System and Method for Color Imaging under Low Light

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Imaging at 0 lux

- Low-light cameras can't handle 0 lux
  - 0 lux means practically no light on scene
  - For example, moonless overcast night: 0.0001 lux ≈ 0 lux

- External illuminators are necessary at 0 lux
  - IR illuminators
    - Monochrome
    - Covert / non-intrusive
  - White light illuminators
    - Color
    - Crime deterrent

Problem: Color imaging at 0 lux

- Traditional approach
  - Color camera
  - White illuminator

- Traditional approach is inefficient
  - Bayer color filter allows only 20% of light entering the camera to be detected
  - Illuminator power limited by PoE (13W in class 3)

- Problems in traditional approach
  1. Increased noise in color images due to low light efficiency
  2. Color crosstalk because of leakage between neighboring pixels
  3. Spatial resolution degradation due to Bayer color filter array

Invention: Spectral multiplexing for super-resolved color imaging

Frame	Red LED	Green LED	Blue LED
Red	ON	OFF	OFF
Green	OFF	ON	OFF
Blue	OFF	OFF	ON
Dark	OFF	OFF	OFF

- Multicolor Illuminator
  - Red/Green/Blue LEDs turn ON at different times
- Camera
  - Monochrome sensor synchronized with illuminator
- Processing
  - R, G, B, and D (dark) monochrome images are combined to produce a true color image with higher resolution than native sensor resolution
  - Color image thus formed has lower noise than a color image from a Bayer color sensor
  - Motion compensation
    - Corrects for color artifacts induced by moving objects
  - True color image generation
    - D image is used to compensate for any residual ambient lighting in scene for enhanced color fidelity
  - Adaptive illumination based on scene content for enhanced color imaging under low-light
    - Scene color metric is estimated
      - Example: Average color levels of R, G, and B in scene
    - Brightness and duty cycle of individual LEDs are adjusted based on scene color metric to produce high-quality color image
      - Example: A scene with less reflectance in blue produces a noisy blue image. This could be compensated by increasing the brightness of blue LEDs.

