Simulation technologies for image systems engineering

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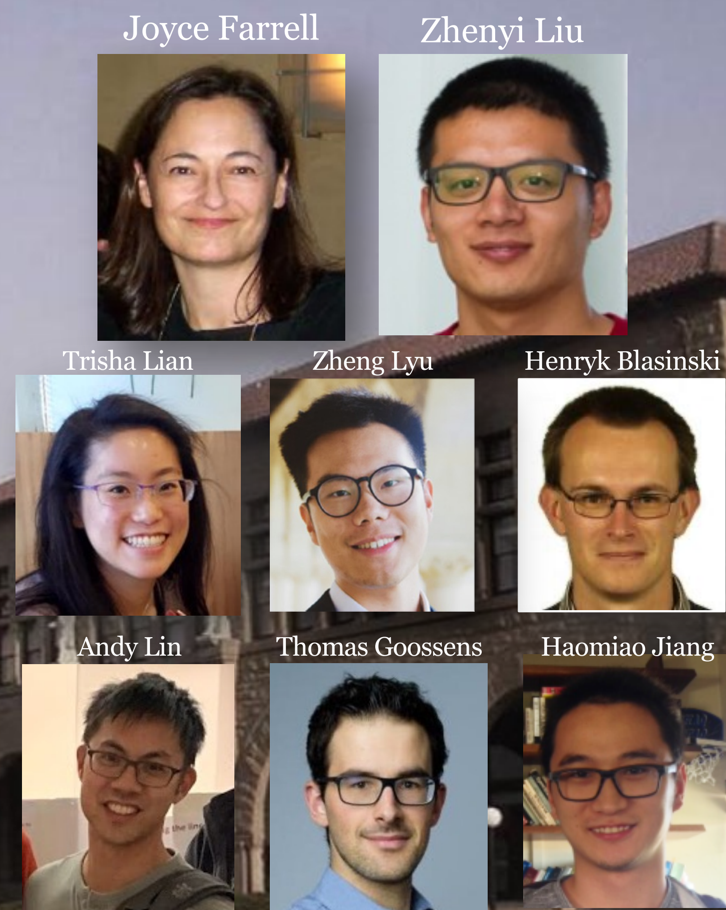
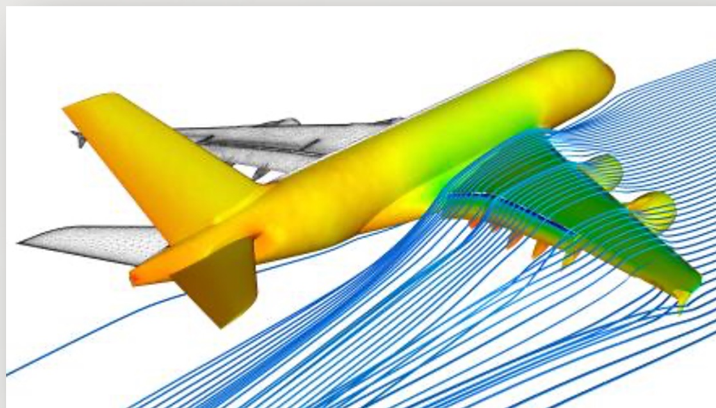
QUANTITATIVE MEASUREMENTS
∞
COMPUTATIONAL MODELS
∞
CHECK AND SHARE



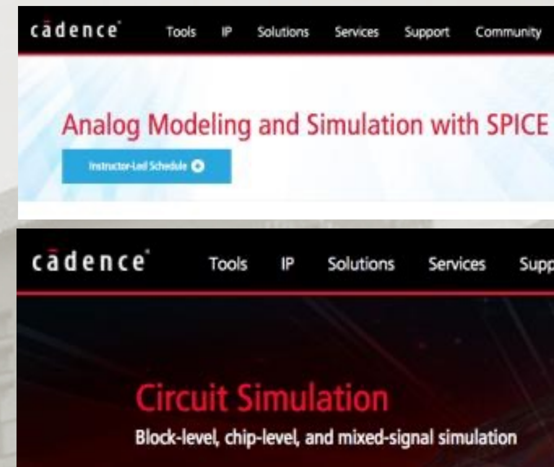
Thanks to Meta, Ford and Google

Systems simulation (digital twin) is important in many mature industries

ECU (Electronic Control Unit) Simulation for Automobiles



Numerical flow simulation on an Airbus A380



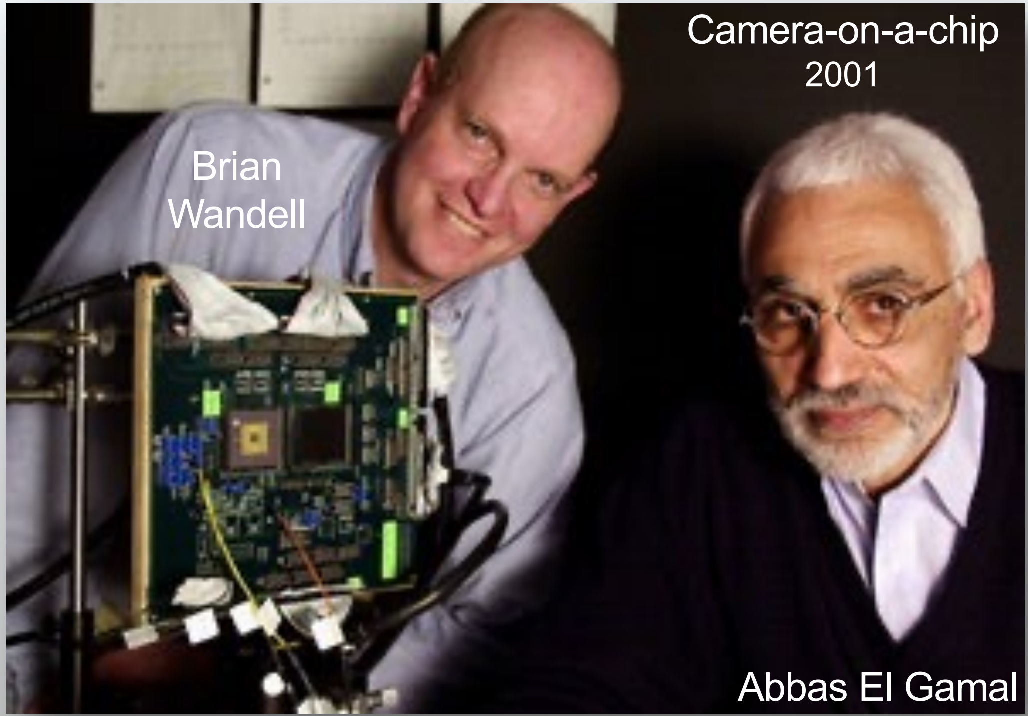
Integrated circuitry

Physics-based image systems simulation: Our origins

Ting Chen

Peter Catrysse

Joyce Farrell



2003: We developed a 2D imaging systems simulation (physical units)

Image Systems Engineering Toolbox for cameras (**ISETCam**)

- End-to-end simulation (radiance to sensor)
  - Physical units (photons to electrons)

Optics

Sensor

Display

Imaging Systems Engineering Toolbox (ISETCam)

More than 500 users in
80 companies,
9 research institutes,
65 universities,
in 24 countries

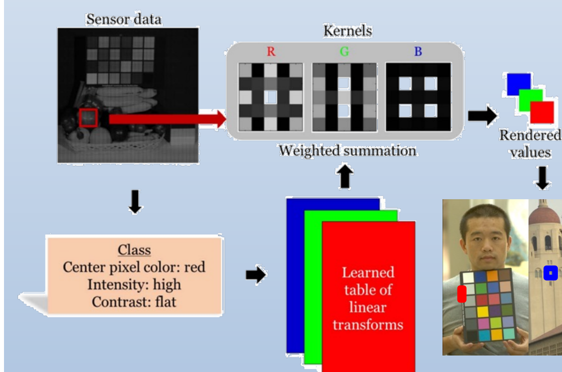
Open Sourced on GitHub
in 2018

Applications: ISP pipeline, optics, biomedical

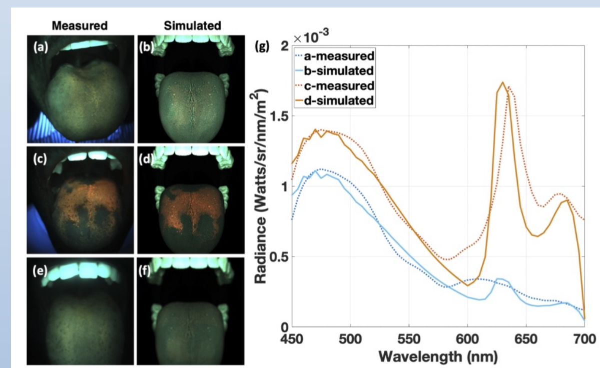
Learning the image processing pipeline (IEEE Transactions on image processing, 2017)
H. Jiang, Q. Tian, J. Farrell, B. Wandell

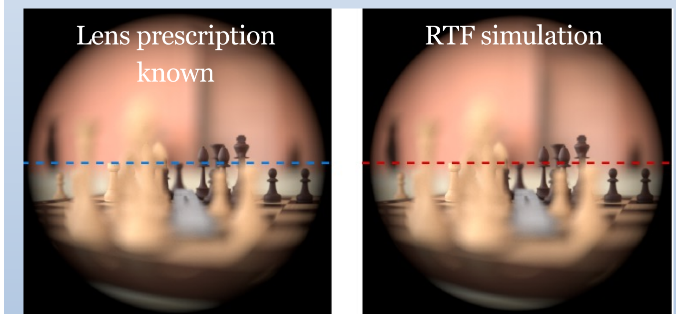
Simulations of fluorescence imaging in the oral cavity (Biomedical Optics Express, 2021)
Z. Lyu, H. Jiang, F. Xiao, J. Rong, T. Zhang, B. Wandell, J. Farrell

Ray-transfer functions for camera simulation of 3D scenes with hidden lens design (Optics Express, 2022)
Z. Lyu, H. Jiang, F. Xiao, J. Rong, T. Zhang, B. Wandell, J. Farrell



5 color channel sensors





Automotive systems simulations

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ISETHDR: A Physics-based Synthetic Radiance Dataset for High Dynamic Range Driving Scenes

Zhenyi Liu, Devesh Shah, and Brian A. Wandell

Neural Network Generalization: The Impact of Camera Parameters

ZHENYI LIU[1,2], TRISHA LIAN[2], JOYCE FARRELL[2], AND BRIAN A. WANDELL[2]
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Corresponding author: Zhenyi Liu (zhenyiliu27@gmail.com)
This work was supported by the Jilin University.

ISETAuto: Detecting vehicles with depth and radiance information

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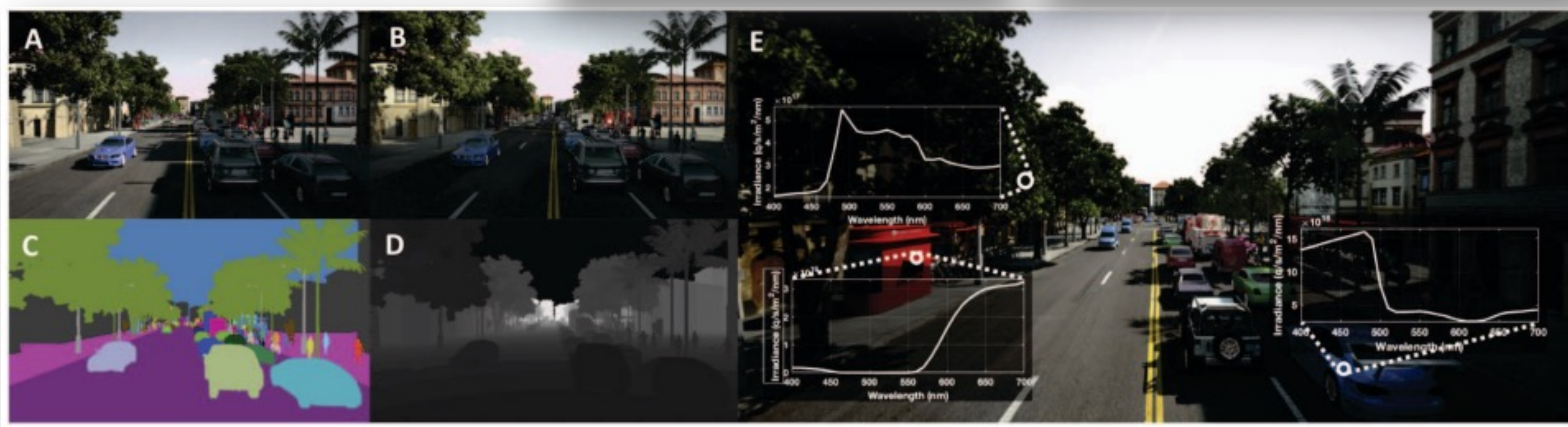
[1]State Key Laboratory of Automotive Simulation and Control, Jilin University (e-mail: zhenyiliu27@gmail.com)
[2]Stanford University (e-mail: jefarrel, wandell@stanford.edu)
Corresponding author: Zhenyi Liu (e-mail: zhenyiliu27@gmail.com)



Imaging systems are increasingly used as input to convolutional neural networks (CNN) for object detection; we would like to design cameras that are optimized for this purpose. It is impractical to build different cameras and then acquire and label the necessary data for every potential camera design; creating software simulations of the camera in context (soft prototyping) is the only realistic approach. We implemented soft-prototyping tools that can quantitatively simulate image radiance and camera designs to create realistic images that are input to a convolutional neural network for car detection. We used these methods to quantify the effect that critical hardware components (pixel size), sensor control (exposure algorithms) and image processing (gamma and demosaicing algorithms) have upon average precision of car detection. We quantify (a) the relationship between pixel size and the ability to detect cars at different distances, (b) the penalty for choosing a poor exposure duration, and (c) the ability of the CNN to perform car detection for a variety of post-acquisition processing algorithms. These results show that the optimal choices for car detection are not constrained by the same metrics used for image quality in consumer photography. It is better to evaluate camera designs for CNN applications using soft prototyping with task-specific metrics rather than consumer photography metrics.

