Optimizing camera design for machine perception via end-to-end camera simulation

2024 Feb, 6th

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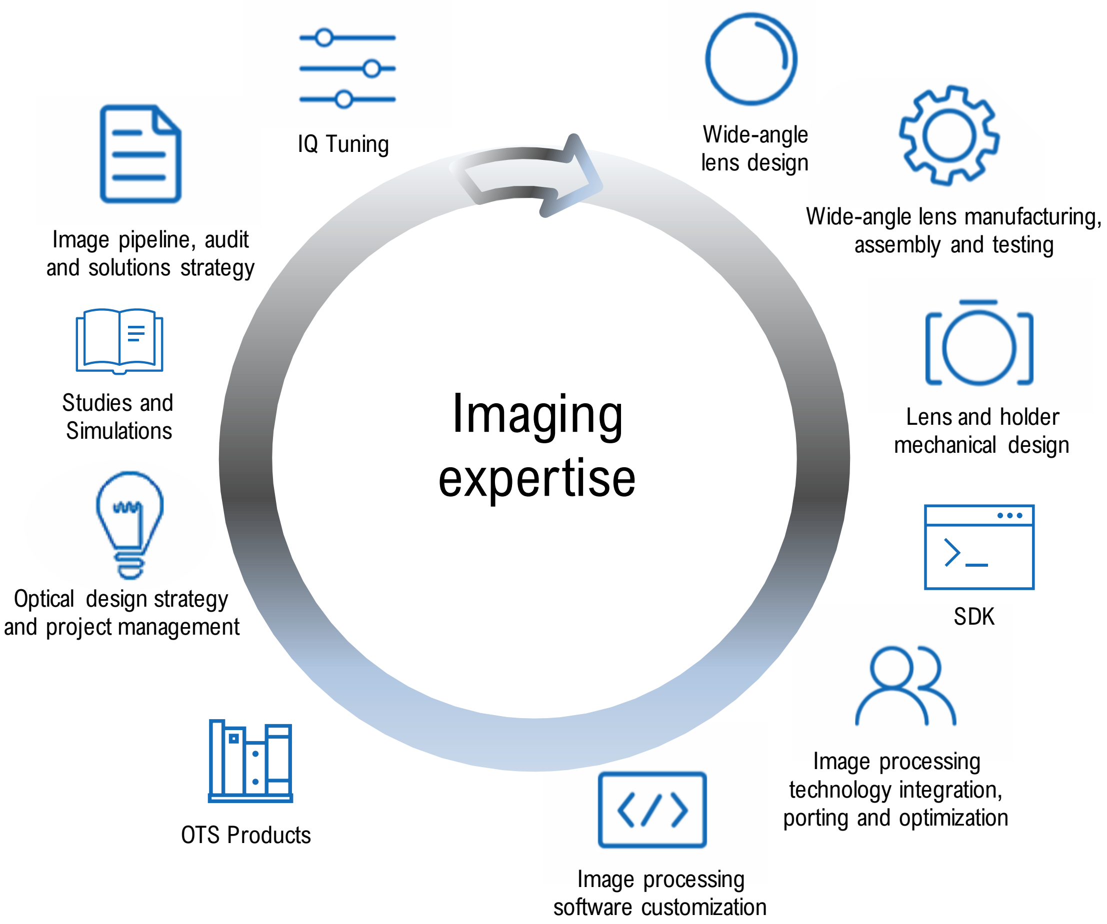
OVERVIEW: VISION SYSTEM CORE TECHNOLOGIES



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OVERVIEW : INDUSTRIES INVOLVED

