STELLAR

Spatio **T**emporal **L**ow **L**ight **AR**chitecture

Prasanna Pavani
Arecont Vision
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Low Light Video Processing

- Noise vs. Motion
  - Low photons produce noisy images
  - Increasing exposure time to reduce noise increases motion blur

- 3D Video Filtering
  - Filters video both in space (2D) and time (1D)
  - Decreases noise without increasing motion blur

Problem: 3D video filtering is complex

- Computationally expensive
  - patch processing required to compensate motion
- High memory and bandwidth
  - computes a denoised image from multiple frames
- Artifacts
  - threshold separating motion from noise leads to unstable separation in low-contrast regions
  - temporal filtering degrades after demosaicing

Invention: **S**patio **T**emporal **L**ow **L**ight **Ar**chitecture (STELLAR)

- Computationally inexpensive
  - motion is compensated with weights without patch processing
  - rigid object processing allows denoising of moving objects with dozens (instead of millions) of patches

- Low memory and bandwidth
  - denoised image generated from only 2 frames (current, reference)
  - reference frame encodes information from multiple previous frames
  - denoising of moving objects requires 3 frames (current, previous, reference)

- No artifacts
  - weights replace thresholds to separate noise from motion
  - STELLAR operates before demosaicing to avoid temporal artifacts
  - compensates for signal dependent (shot) noise

STELLAR Algorithm

Part 1: Temporal

- STELLAR denoising without motion blur
- Requires storage of 2 frames (current, reference)

$$\text{Stellar temporal frame} = \mathrm{I}_{st} = \frac{\mathrm{I_t} + \beta \mathrm{W} \mathrm{I_r}}{1 + \beta \mathrm{W}},$$

$$\text{where, Weight} = \mathrm{W} = \frac{\sqrt{\mathrm{H_r}}}{|\mathrm{H_t} - \mathrm{H_r}| + \mathrm{c}}$$

$$\text{and, reference} = \mathrm{I_r} = \begin{cases} \mathrm{R_t} & ;\ \mathrm{t} = 1 \\ \dfrac{\mathrm{I_t} + \beta \mathrm{I_r}}{1 + \beta} & ;\ \mathrm{t} > 1 \end{cases}$$

$$\text{and, current frame} = \mathrm{I_t} = \begin{cases} \mathrm{R_t} & ;\ \mathrm{t} = 1 \\ \dfrac{\mathrm{R_t} \sum \sum \mathrm{I_r}}{\sum \sum \mathrm{R_t}} & ;\ \mathrm{t} > 1 \end{cases}$$

$$\text{and, ref. weight} = \beta = \begin{cases} \mathrm{t} - 1 & ;\ \mathrm{t} < \mathrm{K} \\ \mathrm{K} & ;\ \mathrm{t} \geq \mathrm{K} \end{cases}$$

$$\text{and, } \mathrm{H_x} = \mathrm{I_x} * \mathbf{1}(\mathrm{b}, \mathrm{b})$$

- $\mathrm{R_t}$: raw frame
- β: reference weight
- b: block size
- K: max. weight
- c: raiser
- **1**: matrix of ones

STELLAR Algorithm

Part 2: Spatial

- STELLAR denoising without edge blur

1. Extract R, G1, G2, B from raw bayer image
2. For each color channel, perform:

$$\text{Stellar frame} = \mathrm{S}_t = \frac{\mathrm{I}_{st} + b^2\mathrm{W}\mathrm{I}_\mathrm{r}}{1 + b^2\mathrm{W}},$$

$$\text{where, Weight} = \mathrm{W} = \frac{\sqrt{\mathrm{I}_\mathrm{r}}}{|\mathrm{I}_{\mathrm{st}} - \mathrm{I}_\mathrm{r}| + \mathrm{c}}$$

$$\text{and, reference} = \mathrm{I}_\mathrm{r} = \mathrm{I}_{\mathrm{st}} * \mathbf{1}(\mathrm{b}, \mathrm{b})$$

- I_{st}: Stellar temporal frame
- b: block size
- c: raiser
- **1**: matrix of ones