First point

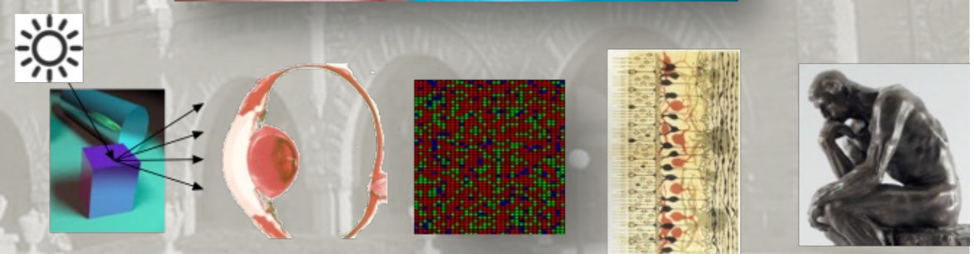
Image systems simulation software that is trusted by key stakeholders in industry and academia can speed the development of next generation image sensors, camera arrays and displays.

Image systems engineering tools (ISET) – What is it?

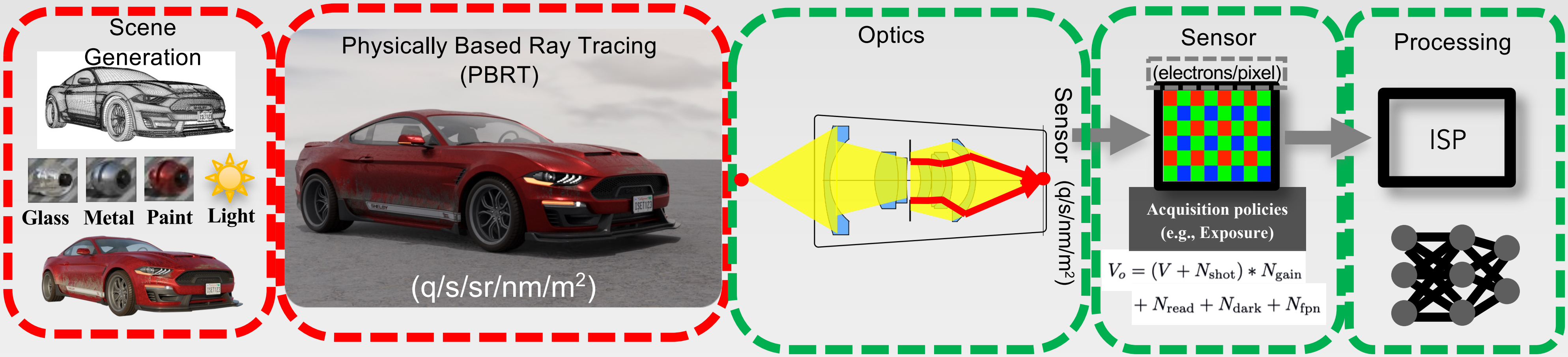
- **ISETCam** is a Matlab toolbox that computes the image sensor response from the sensor irradiance; it also includes many industrial tools for evaluation of color (CIE standards) and spatial resolution (ISO standards)

- **ISET3d** is a Matlab toolbox that uses **Physically Based Rendering Tools (PBRT)** to calculate three-dimensional scene spectral radiance and sensor irradiance for certain lenses and complex scenes

- **ISETBio** is a Matlab toolbox that builds on ISET3d and ISETCam to compute the human visual system's encoding



ISET computational pipeline



ISET3d – Matlab toolbox that uses PBRT-V4 to calculate the sensor spectral irradiance of complex scenes

ISETCam – Matlab toolbox that computes the image sensor response from the sensor spectral irradiance; it includes many evaluation tools for color and spatial resolution

Scene generation: Quantitative computer graphics

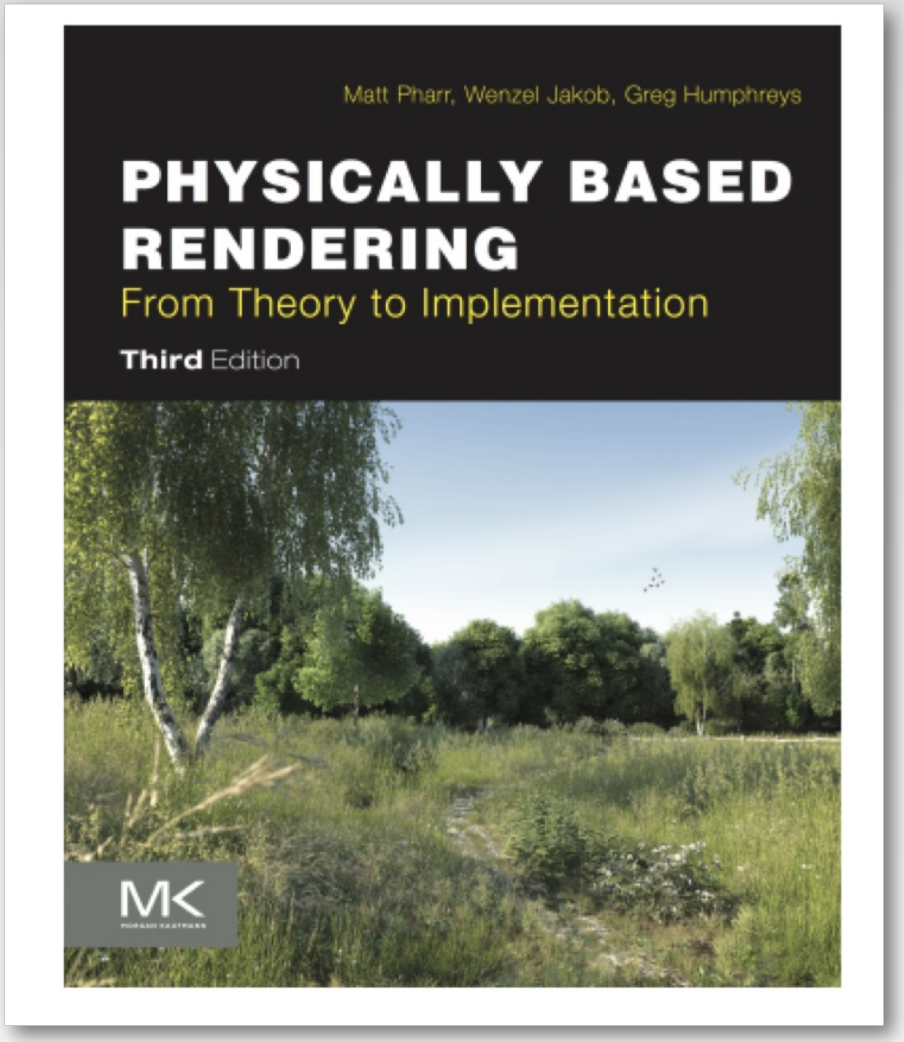
- Progress in computer graphics enables us to create synthetic and yet highly realistic input data.
- For digital twins we need simulations with **physical units**; quantitative computer graphics
- PBRT uses path tracing from the sensor, through multi-element optics, into the scene spectral radiance.
- PBRT is open-source and well documented, enabling us to add custom features
- N.B. This is not Generative AI of RGB

Spectral ray tracing examples (PBRT, ISET3d)

Scene generation: Quantitative computer graphics

We added ISET methods to PBRT-V4 in order to compute

- Diffraction
- Human eye models
- Aspherical lenses
- Microlens arrays
- Linear models of texture maps to control surface spectral reflectance
- Fluorescence (Medical imaging)
- Participating media (Underwater)
- Flare (aperture, scratches)
- Computational imaging (CNN, Ideal observer)



Optics simulation

Wide Angle 56 Deg

FishEye 87 Deg

Light Field Camera
Main lens: Double Gauss 22 Deg
Microlens: 1.2 mm with 10 x 10 pixels

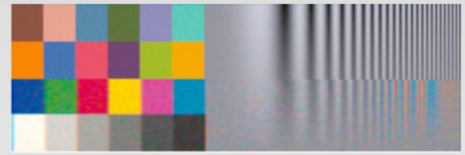
All used 12.5 mm focal length

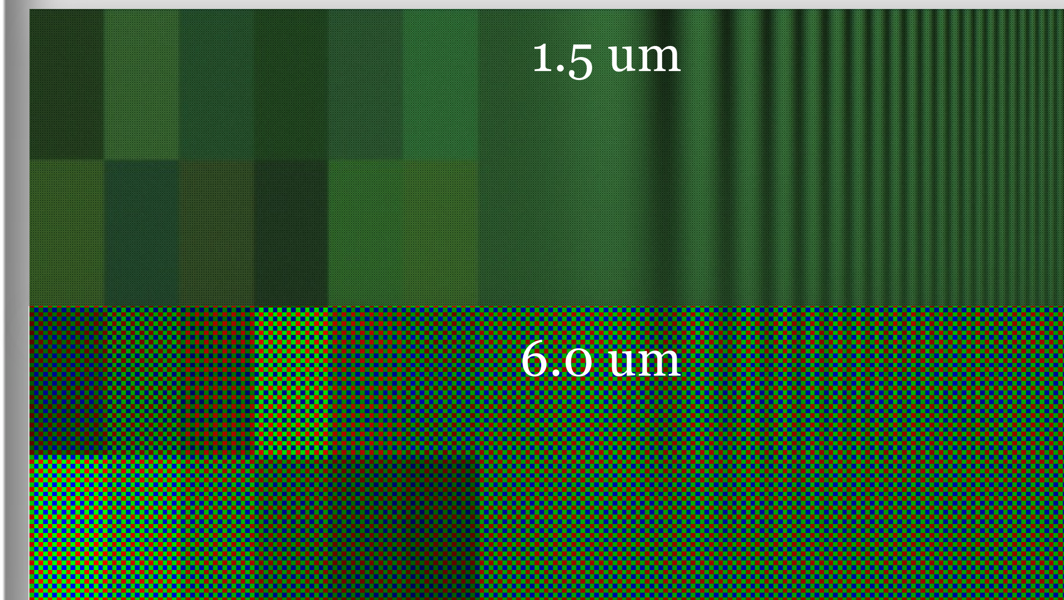
System modeling: Sensor properties (ISETCam)

ISET Parameter Table for a Sensor

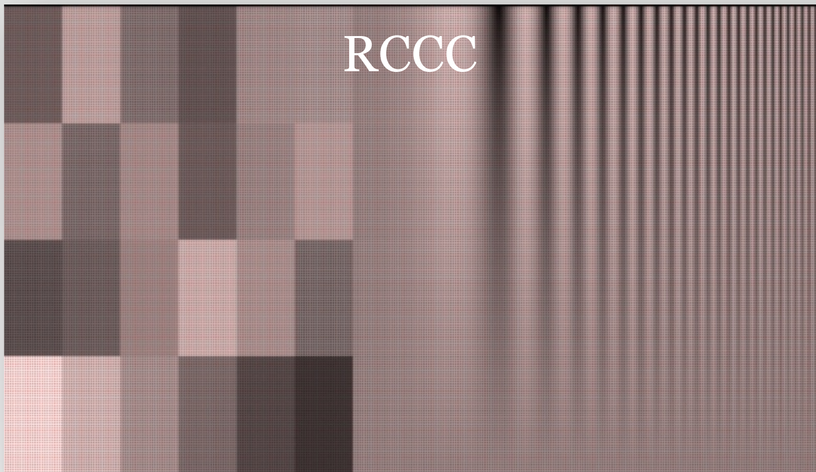
File

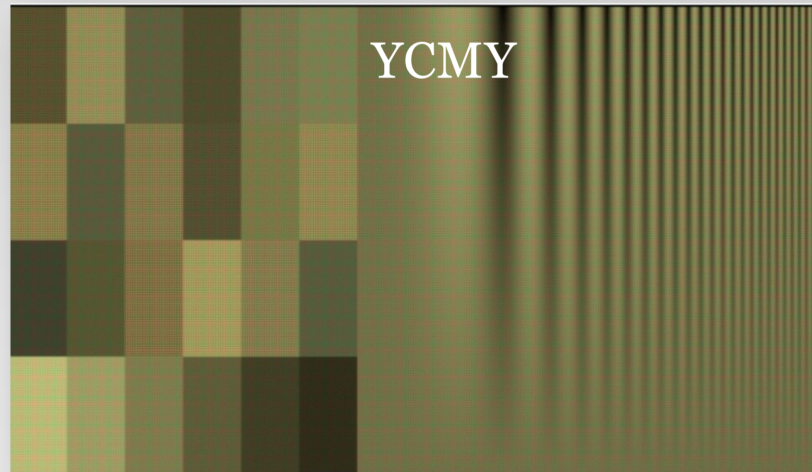
Property	Value	Units
Name	IMX363	
Size	0.786 1.36	mm
Rows and Columns	524 908	
Horizontal FOV	20	deg
Horizontal Res / dista…	1.5	um
Horizontal Res / degre…	0.022	deg/pixel
Exposure time	0.0020219	s
DSNU	0	V
PRNU	0.7	%
Analog gain	0.204	
Analog offset	0.00585	V
------------------	------- Pixel -------	------------------
Width & height	1.5	um
Fill factor	0.871	
Dark voltage (V/sec)	0	V/sec
Read noise (V)	0.000383	V
Conversion Gain (V/e-)	7.65e-05	V/e-
Voltage Swing (V)	0.459	V
Well Capacity (e-)	6e+03	e-



