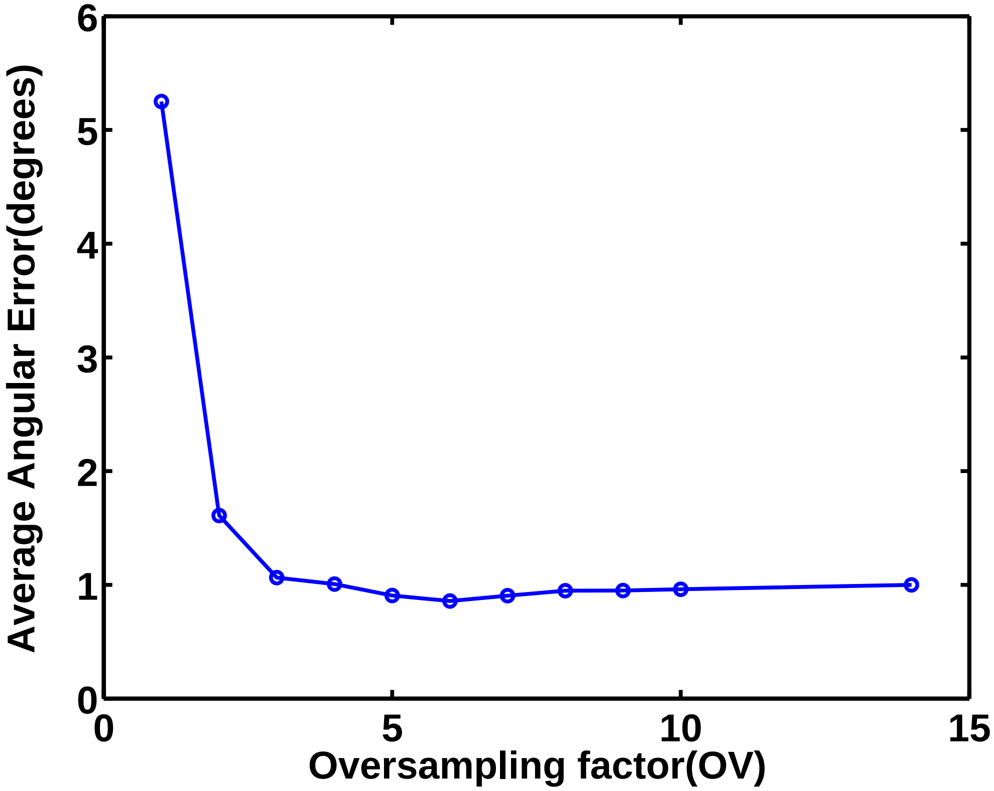


Our OFE (OV=1)

Our OFE (OV=2)

Our OFE (OV=10)

Result III



Temporal aliasing, temporal gradient estimation error, failure in brightness constancy and sensor SNR are affected by OV

Hardware Complexity

	Our method	**Lucas−Kanade method**
Memory (bytes)	$12mn$	$16mn$
Operations	$190mnOV$	$105mn$

- Assumptions:
  - $m \times n$ image with oversampling factor of OV
  - 5-tap spatial filter for gradient estimation and smoothing
  - 2-tap temporal filter for our method and 5-tap for Lucas-Kanade method
- Note memory requirement is independent of OV since our method is iterative

Conclusion

- High frame rate and integration capabilities of CMOS image sensors can be exploited to improve the performance of video processing applications
- Developed a method for accurate optical flow estimation using high frame rate sequences
- Demonstrated that our method
  - obtains higher accuracy than OFE using standard frame rate sequences
  - works well for large displacements
  - requires modest memory and computational power since our method is iterative