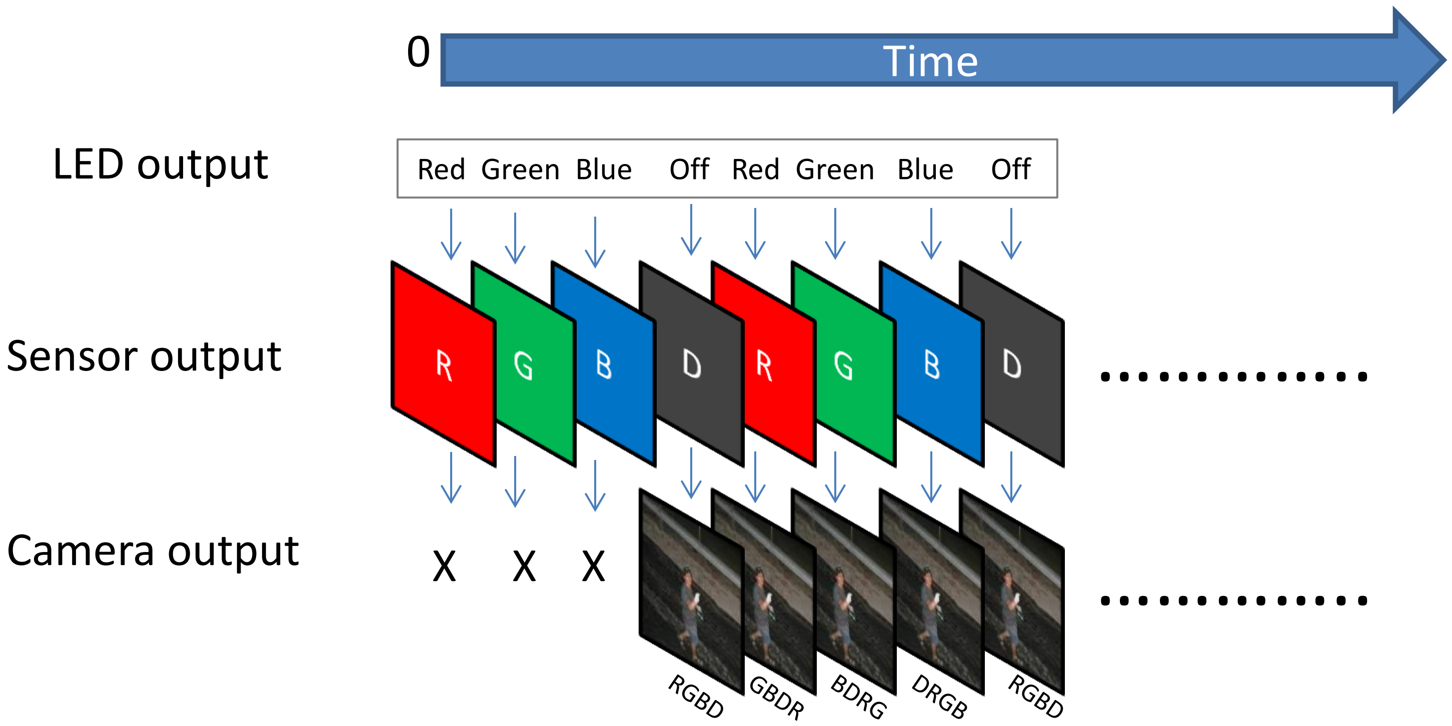
Processing steps

1. Detect R, G, B, and D frames
2. D frame is subtracted from R, G, and B frames to compensate for ambient lighting
3. An intermediate color frame (Cit) is generated by using {R-D, G-D, B-D} frames as the {Ri,Gi,Bi} color components of Cit
4. Find moving pixels in Cit by calculating the sum of absolute differences of Cit and Ct-1, where Ct-1 is the generated color frame from a previous time
5. Generate Ct, the true color image for time t, by replacing colors in moving regions of Cit with their true color
6. True color of a moving pixel is determined as the majority color of the moving pixel's non-moving neighborhood
7. Compute scene color statistics and adaptively adjust the illumination levels of R, G, and B for enhancing image quality under low-light

Characteristics of proposed solution

- High sensitivity color imaging
  - ~4x more light detection than traditional approach
- High resolution with no frame rate reduction
  - 3.3x higher resolution due to lack of Bayer arrangement
- Flexibility
  - LEDs available with various colors, unlike Bayer filters
  - Example: Designing a [R, G, B, W] camera is straightforward

No reduction in frame rate



- At any given time, current frame is combined with previous three frames to generate the color image
- Frame rate is identical to sensor frame rate

3.3x higher resolution

[Example: 33MP with one 10MP sensor!]

- Traditional Bayer image with *m* rows and *n* columns
  - R pixels: ${}^{m*n}/_{4}$
  - G pixels: ${}^{m*n}/_{2}$
  - B pixels: ${}^{m*n}/_{4}$

- Demosaiced color image
  - R interpolation factor: 4x
  - G interpolation factor: 2x
  - B interpolation factor: 4x
  - Average interpolation factor: 3.3x

- Spectral multiplexing
  - R pixels: $m * n$
  - G pixels: $m * n$
  - B pixels: $m * n$
  - Processed image with Bayer equivalent resolution: $3.3 * m * n$

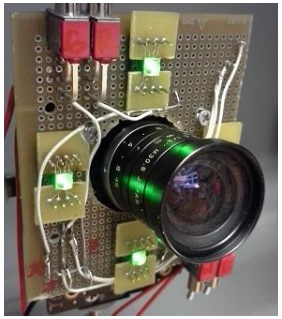
Reducing invention to practice

[Preferred embodiment]

