Automotive Image Sensors

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Outline

Automotive Image Sensor Market and Applications

Viewing Sensors
  • HDR
  • Flicker Mitigation

Machine Vision Sensors
  • In cabin monitoring
  • LiDAR

Conclusions
Automotive Imaging Segments

Rear View Camera (RVC)

Surround View System (SVS)

Camera Monitor System (CMS)

FVMV

DMS/IMS
Automotive Image Sensor TAM

Image sensors global TAM

<table>
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<tr>
<th>Year</th>
<th>RVC</th>
<th>SVS</th>
<th>FV/MV</th>
<th>CMS</th>
<th>DMS</th>
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kk/yr
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Viewing Sensor Technology Trends

- High dynamic range
- Flicker mitigation
- Low light sensitivity
- Larger format
- Lower cost

Camera Monitor System (CMS)
Dynamic Range

- Ratio of the max to the min detectable signal for the sensor
  - *Difference between the brightest area and darkest areas in scene*

- Sensor pixel DR is the limiting factor of how it can represent the scene’s DR in one frame
  - Full-well capacity (e-) represents how much charge can be stored within the photodiode before saturation
  - Read noise (e-) represents the minimum detectable / quantifiable signal given the amount of noise in the pixel and sensor readout

**Dynamic Range Formula**

\[
DR = \frac{\text{Max Detectable Signal}}{\text{Min Detectable Signal}} = \frac{\text{Saturation level}}{\text{Noise floor}}
\]

**Dynamic Range in Decibels**

\[
DR(dB) = 20\log\left(\frac{\text{Full well capacity}}{\text{read noise}}\right)
\]
**HDR Technique Methods**

**Time multiplexed**
- Same pixel array is used to capture multiple frames by using multiple rolling shutters (staggered HDR)
  - Benefits:
    - Simplest HDR scheme compatible with traditional sensor pixel technology
  - Drawbacks:
    - Motion artifacts due to captures occurring at different times

**Spatially multiplexed**
- A single pixel array frame is broken up into multiple captures via different methods:
  1. Independent exposure control at the pixel or row level
    - Benefits: Less motion artifacts in a single frame than staggered
    - Drawbacks: Resolution loss, motion artifacts still exist on edges
  2. Multiple photodiodes per pixel sharing same microlens
    - Benefits: No motion artifacts in a single multi-capture frame
    - Drawbacks: Reduced sensitivity from equivalent pixel area

**Very large full well capacity**
Staggered HDR Motion Artifacts

Time-multiplexed staggered HDR scheme introduces motion artifacts ("ghosting") due to motion in scene, as objects are in different position for each capture.
Spatially Multiplexed HDR Edge Artifacts

- Image artifacts exist due to decrease in resolution from each captured frame.
- Artifacts can be mitigated with Split Pixel (multiple photodiodes per pixel sharing the same microlens).
A 1392x976 2.8um 120dB CIS with Per-Pixel Controlled Conversion Gain

- J. Solhusvik et al. from OmniVision Technologies
- 1.3Mpixel CIS design for automotive applications
- 5T1C pixel is used to switch between high gain and low gain in a single frame, pixel by pixel
- 94dB DR is achieved with dual gain and 120dB DR is achieved with dual gain and dual exposure
A 1392x976 2.8um 120dB CIS with Per-Pixel Controlled Conversion Gain II

- DCG pixel is a **high-FWC, low-read noise**, BSI pixel technology
- Pixel charge signal is read *twice every row time*
- High FWC of pixel in LCG mode and low read noise in HCG
  - FWC: >50ke- & Read Noise: <1e-
A 1392x976 2.8um 120dB CIS with Per-Pixel Controlled Conversion Gain III

DCG HDR (Dual-Exposure: 20-bit)
DCG HDR (Single Exposure: 16-bit)
DCG Pixel Non-HDR** (12-bit)

**Non-HDR image example above has benefit of DCG pixel's high FWC / low read noise
→ Traditional sensor with ~15k FWC would show worse IQ
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Pulsed Illumination

- LED array is widely used for Variable Message Sign (VMS). LED is getting popular in vehicle light thanks to high power efficiency, long lifetime, etc.

- LED vehicle light driver is usually PWM, which allows quick adjustment over a wide brightness range without changing the color.

Frame i  Frame i+1

Frequency: 90Hz
Duty cycle: 20%

LED on period
LED off period
How LED Light Pulses are Missed

A pulsing LED in a scene is usually not synchronized with a camera’s shutter, so the camera may not catch the LED on period and capture a dark LED.