3. Reform ‘grbg’ bayer image

STELLAR Algorithm

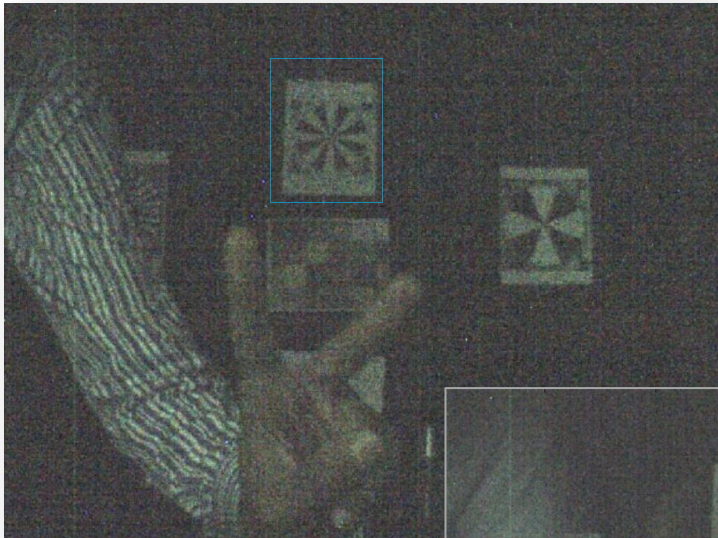
Part 3: Motion denoising

- STELLAR denoising of moving objects exploits the fact that pixels of rigid objects move in unison
- Requires storage of 3 frames (current, previous, reference)

1. Perform STELLAR: Part 1
2. Identify M large rigid objects from $(\mathrm{H_t} - \mathrm{H_r}) > 0$
   a. adaptive theshold computed from noise statistics
3. Compute centroids of rigid objects
4. Find matching patches in previous frame for image patches around each centroid
5. Average individual pixels of rigid objects with their counterparts in previous frame
   a. Counterparts are located with respect to centroid, so there is only one patch processing per rigid object

Prior Art Literature

- US Patent US7034892: Spatio-temporal filter unit and image display apparatus comprising such a spatio-temporal filter unit, Philips (2001)
- US Patent US8446964: Method and system for noise reduction with a motion compensated temporal filter, Broadcomm (2005)
- US Patent US8320698: System and method for denoising using signal dependent adaptive weights, Sony (2008)
- US Patent US8345971: Method and system for spatial-temporal denoising and demosaicking for noisy color filter array videos, HKPU (2010)



Raw frame
at 0.01 lux

Raw

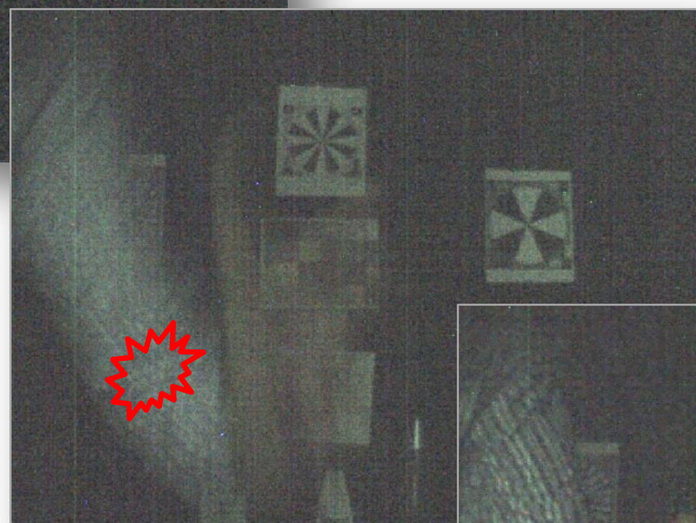
SNR: 16.9dB

STELLAR

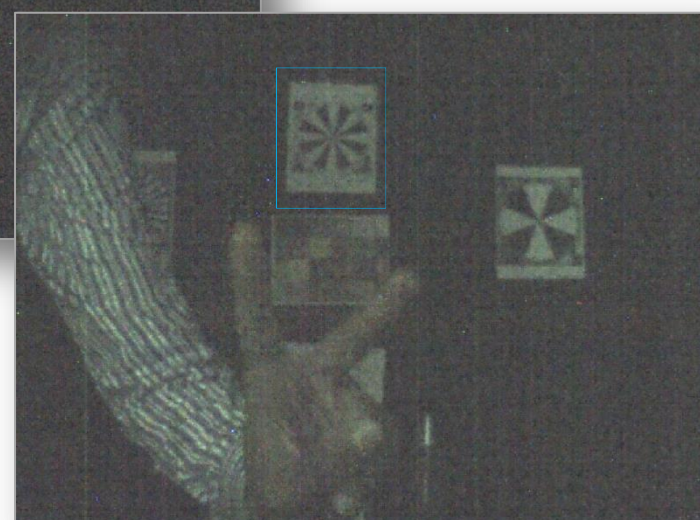
SNR: 23.3dB

STELLAR pixel collects **4.4x more light** than regular pixel without compromising resolution

Average of
10 frames



Motion blur



STELLAR
frame