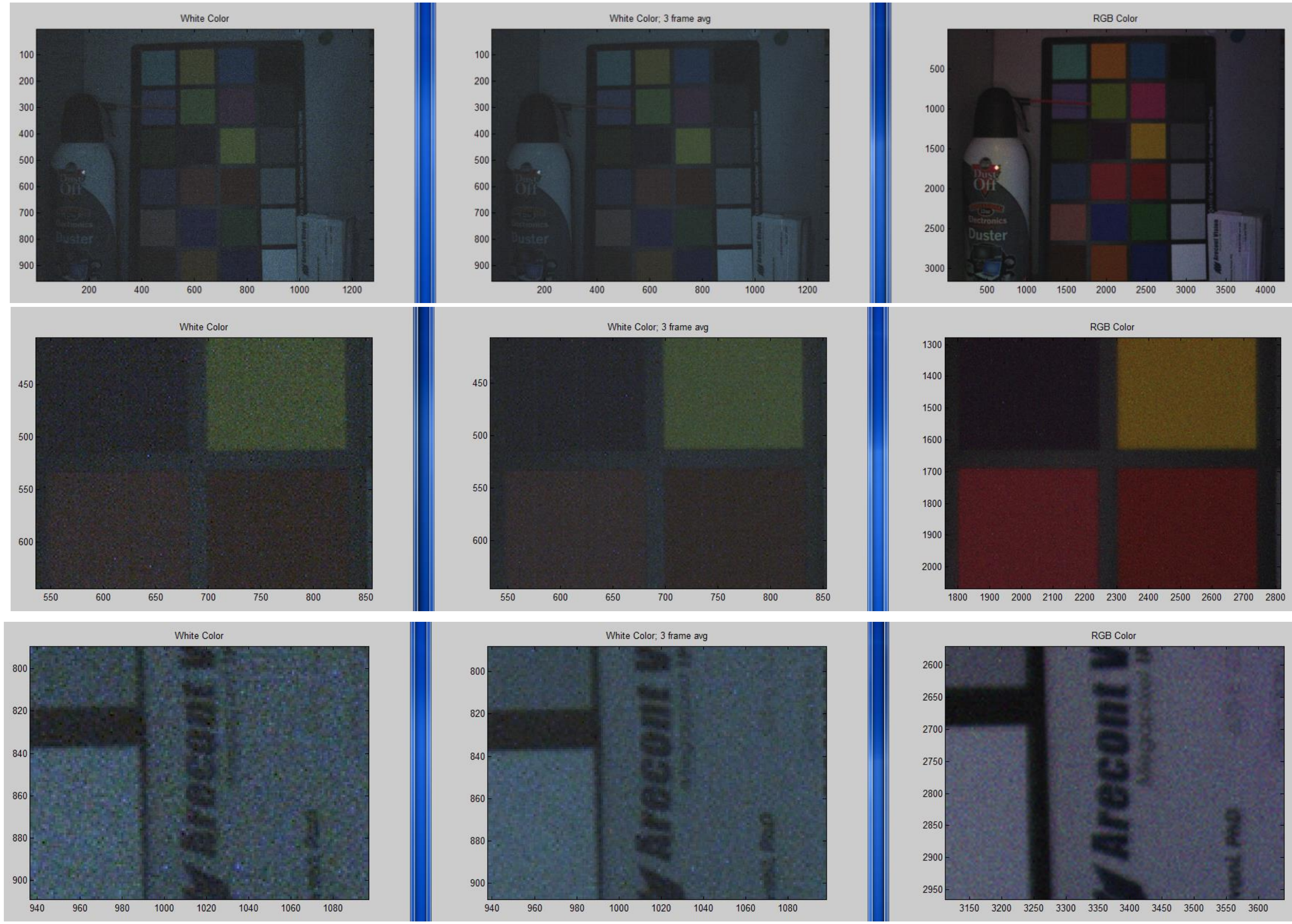
- Modulating LEDs could cause perceptible flicker
  - Frame rates >75 fps required to make flicker imperceptible
  - However, flickering visible LEDs could be a deterrent for crime

- Illumination crosstalk
  - Multiple cameras viewing the same scene are synced to avoid color crosstalk