LED light

Shutter (daytime)

LED image (Flickering)

Frame N

Frame N+1

$\text{LED} \leq 11\text{ms}$

LED light

Shutter (night)

LED image (No Flickering)

$t_{\text{Exposure}} \geq t_{\text{LED}}$
Flicker Location Dependence

A rolling shutter integrates in time shifted row by row, so whether the pixel can capture the LED PWM pulse is dependent on its vertical location in the image.
Flicker Mitigation Techniques

- Multiple integration periods (time multiplex)
  - Subsample the photodiode charge many times during each integration period
  - Sample photodiodes at a higher frequency than the LED source

- Multiple photodiodes (spatial multiplex)
  - Use a larger photodiode to capture lower light scenes
  - Use smaller insensitive photodiode to integrate during the entire frame time (mitigate the LED flicker)

- Very Large Full Well Capacity

- Array camera
Distributed exposure time concept

- Instead of opening the shutter once for the entire exposure, it can be sliced and distributed over 11ms or longer to increase the probability of catching the LED pulse.
- The signal of each exposure slice are stored and then summed for each pixel.

![Diagram showing LED and shutter timing](image.png)
A 1.2Mpixel ⅓” CIS with Light Flicker Mitigation

- IISW 2015 C. Silsby et al. from On Semiconductor
- Flickering lights and objects with changing illumination can cause imaging artifacts for rolling shutter CIS
- Pseudo global shutter readout techniques can be used to mitigate these effects

Figure 1. LED Pulsing vs. Pixel Integration Sample Window

Figure 2a. LFM and AB gate added to typical automotive 4T pixel

Figure 2b. LFM and AB gate added to typical automotive 5T pixel
A 1.2Mpixel 1/3” CIS with Light Flicker Mitigation

- Horizontal anti-blooming drain is used to reduce pixel sensitivity

- Multiple charge dump and integration cycles during each frame integration period
A 1.2Mpixel ⅓” CIS with Light Flicker Mitigation

**Figure 10.** Left: Flicker problem missing information. Right: Light Flicker Mitigation captures all sign information.

**Figure 11.** Lab set-up LIF and Fluorescent flicker in ERS mode (left), no flicker LFM mode (middle), saturation ERS mode (right).

**Figure 12.** Outdoor car missed brake lights in ERS mode (left) captured in LFM mode (right).
Multiple Photodiodes for each Pixel

Each pixel is constructed with two photodiodes
  • A large sensitive photodiode and a small insensitive photodiode
  • Small insensitive photodiode can integrate during entire frame, mitigating LED flicker

Advantages include
  • Excellent flicker mitigation
  • Low computational complexity

Disadvantages include
  • Larger more complex pixel architecture
  • More complex readout and circuit timing
  • Spectral sensitivity mismatch between large and small photodiode
## Very Large FWC

<table>
<thead>
<tr>
<th>Illuminance</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>120,000 lux</td>
<td>Brightest sunlight</td>
</tr>
<tr>
<td>1,000 - 2,000 lux</td>
<td>Typical overcast day, midday</td>
</tr>
<tr>
<td>400 lux</td>
<td>Sunrise or sunset on a clear day (ambient illumination).</td>
</tr>
<tr>
<td>0.25 lux</td>
<td>Full Moon on a clear night</td>
</tr>
<tr>
<td>0.002 lux</td>
<td>Starlight clear moonless night sky including airglow</td>
</tr>
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</table>

For a typical 2.8um CIS pixel, F/2.0 lens, 18% reflectance object, each pixel captures about 350 $Ke^-$ during an 11ms integration time at 120Klux. Reasonable average image level for 18% reflectance is about 25% of saturation level, therefore the minimum pixel FWC should be above 1400Ke-.
Array Camera

Array-cam is an emerging camera technology and could be a viable solution for LED detection.

- A low sensitivity CAM for LED detection
- Combined output by image fusion, separate output, or both.

Challenges

- Difficult to maintain optical alignment error across automotive temperature range.
- Image fusion is application oriented and computationally complex
- Difficult to fuse high sensitivity and low sensitivity images
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Machine Vision Sensor Technology Trends

- Global shutter
- Improved near infrared (NIR) response
- Higher sensitivity color filter arrays (RCCB)
- Data encryption
- Higher frame rates
- Integrated sensing and processing
- 3D imaging
A 3D Stacked CIS with 16Mpixel Global-Shutter using 4M Interconnections

- IISW 2015 T. Kondo et al. from Olympus Corp.
- Stacked CIS for DSC applications
- 16Mpixel CIS with global shutter and pixel level chip to chip interconnections at 7.6um pitch
- Top substrate is optimized for photo-collection and bottom substrate for low noise analog readout
- Shutter inefficiency is -180dB
A 3D Stacked CIS with 16Mpixel Global-Shutter using 4M Interconnections

- **Top substrates includes**
  - hole accumulation diodes, transfer gates
  - source follower transistor
  - reset transistor and access transistor

- **Bottom substrate includes**
  - CDS circuitry
  - sample and hold caps
  - ADCs
  - digital control circuitry
A 3D Stacked CIS with 16Mpixel Global-Shutter using 4M Interconnections

<table>
<thead>
<tr>
<th></th>
<th>This paper</th>
<th>Previous work [1]</th>
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<tbody>
<tr>
<td><strong>Pixel size</strong></td>
<td>3.8um</td>
<td>4.3um</td>
</tr>
<tr>
<td><strong>Conversion gain</strong></td>
<td>35uV/h+</td>
<td>26uV/h+</td>
</tr>
<tr>
<td><strong>FWC</strong></td>
<td>35000h+</td>
<td>30000h+</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>35000h+/lux-s</td>
<td>60000h+/lux-s</td>
</tr>
<tr>
<td><strong>Dark Current @ 60C</strong></td>
<td>50h+/s</td>
<td>1000h+/s</td>
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<tr>
<td><strong>Parasitic light sensitivity</strong></td>
<td>-180dB</td>
<td>-160dB</td>
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Nyixel™ Technology