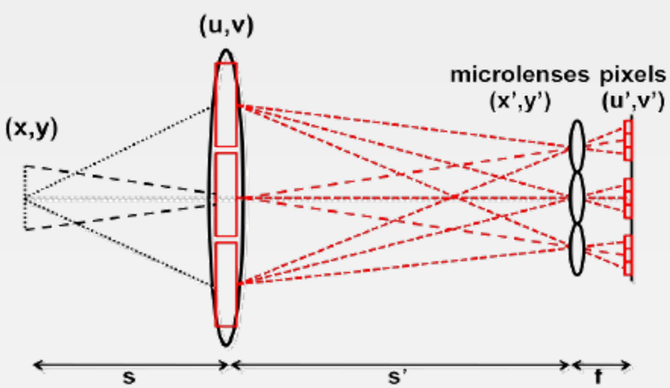


ISETCam: Advanced sensor simulations

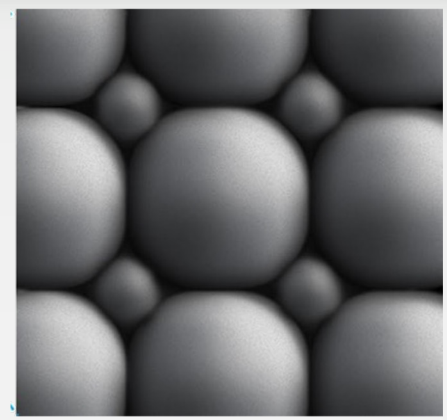


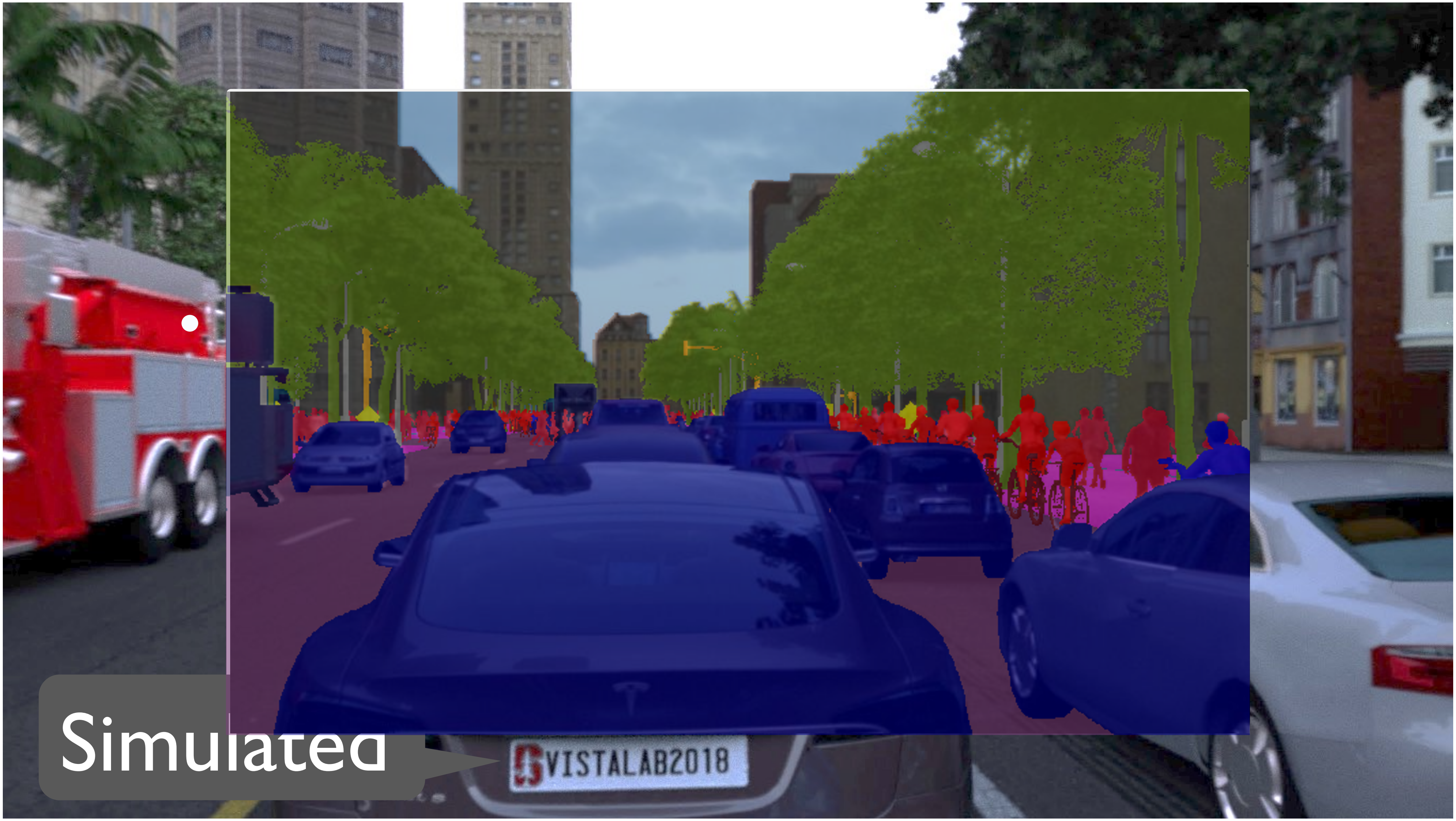


Light field

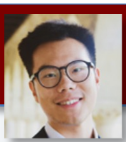


Split pixel

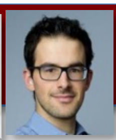



Simulated
VISTALAB2018

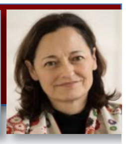
Evaluation of the simulation accuracy



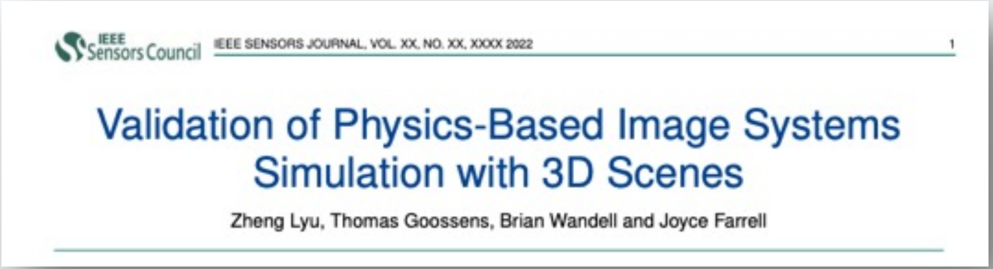
Zheng Lyu



Thomas Goossens



Joyce Farrell



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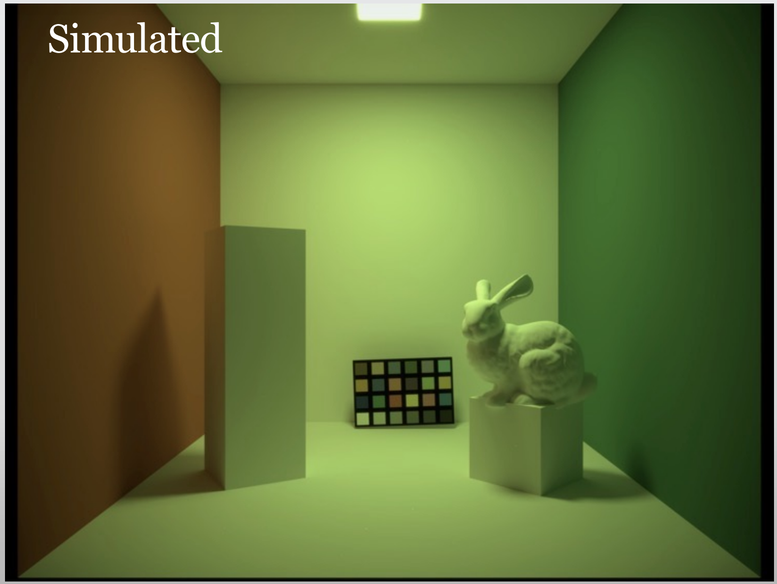
Validation of Physics-Based Image Systems Simulation with 3D Scenes

Zheng Lyu, Thomas Goossens, Brian Wandell and Joyce Farrell



Validation tests: Cornell Box Construction

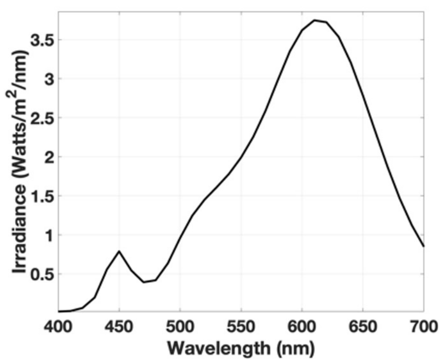
- The Cornell Box has been widely used to evaluate the **accuracy of computer graphics rendering**

- We use it to quantitatively test end-to-end simulation of **3D scenes, optics, and image sensors**

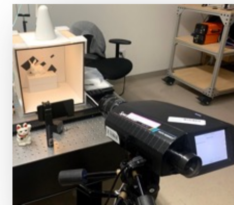
- Goral, Torrance, Greenberg, and Battaile, "Modeling the Interaction of Light Between Diffuse Surfaces," Computer Graphics (Proc. SIGGRAPH 84), Vol. 18, No. 3, July **1984**, pp. 213-222
- Meyer, Rushmeier, Cohen, Greenberg, and Torrance, "An Experimental Evaluation of Computer Graphics Imagery" ACM Transactions on Graphics, Vol. 5, No. 1, January **1986**, Pages 30-50

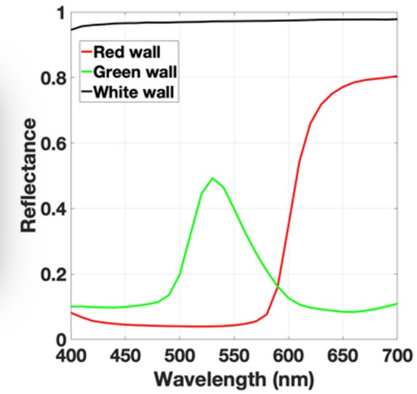
We built one (the 3D scene)

- We measured the asset sizes and scene geometry, surface reflectance, illuminant spectral power distribution

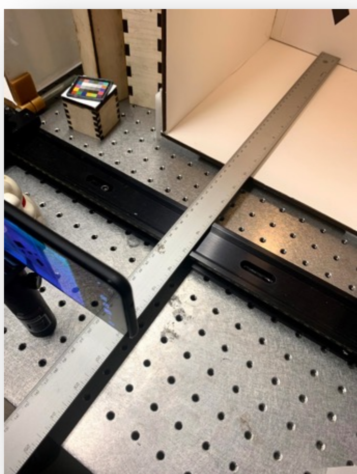


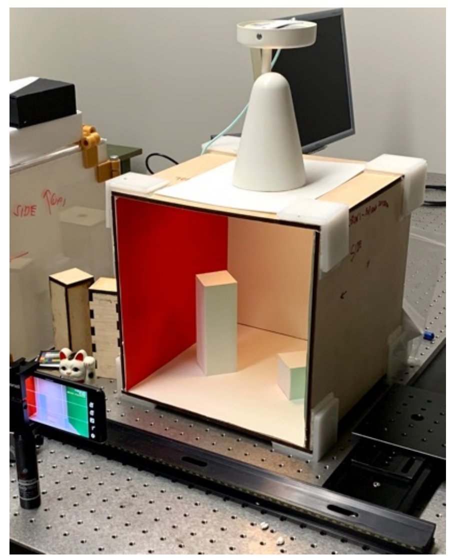
Illuminant SPD





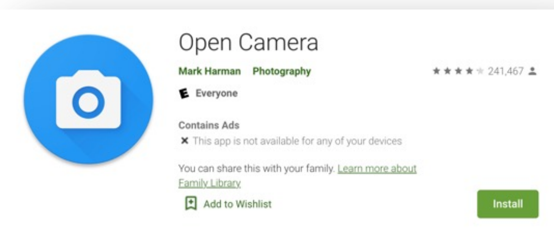
Surface spectral reflectance

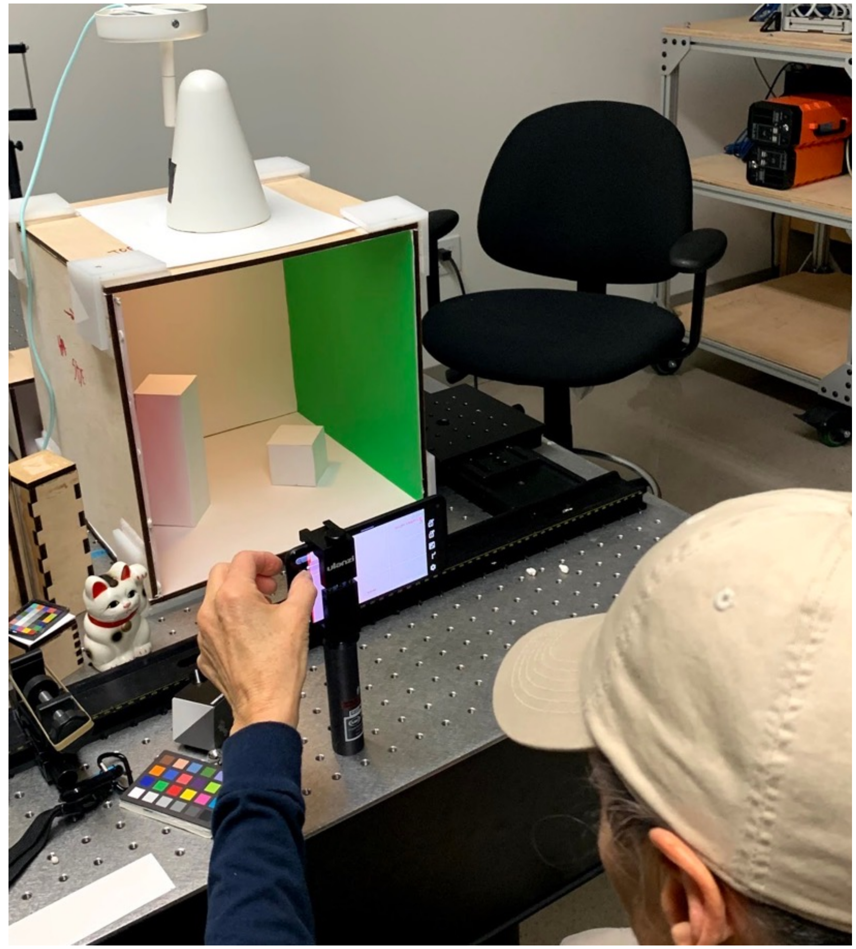




Validation test: Raw sensor data from the camera

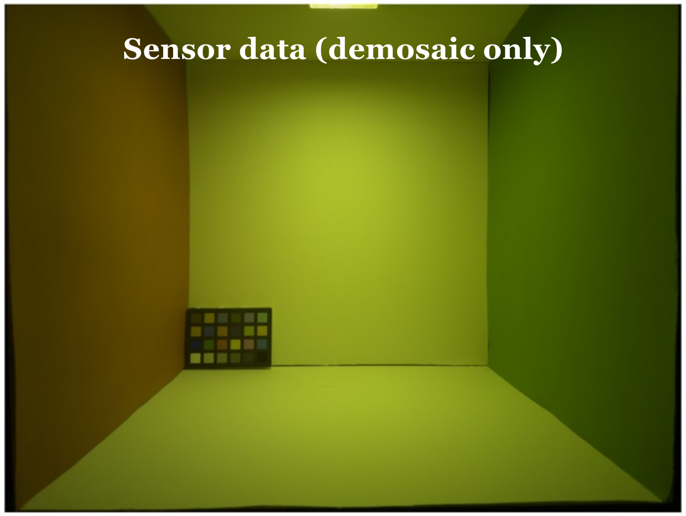
- We used a Google Pixel 4a and the OpenCamera app to acquire **relatively raw data**