RGB illuminator prototype



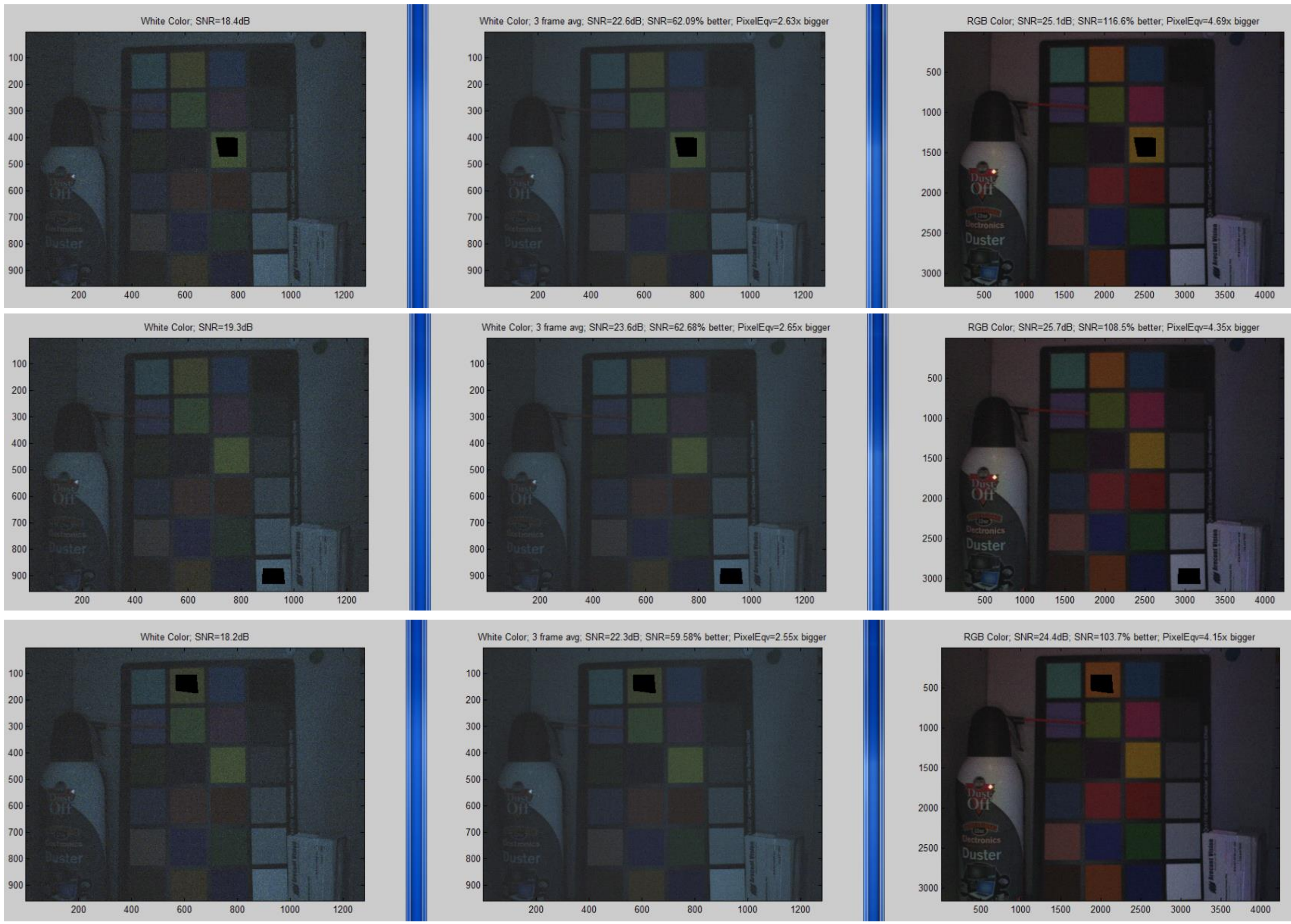
Results: Resolution Enhancement



3.3x resolution improvement!

Results: Noise reduction

>6dB SNR improvement!



Prior Art

- US20130027596 A1, Color imaging using time-multiplexed light sources and monochrome image sensors with multi-storage-node pixels, (Aptina, 2013)
- US5523786 A, Color sequential camera in which chrominance components are captured at a lower temporal rate than luminance components (Kodak, 1993)
- US5264925 A, Single sensor video imaging system and method using sequential color object illumination, Life surgery (1993)
- US4845553 A, Image data compressing device for endoscope (Olympus, 1989)