IR LED assisted Security Camera

Less light source power

Defining the Future of Digital Imaging™
Nyixel™ Technology Advantage
Quantum Efficiency measurement data from 2.8um pixel

QE improvement by Nyxel

QE improved 3x to 60% @ 850nm
QE improved 5x to 40% @ 940nm

Visible light region cross-talk not changed
Nyixel™ Technology Advantage

*Image comparison under 850nm IR LED illumination*

OV2770 image sensor

OV2770 with Nyixel
Nyixel™ Technology Advantage

Image comparison under 850nm IR LED illumination

OV2770 with Nyxel

OV2770 image sensor

No sharpness degradation
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Automotive LiDAR

- **LiDAR** is light based radar
- It uses time of flight to measure the distance of far field objects
- Typically uses a point or line of illumination and then scans the field of view (FOV)
- Both mechanical and solid state scanning techniques are used
A 1x16 Silicon Photo-multiplier Array for Automotive 3D Imaging LiDAR Systems

- IISW 2017 S. Gnicchi et al. from SensL Technologies
- Automotive 1D scanned LiDAR sensor for long range 3D measurement
- Peak laser power of 400W at 905nm
- 50nm FWHM optical filter used to reduce background illumination
- SiPM array connected to a TIA then feeds a comparator whose output feeds a TDC for final ToF measurement
A 1x16 Silicon Photo-multiplier Array for Automotive 3D Imaging LiDAR Systems II

Figure 1. Coaxial 1D Scanning System - A vertical laser beam is scanned horizontally with the usage of an electromechanical mirror which also focuses the return light back onto a 1 x 16 SiPM array. A polarizer beam splitter is used to direct the transmitted light onto the rotating mirror. The return light sees a worst-case reduction in intensity of 50%.

Figure 2. SensL 1 x 16 SiPM Array - The sensor consists of a monolithic array of 16 pixels in a vertical line. The dimensions are reported in Table I. The geometry of the pixels follows the required angle of view in both horizontal and vertical direction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Array size</td>
<td>1 x 16</td>
</tr>
<tr>
<td>SiPM pixel length (x)</td>
<td>171 (\mu)m</td>
</tr>
<tr>
<td>SiPM pixel height (y_1)</td>
<td>491 (\mu)m</td>
</tr>
<tr>
<td>Pixel spacing (y_2)</td>
<td>59 (\mu)m</td>
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<tr>
<td>Total array length (y_3)</td>
<td>8.741 mm</td>
</tr>
<tr>
<td>SPAD cells per pixel (N_{cells})</td>
<td>133</td>
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<tr>
<td>PDE @ 905 nm</td>
<td>8.4 %</td>
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<tr>
<td>SPAD cell dead time (\tau_{dead})</td>
<td>23ns</td>
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<tr>
<td>SiPM pixel gain (G)</td>
<td>10^6</td>
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<tr>
<td>SiPM rise time (\tau_{rise})</td>
<td>100 ps</td>
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<tr>
<td>Laser divergence</td>
<td>0.1° × 5°</td>
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<tr>
<td>Laser peak power (P_{laser})</td>
<td>400 W</td>
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<tr>
<td>Laser pulse width (\tau_{pulse})</td>
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<tr>
<td>Laser pulse repetition rate PRR</td>
<td>500 kHz</td>
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<tr>
<td>Frames per second</td>
<td>30 fps</td>
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<tr>
<td>Optical aperture (D_{lens})</td>
<td>22 mm</td>
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<tr>
<td>Scanning angle of view</td>
<td>80° × 5°</td>
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<tr>
<td>Static angle of view (AoV_x \times AoV_y)</td>
<td>&lt; 0.1° × 5°</td>
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<tr>
<td>Angular resolution</td>
<td>0.1° × 0.312°</td>
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<tr>
<td>Optical bandpass (\lambda \pm \Delta \lambda)</td>
<td>(905 ± 25) nm</td>
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</table>
A 1x16 Silicon Photo-multiplier Array for Automotive 3D Imaging LiDAR Systems III

Figure 3. **Array performance at 100 klux** - The probability of detecting the return laser depends on the distance and the reflectivity of the target within the field of view. No sensor saturation occurs. The multishot approach allows longer distances to be efficiently ranged.

Figure 4. **Array performance at 10 klux** - The probability analysis shows ranging improvement when the system operates at a moderate ambient light level of 10 klux showing ranging over 200 m for low reflective targets.
Conclusions

Automotive imaging is a large and growing market, with rapidly changing and increasing needs.

Both direct view and machine vision applications will require a multitude of new technologies to enable next generation automobiles.

Machine vision including 3D will be the biggest growth areas.