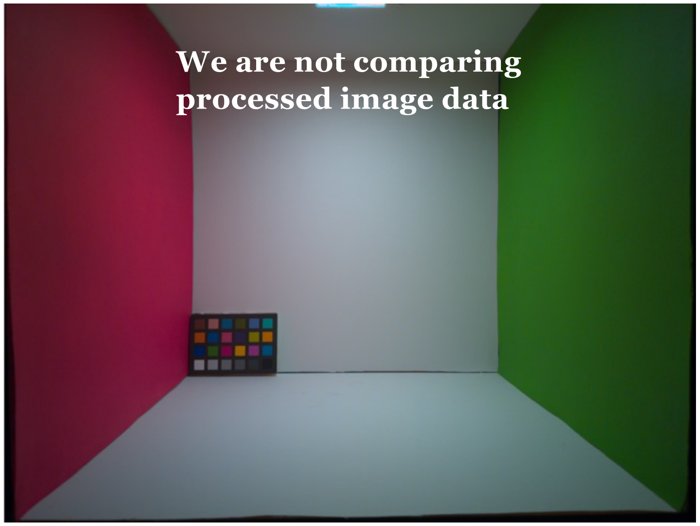




Sensor renderings

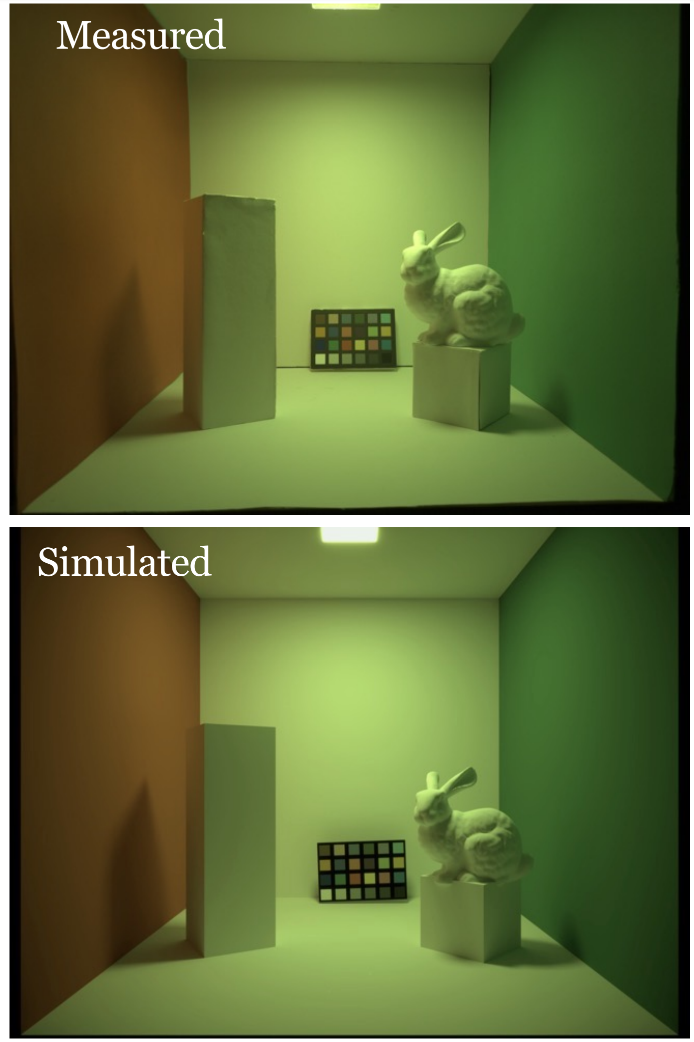
- Our goal is to match the **digital sensor values**, not the processed data
- The renderings we show are **simulated or measured sensor data**, with only bilinear demosaicking





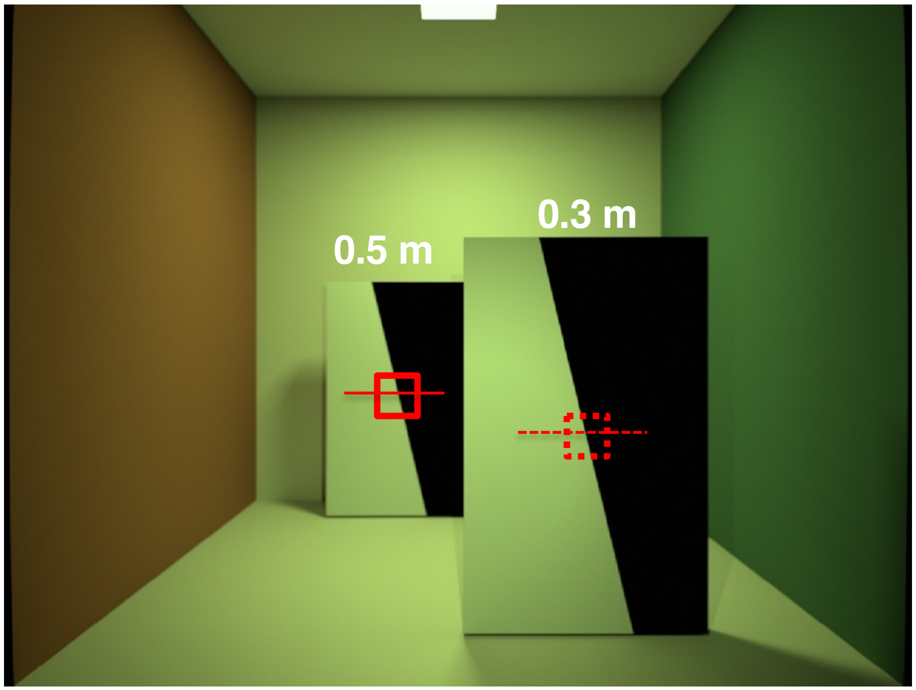
Quick check based just on appearance

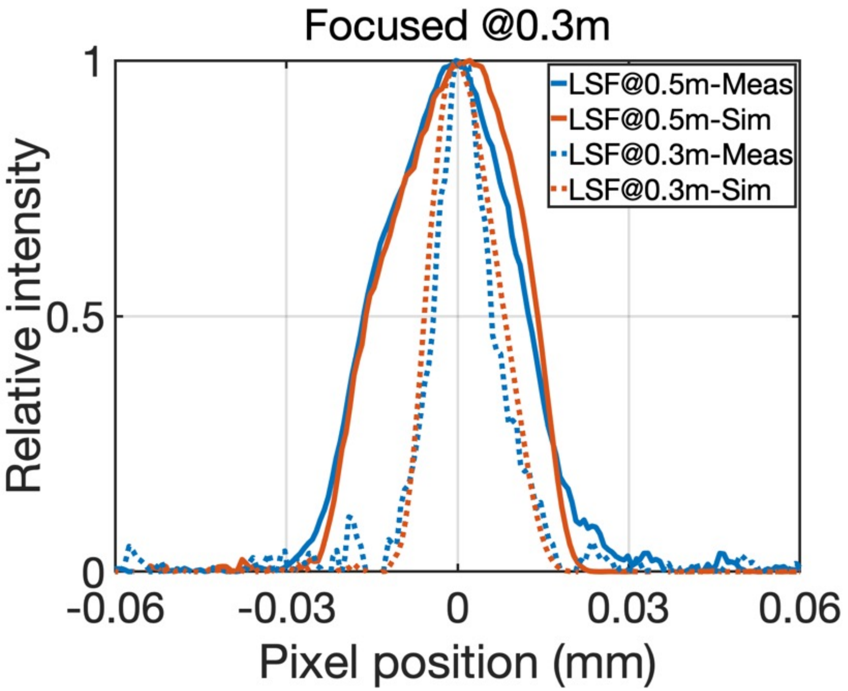
- Overall similarity is good
- High dynamic range
- Shadows
- Color interreflections (sides of the box reflect light from the wall)
- If you are designing hardware, this check is far from adequate: quantify!



Optics validation: Resolution and depth of field

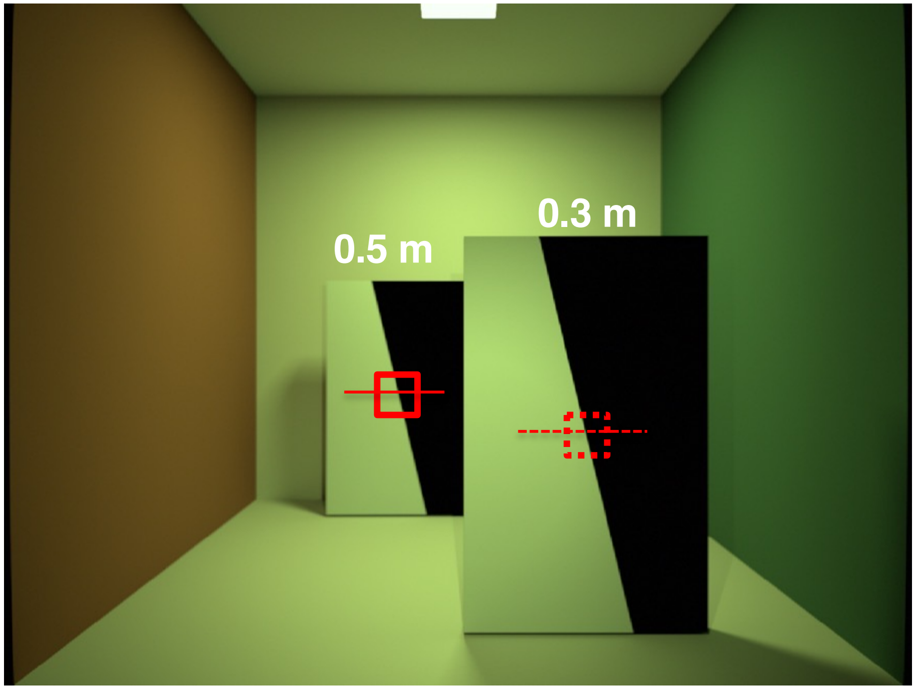
Focused at 0.3 meters

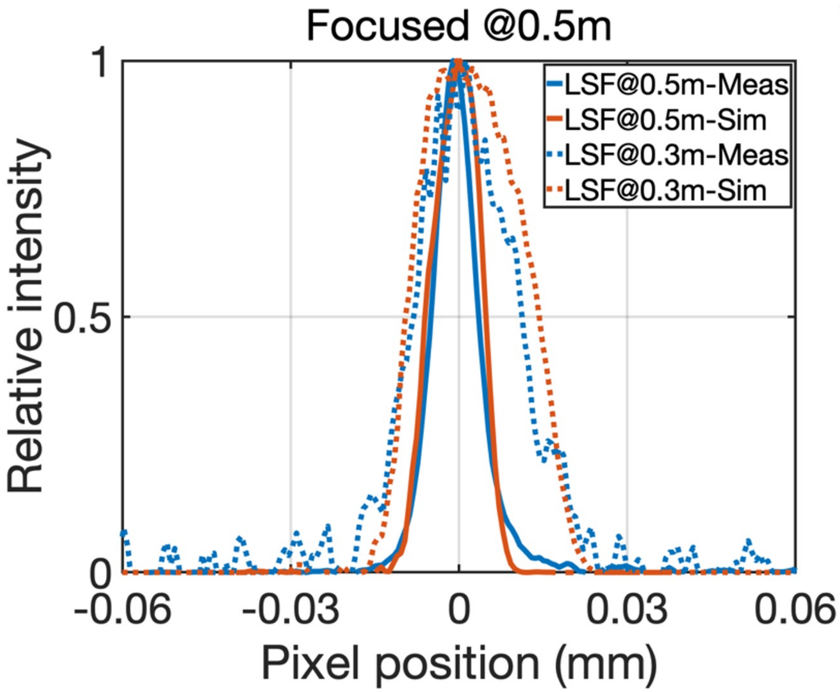




Focus-dependent LSF/MTF (depth of field)

Focused at 0.5 meters





Mention Goossens Ray Transfer Function Extension

Since then, we have improved our optics modeling

Research Article Vol. 30, No. 13 / 20 Jun 2022 / *Optics Express* 24031

Optics EXPRESS

Ray-transfer functions for camera simulation of 3D scenes with hidden lens design

THOMAS GOOSSENS,[1,*] ZHENG LYU,[1] JAMYUEN KO,[2] GORDON C. WAN,[2] JOYCE FARRELL,[1] AND BRIAN WANDELL[1]

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[2] *Google, Mountain View, California 94043, USA*
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Abstract: Combining image sensor simulation tools with physically based ray tracing enables the design and evaluation (soft prototyping) of novel imaging systems. These methods can also synthesize physically accurate, labeled images for machine learning applications. One practical limitation of soft prototyping has been simulating the optics precisely: lens manufacturers generally prefer to keep lens design confidential. We present a pragmatic solution to this problem using a black box lens model in Zemax; such models provide necessary optical information while preserving the lens designer's intellectual property. First, we describe and provide software to construct a polynomial ray transfer function that characterizes how rays entering the lens at any position and angle subsequently exit the lens. We implement the ray-transfer calculation as a camera model in PBRT and confirm that the PBRT ray-transfer calculations match the Zemax lens calculations for edge spread functions and relative illumination.

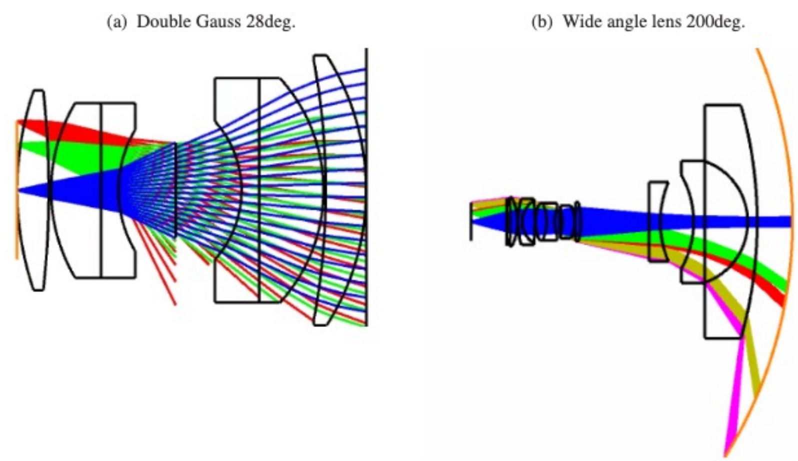


Fig. 2. Illustration of the Ray Transfer Function (RTF). (a) The Double Gauss lens can be accurately simulated with rays represented on an input and output plane. (b) The wide angle lens can be accurately simulated with input rays on a plane and output rays on a spherical surface. Because of the high degree of bending near the aperture edge, certain rays would not intersect any output plane to the right of the final vertex.

Surface inter-reflections and electronic sensor noise

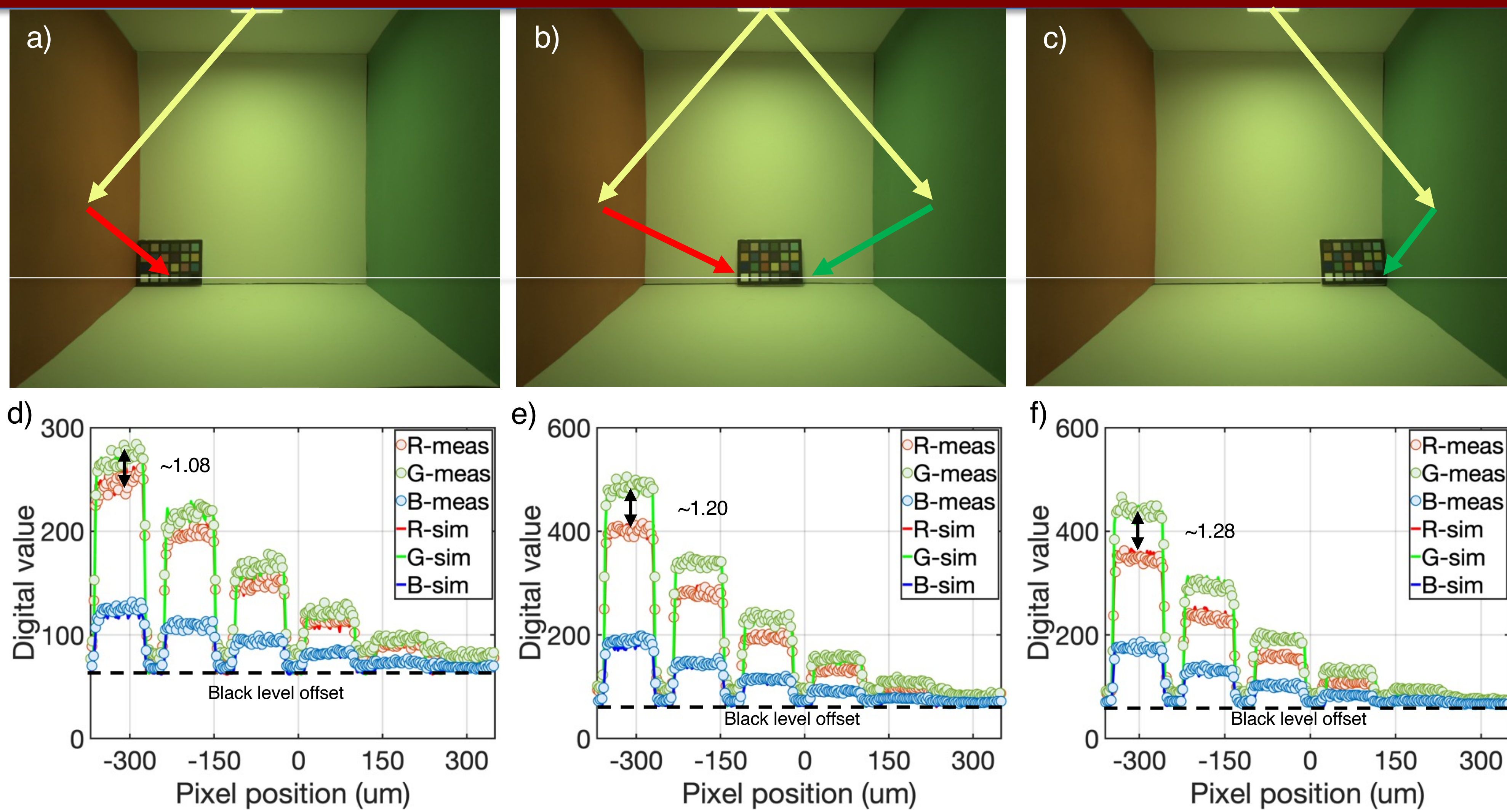
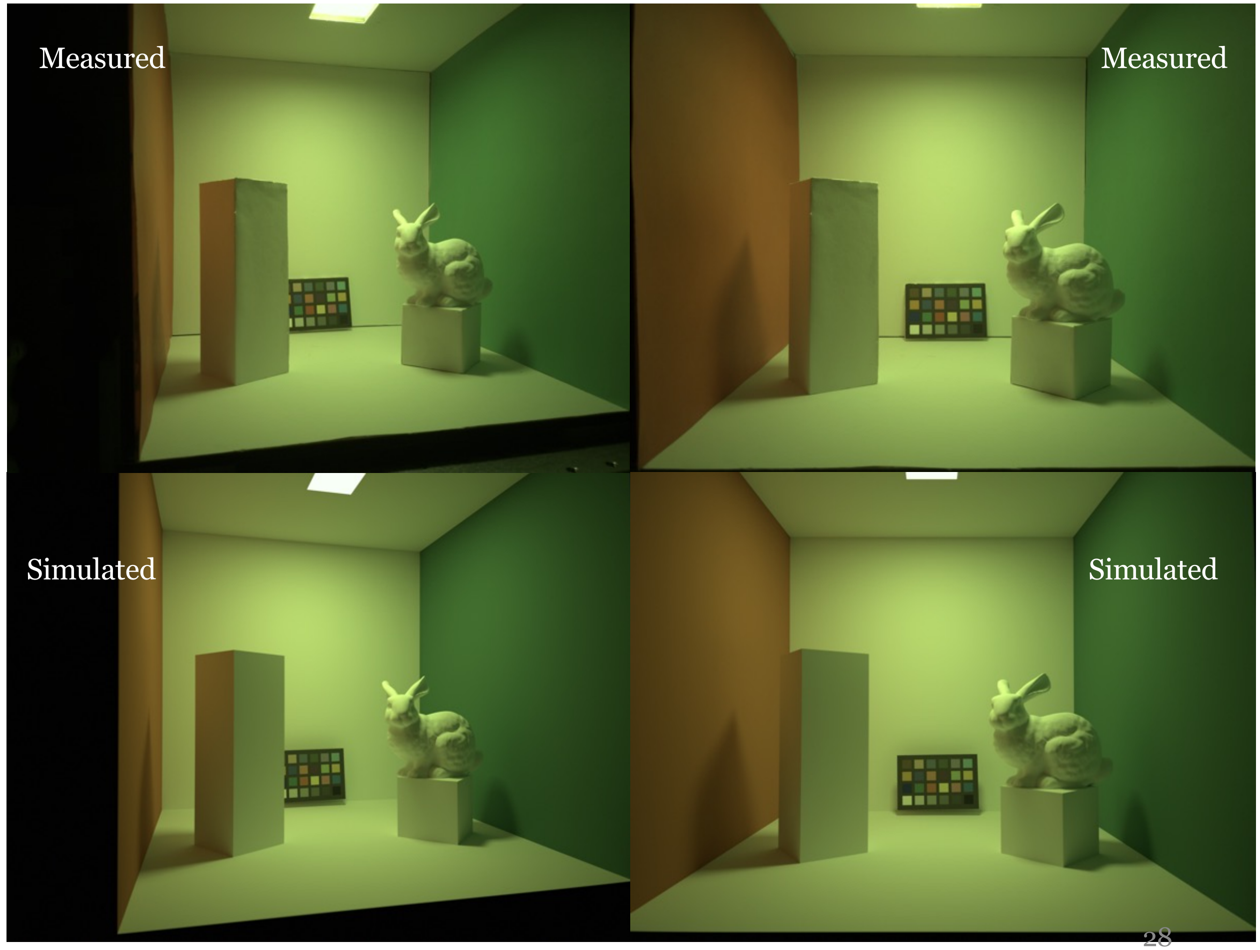


Image system simulation evaluation using 3D scenes

- ✓ Surface inter-reflections
- ✓ Depth of focus
- ✓ Vignetting
- ✓ Sensor quantum efficiency
- ✓ Sensor noise



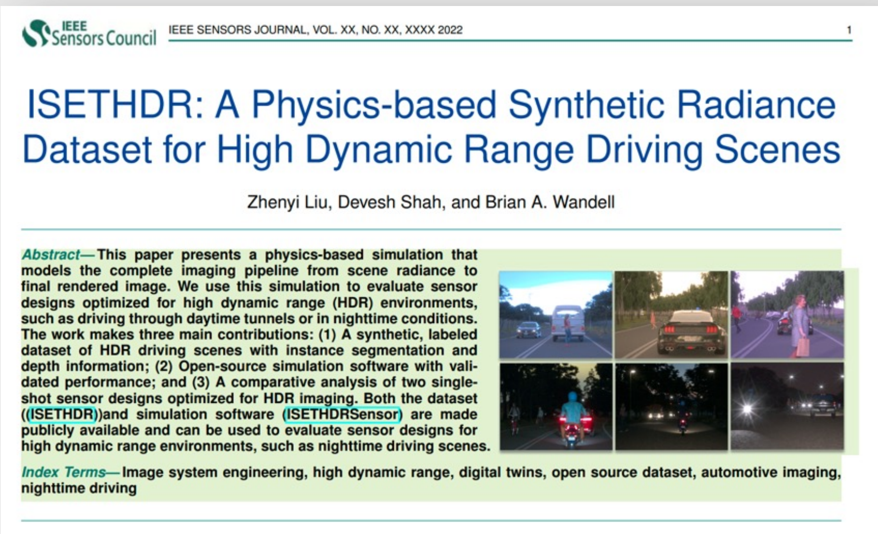
Second point

29

- Image systems simulations can accurately create physical descriptions of realistic scenes and compute the expected sensor response
- We are working to expand the range of conditions – particularly HDR - and to validate quantitative, spectral simulations

ISETHDR: Data set for nighttime driving sensor evaluation

- HDR nighttime data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ISETHDR: A Physics-based Synthetic Radiance Dataset for High Dynamic Range Driving Scenes

Zhenyi Liu, Devesh Shah, and Brian A. Wandell

Abstract—This paper presents a physics-based simulation that models the complete imaging pipeline from scene radiance to final rendered image. We use this simulation to evaluate sensor designs optimized for high dynamic range (HDR) environments, such as driving through daytime tunnels or in nighttime conditions. The work makes three main contributions: (1) A synthetic, labeled dataset of HDR driving scenes with instance segmentation and depth information; (2) Open-source simulation software with validated performance; and (3) A comparative analysis of two single-shot sensor designs optimized for HDR imaging. Both the dataset ((ISETHDR))and simulation software (ISETHDRSensor) are made publicly available and can be used to evaluate sensor designs for high dynamic range environments, such as nighttime driving scenes.

Index Terms—Image system engineering, high dynamic range, digital twins, open source dataset, automotive imaging, nighttime driving

Prior work: daytime images

A nighttime scene (Real Image)

- High dynamic range (HDR).
- Lots of bright lights.
- Low SNR.
- Image labeling is hard.

Modeling flare in the pupil function

We implemented methods for simulating **two sources** of flare

- Aperture shape
- Lens dust and scratches
- We model lens wavefront phase aberrations

We have not yet found an efficient representation for inter-reflections

Point Spread Function is Fourier Transform of the Pupil Function

$$I(x,y) = |\mathcal{F}\{P(u,v)\}|^2$$

Pupil Function is represented by amplitude transmission function and phase shift function

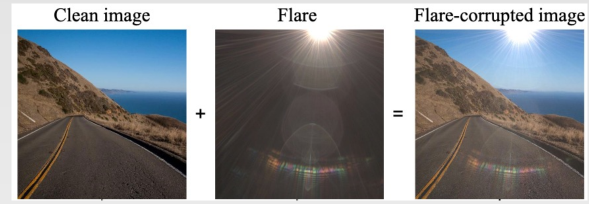
$$P(u,v) = \boxed{A(u,v)} \cdot e^{i\phi(u,v)}$$

The phase shift function is represented using Zernike Polynomials

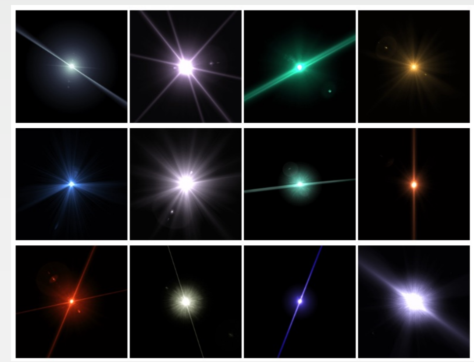
$$P(u,v) = A(u,v) \cdot e^{i \sum_{n,m} \boxed{a_{nm}} Z_{nm}(u,v)}$$

N.B. We point out imperfections in the methods of prior papers concerning flare

Wu, et al. (2021, ICCV)



Dai, et al. (2022, NeurIPS)



Wu, Yicheng, Qiurui He, Tianfan Xue, Rahul Garg, Jiawen Chen, Ashok Veeraraghavan, and Jonathan T. Barron. "How to train neural networks for flare removal." In Proceedings of the IEEE/CVF International Conference on Computer Vision, pp. 2239-2247. 2021.

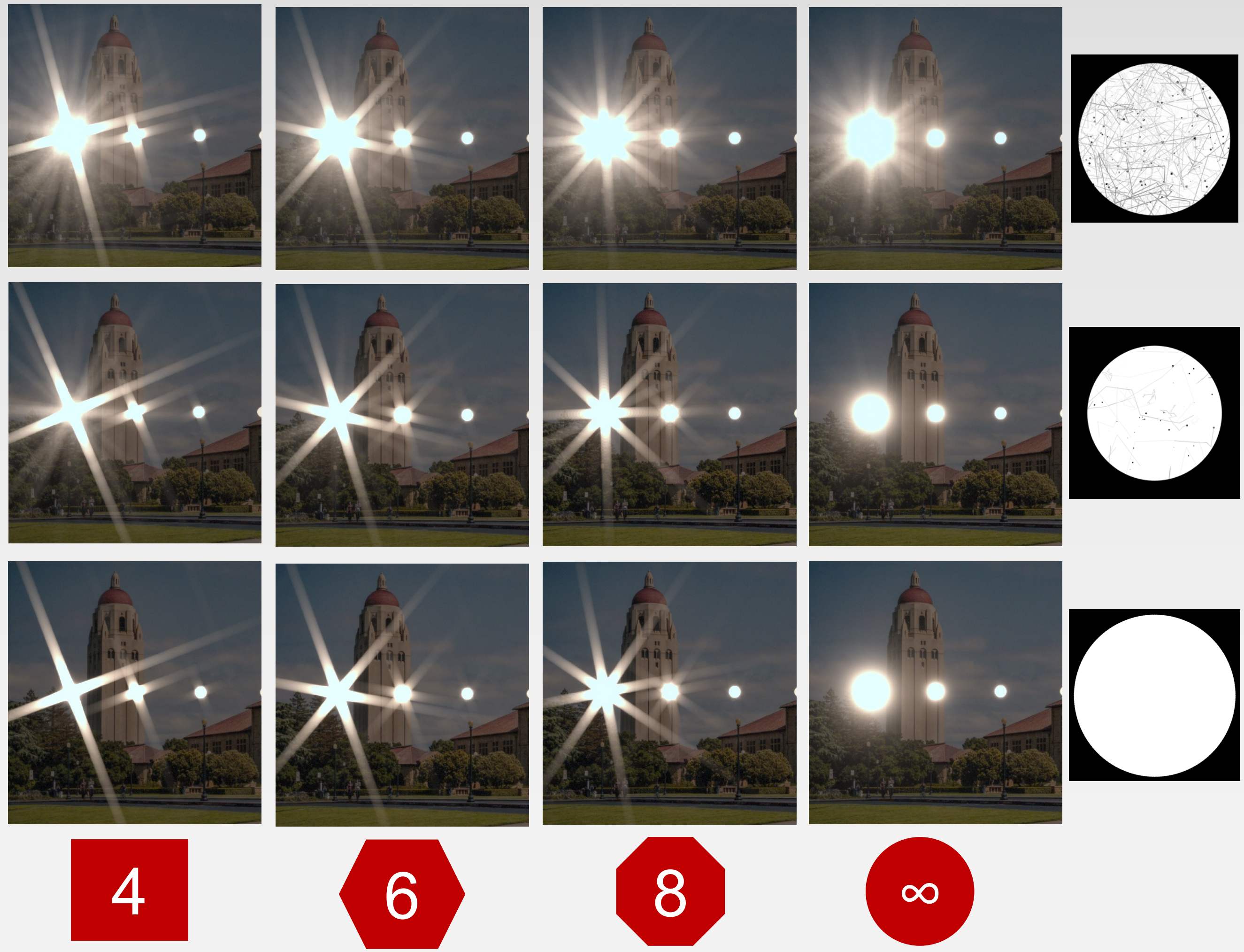
Dai, Yuekun, Chongyi Li, Shangchen Zhou, Ruicheng Feng, and Chen Change Loy. "Flare7k: A phenomenological nighttime flare removal dataset." Advances in Neural Information Processing Systems 35 (2022): 3926-3937.

Flare due the aperture shape and scratches (apodization)

We implemented methods for simulating **two sources** of flare

- Aperture shape
- Lens dust and scratches
- We model lens wavefront phase aberrations

We have not yet found an efficient representation for inter-reflections

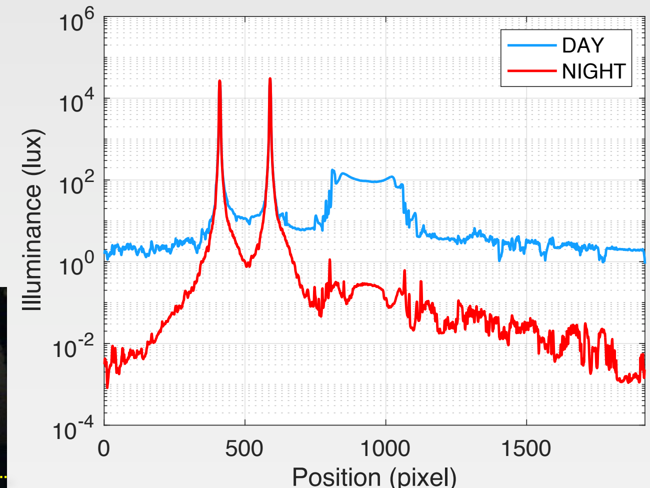


Daytime images – flare not important

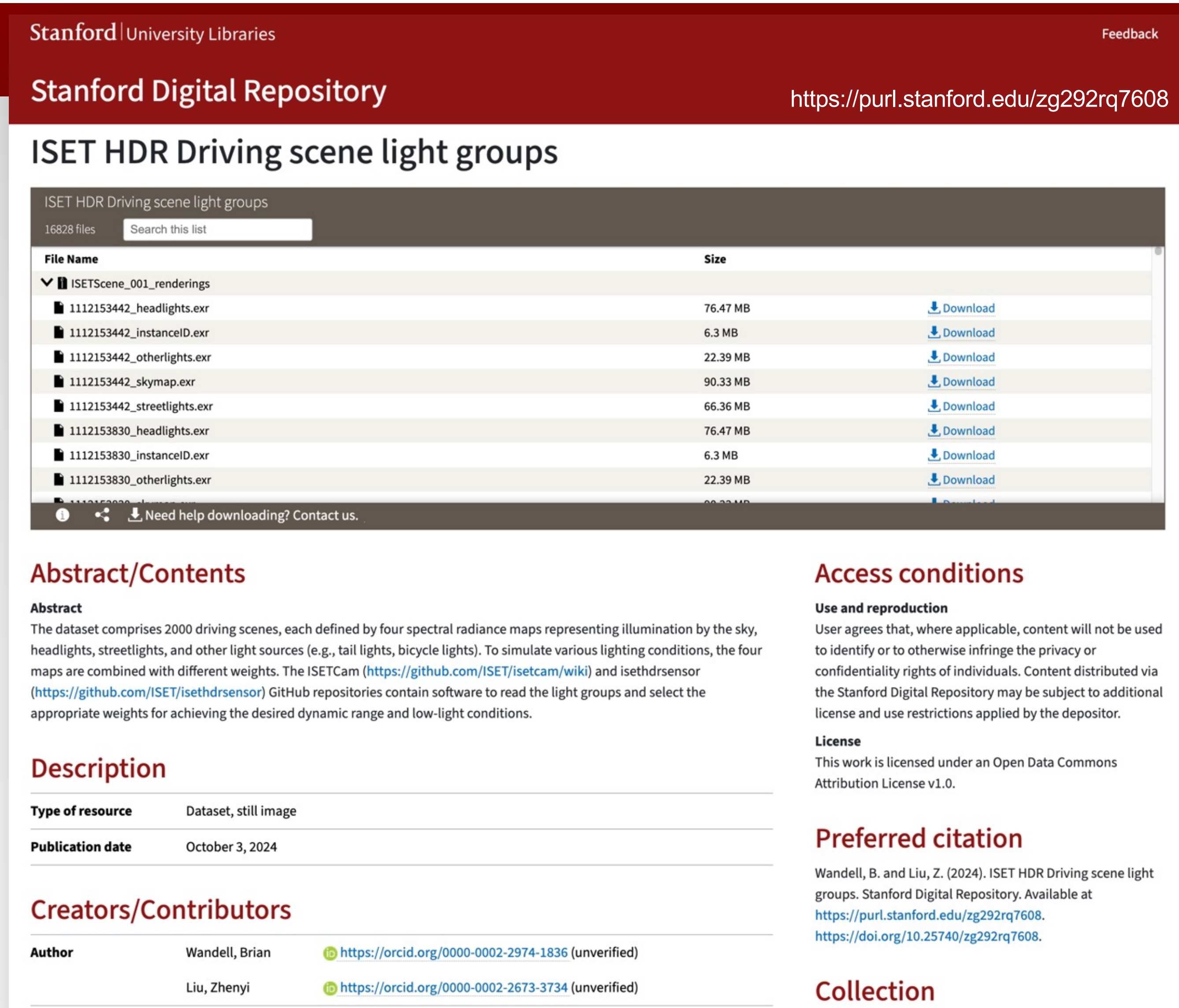
Nighttime HDR images – flare becomes important

ISETHDR – Light group concept

Four renderings with different lighting models
(2000 scenes at https://purl.stanford.edu/zg292rq7608



- 2000 Highway and country road driving scenes
- Spectral radiance light groups
- Depth maps, pixel-level object ids
- Freely available for download using methods in ISETCam



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Feedback

Stanford Digital Repository

https://purl.stanford.edu/zg292rq7608

ISET HDR Driving scene light groups

ISET HDR Driving scene light groups

16828 files

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File Name	Size	
ISETScene_001_renderings		
1112153442_headlights.exr	76.47 MB	Download
1112153442_instanceID.exr	6.3 MB	Download
1112153442_otherlights.exr	22.39 MB	Download
1112153442_skymap.exr	90.33 MB	Download
1112153442_streetlights.exr	66.36 MB	Download
1112153830_headlights.exr	76.47 MB	Download
1112153830_instanceID.exr	6.3 MB	Download
1112153830_otherlights.exr	22.39 MB	Download

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Abstract/Contents

Abstract

The dataset comprises 2000 driving scenes, each defined by four spectral radiance maps representing illumination by the sky, headlights, streetlights, and other light sources (e.g., tail lights, bicycle lights). To simulate various lighting conditions, the four maps are combined with different weights. The ISETCam (https://github.com/ISET/isetcam/wiki) and isethdrsensor (https://github.com/ISET/isethdrsensor) GitHub repositories contain software to read the light groups and select the appropriate weights for achieving the desired dynamic range and low-light conditions.

Description

Type of resource	Dataset, still image
Publication date	October 3, 2024

Creators/Contributors

Author	Wandell, Brian	https://orcid.org/0000-0002-2974-1836 (unverified)
	Liu, Zhenyi	https://orcid.org/0000-0002-2673-3734 (unverified)

Access conditions

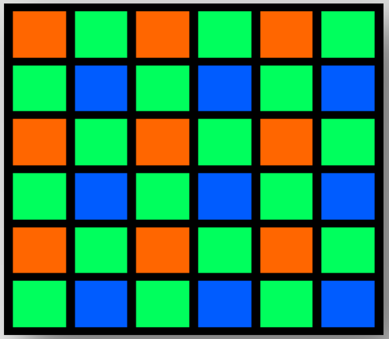
Preferred citation

Wandell, B. and Liu, Z. (2024). ISET HDR Driving scene light groups. Stanford Digital Repository. Available at https://purl.stanford.edu/zg292rq7608. https://doi.org/10.25740/zg292rq7608.

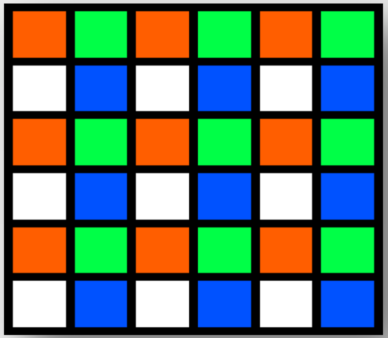
Collection

Experiments with HDR sensor designs

- Split photodiode
- RGBW sensor

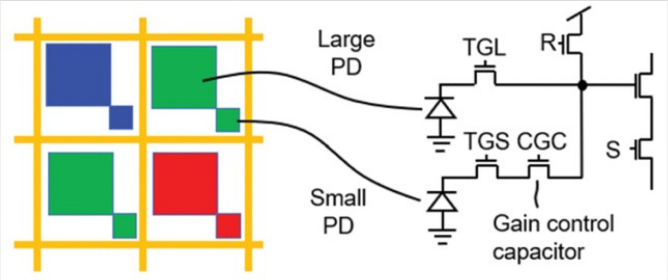


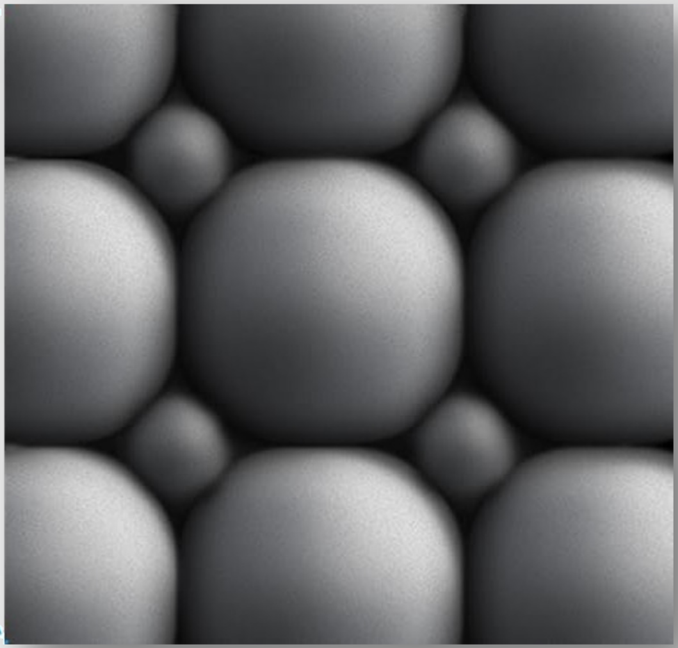
Bayer



RGBW

low-light sensitivity
dynamic range





Using simulation to quantify the performance of automotive perception systems

• Autonomous driving • Image systems simulation • Automotive perception system • Neural network

Zhenyi Liu, Devesh Shah, Alireza Rahimpour, Devesh Upadhyay, Joyce Farrell, Brian Wandell

DOI: 10.2352/EI.2023.35.16.AVM-118 | Published Online: January 2023

IEEE Sensors Council IEEE SENSORS JOURNAL, VOL. XX, NO. XX, XXXX 2022 1

ISETHDR: A Physics-based Synthetic Radiance Dataset for High Dynamic Range Driving Scenes

Zhenyi Liu, Devesh Shah, and Brian A. Wandell

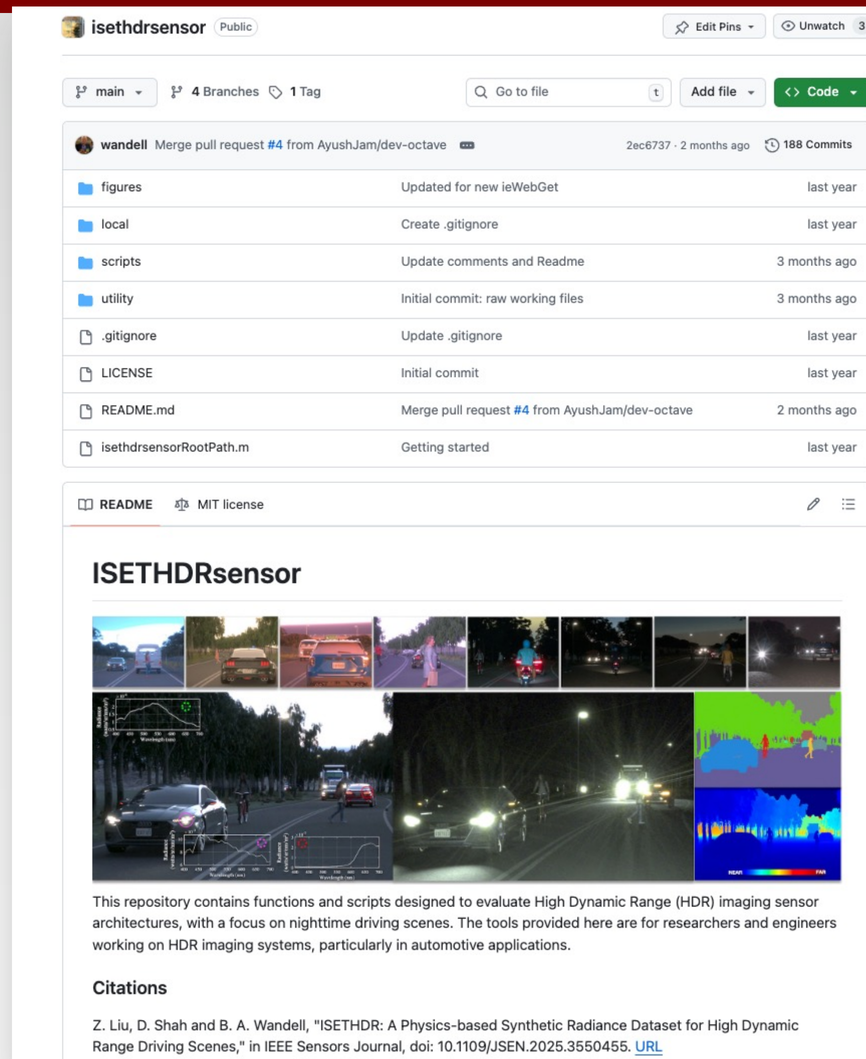
Abstract—This paper presents a physics-based simulation that models the complete imaging pipeline from scene radiance to final rendered image. We use this simulation to evaluate sensor designs optimized for high dynamic range (HDR) environments, such as driving through daytime tunnels or in nighttime conditions. The work makes three main contributions: (1) A synthetic, labeled dataset of HDR driving scenes with instance segmentation and depth information; (2) Open-source simulation software with validated performance; and (3) A comparative analysis of two single-shot sensor designs optimized for HDR imaging. Both the dataset (ISETHDR) and simulation software (ISETHDRSensor) are made publicly available and can be used to evaluate sensor designs for high dynamic range environments, such as nighttime driving scenes.

Index Terms—Image system engineering, high dynamic range, digital twins, open source dataset, automotive imaging, nighttime driving

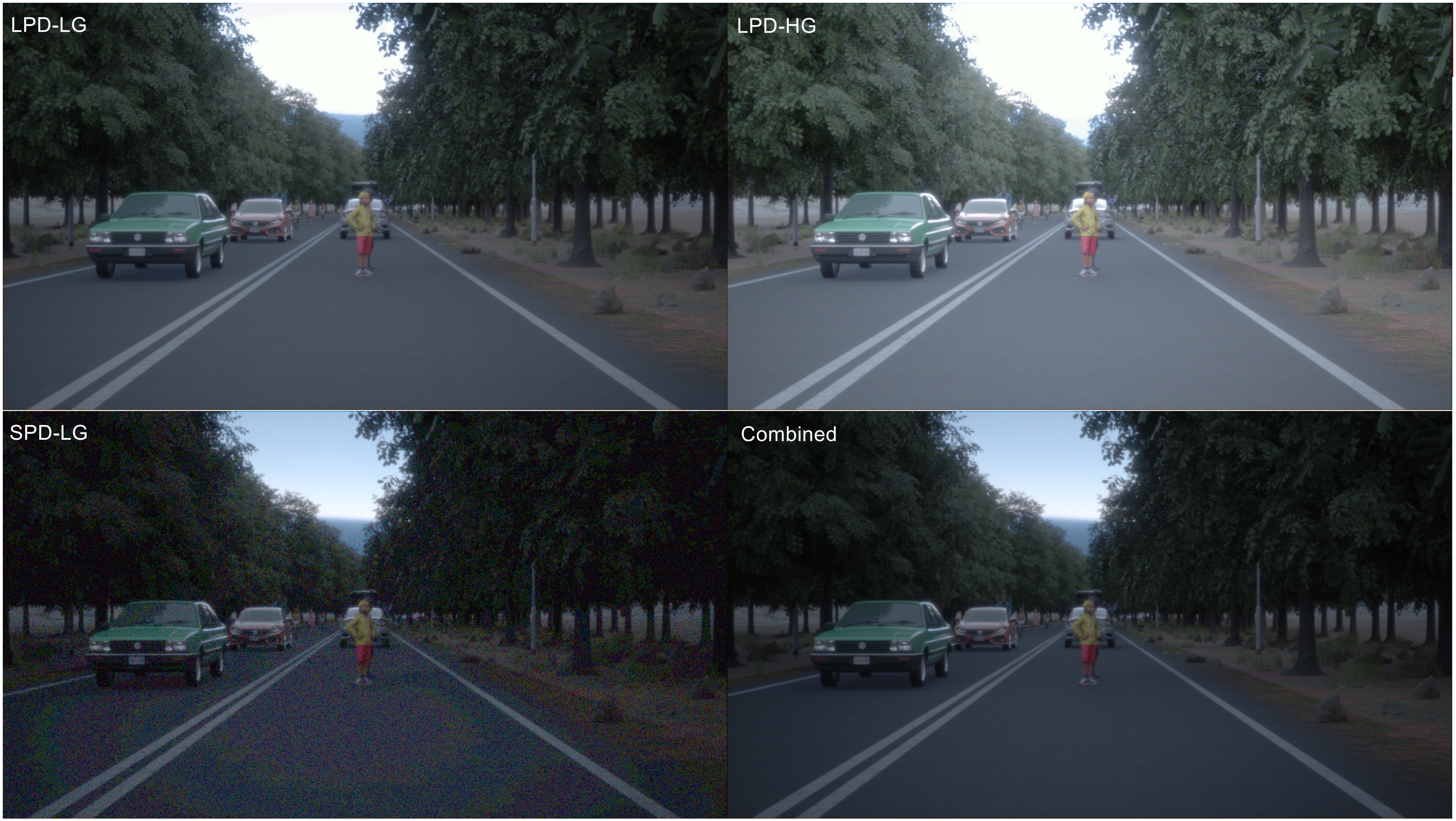
ISET HDR sensor computational methods

- Reproducible software repositories

- Two types of experiments
  1. Split photodiode model
  2. RGBW CFA model



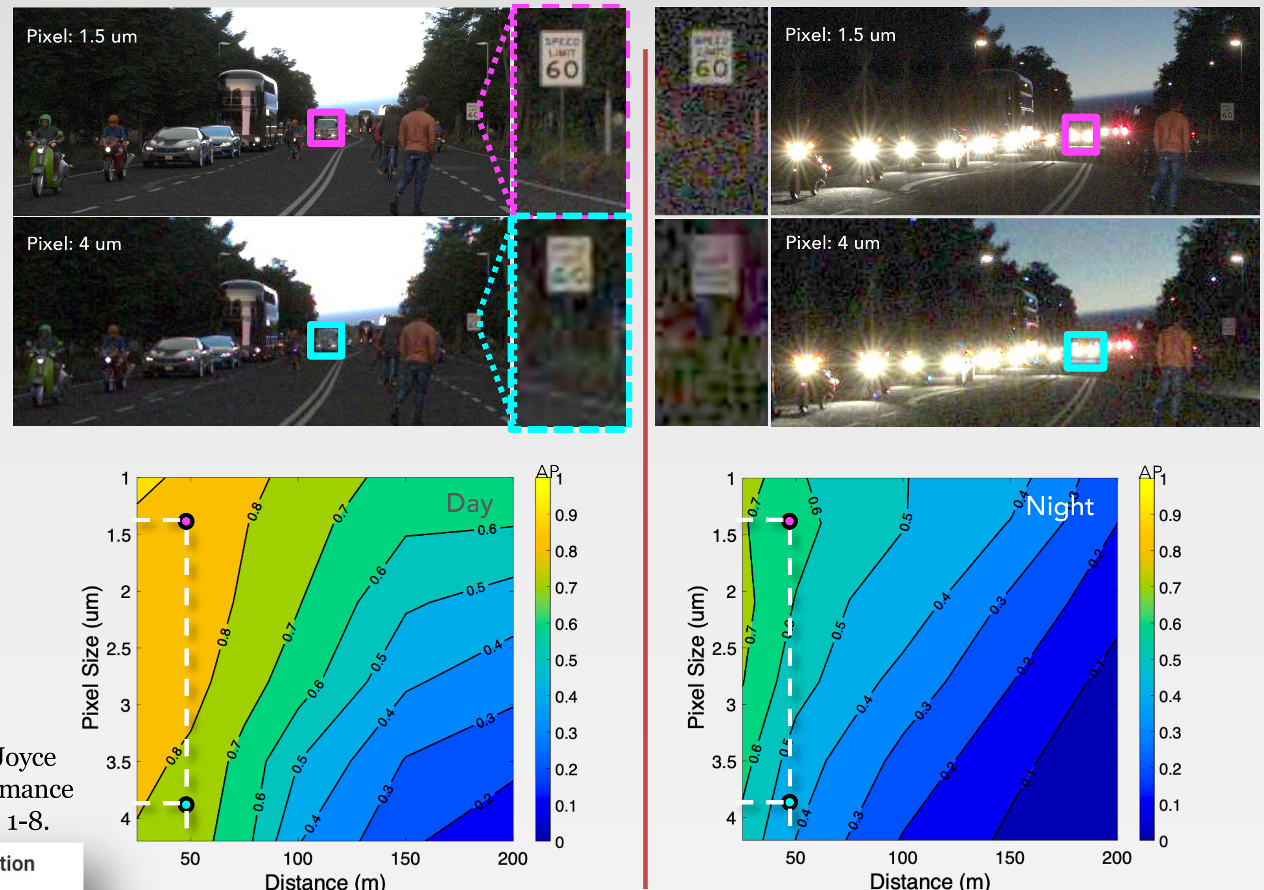
https://github.com/ISET/isethdrsensor
https://github.com/ISET/isethdrsensor/wiki


LPD-LG
LPD-HG
SPD-LG
Combined

Machine learning applications: Evaluation

- We used the simulated data to evaluate performance with different sensors (pixel size) under different conditions

- These provide global assessments of the design tradeoffs



Liu, Zhenyi, Devesh Shah, Alireza Rahimpour, Devesh Upadhyay, Joyce Farrell, and Brian Wandell. "Using simulation to quantify the performance of automotive perception systems." Electronic Imaging 35 (2023): 1-8.

Using simulation to quantify the performance of automotive perception systems

Autonomous driving · Image systems simulation · Automotive perception system · Neural network

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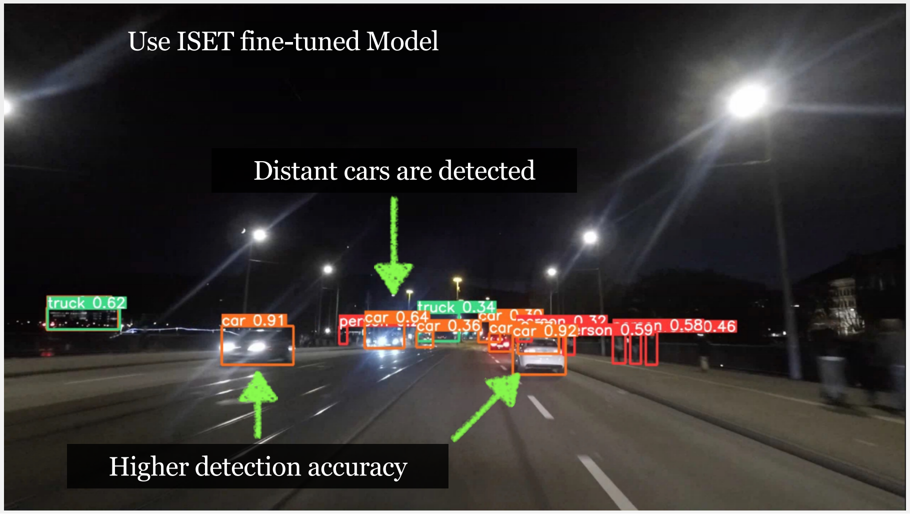
PDF XML BIB

Machine learning application

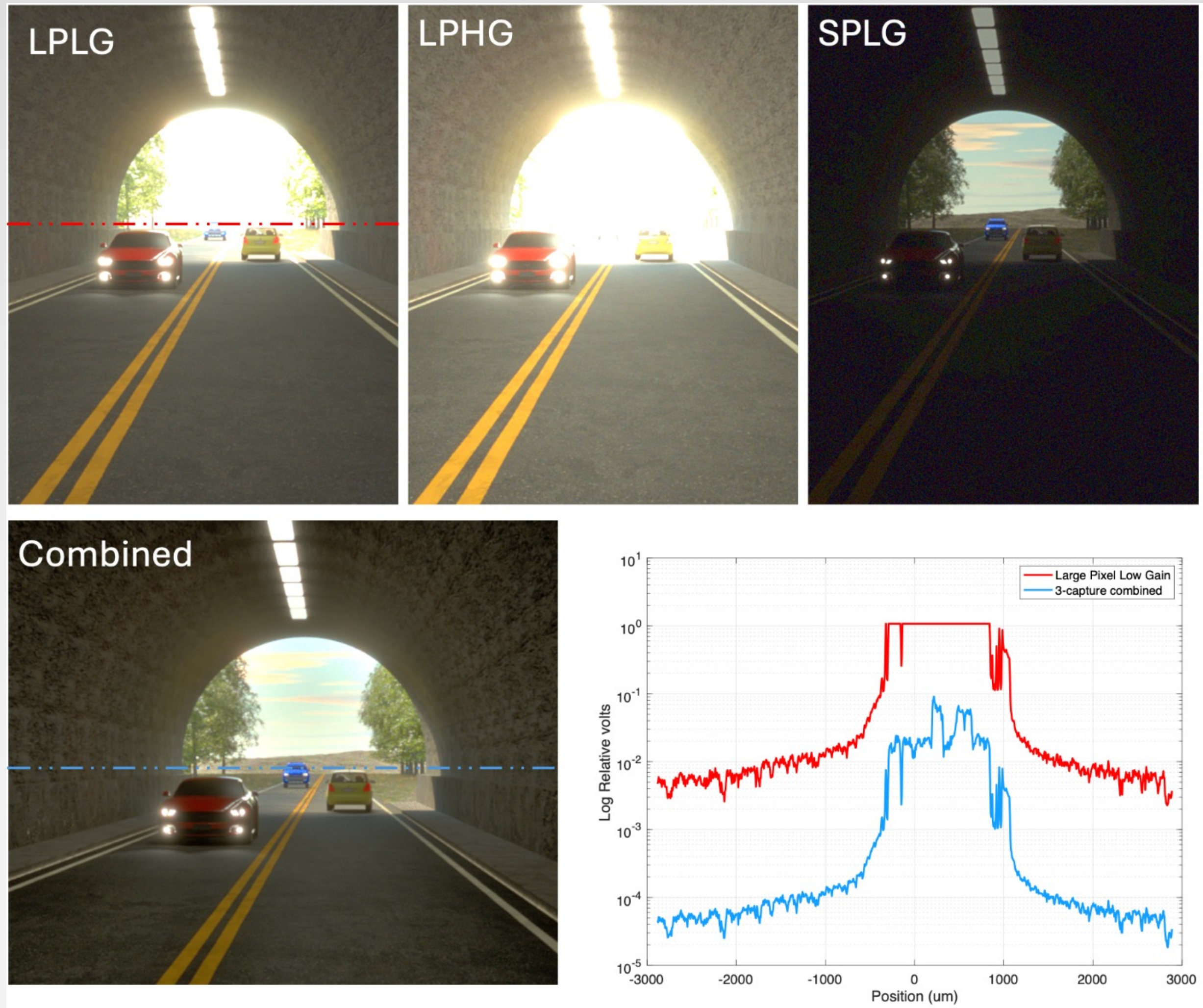
- We used the simulated data for fine-tuning pretrained models (in this case Yolo-7
- Using the ISETHDR flare data set improved the model performance



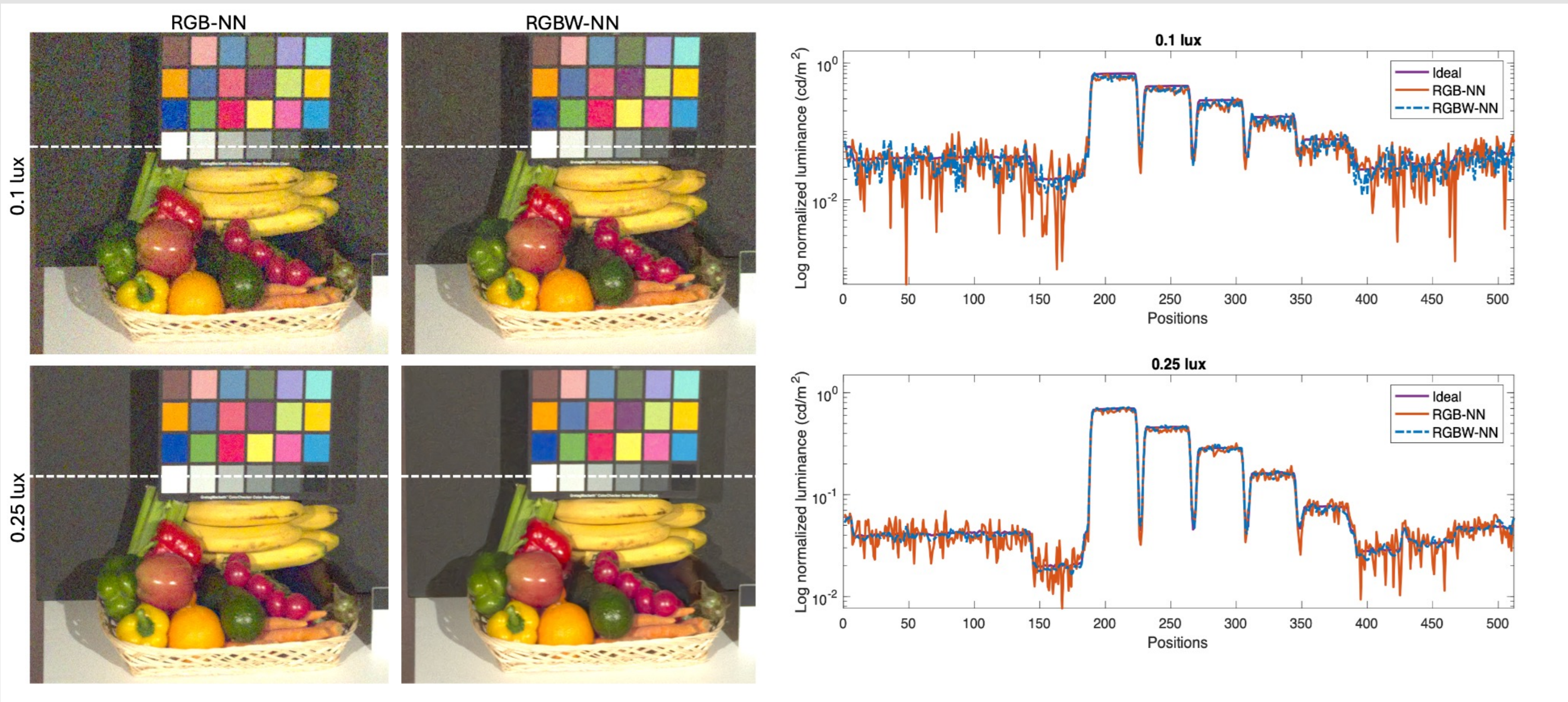
The value of designed case analysis compaed to group analysis

- We used the simulated data to investigate edge-cases

- This is an example of how the split photodiode improves the rendering of a classic driving performance issue

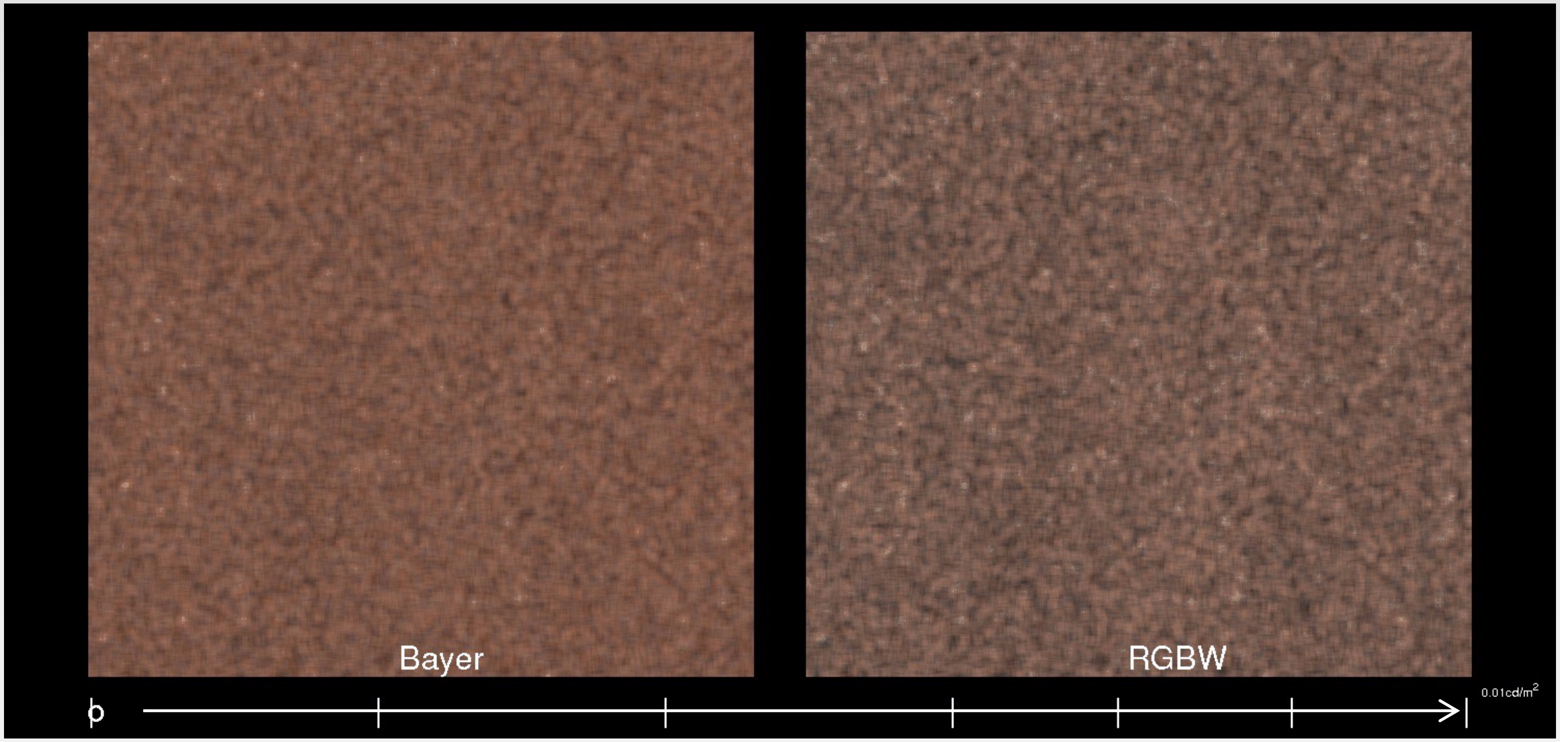


Experiments with RGB and RGBW sensors



RGBW compared to Bayer

RGBW: better in low light & same in high light



.01 .1 1 10 100 200 300 cd/m^2

Scene luminance (cd/m²)

Third point

- There are opportunities for digital twinning novel sensor and optics configurations
- Digital twin data and be used for network training and end-to-end system evaluation

Simulation technologies for image systems engineering

Professor Brian A. Wandell
Stanford University

Stanford Center for Image Systems Engineering
Wu Tsai Neurosciences Institute
Stanford Center for Cognitive and Neurobiological Imaging

QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

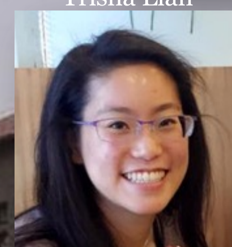
∞

CHECK AND SHARE

Joyce Farrell

Zhenyi Liu

Trisha Lian



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Henryk Blasinski

Andy Lin

Thomas Goossens

Haomiao Jiang

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