COMPUTER VISION AND MACHINE PERCEPTION HAVE BECOME PRIMARY PLAYERS IN MANY BOOMING INDUSTRIES

Communication and Mobile

Automotive

Security

Healthcare & Science

IP Architects

Virtual Reality

Robotics

Aerospace

Broadcast & Live Streaming

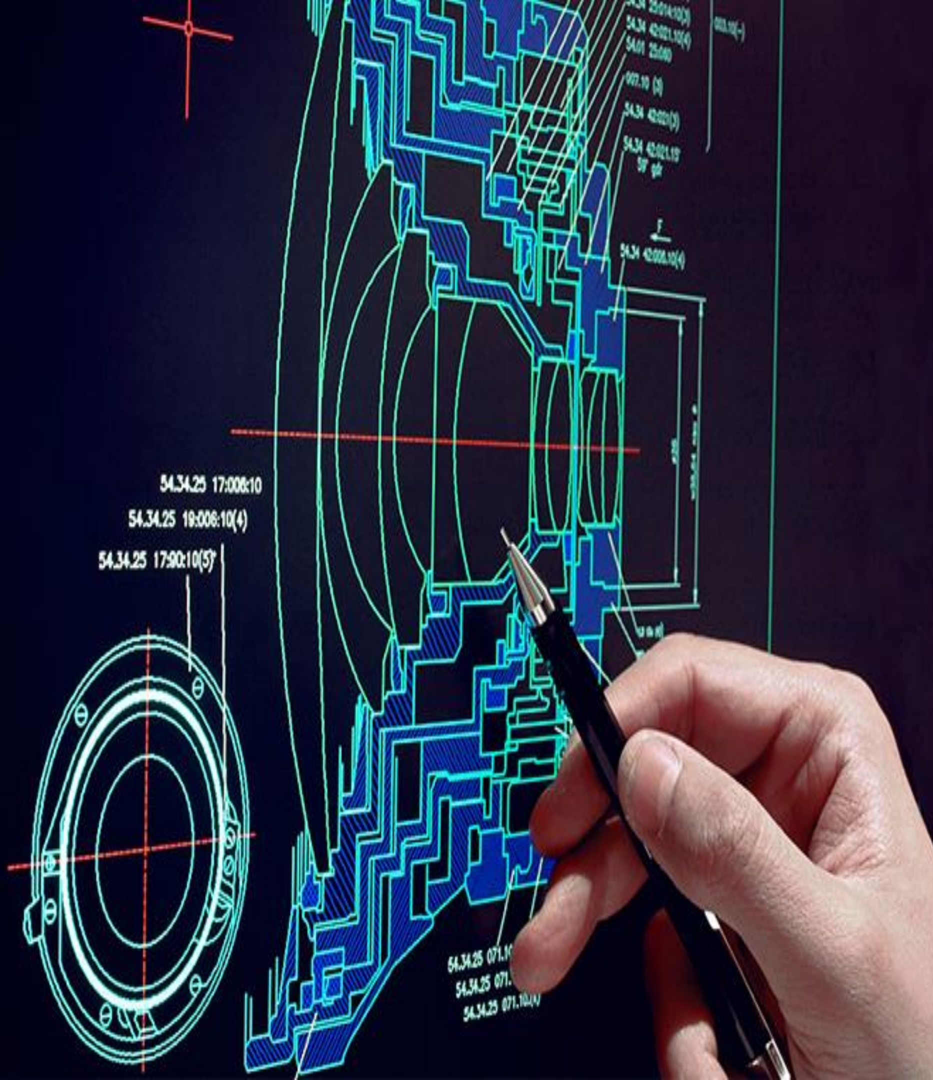
Video Cameras & Photography

Home Devices, Wearables & Other IoT Devices

Defence

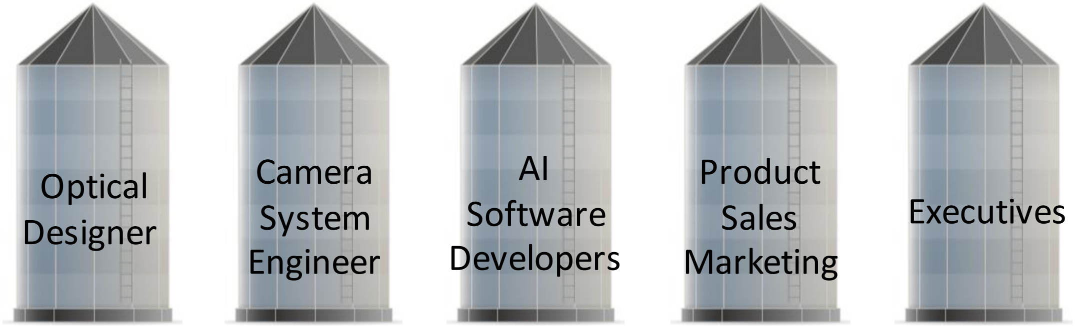
OUTLINE

- What are the benefits of simulating imaging systems ?
- How do we simulate the entire image formation pipeline ?
- Practical use case 1: Using camera simulation tool for custom in-cabin lens design
- Practical use case 2: Using image simulation tool to redefine KPI for machine perception



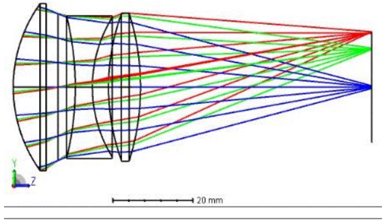
WHAT ARE THE BENEFITS OF SIMULATING IMAGING SYSTEMS?

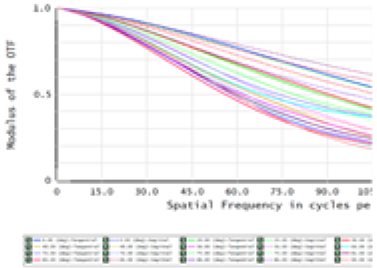
BRINGING BENEFITS TO MULTIPLE STAKEHOLDERS

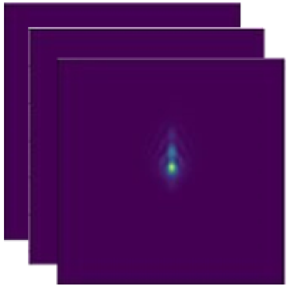


WHY USING VISION SYSTEMS SIMULATION

CURRENT VISION SYSTEM DESIGN PRACTICES







Starting point
Optical design software

Design

Evaluation of performances

- Long, cumbersome process based on specific performance indicator target numbers
- How can we validate the target number before engaging in the prototyping phase?

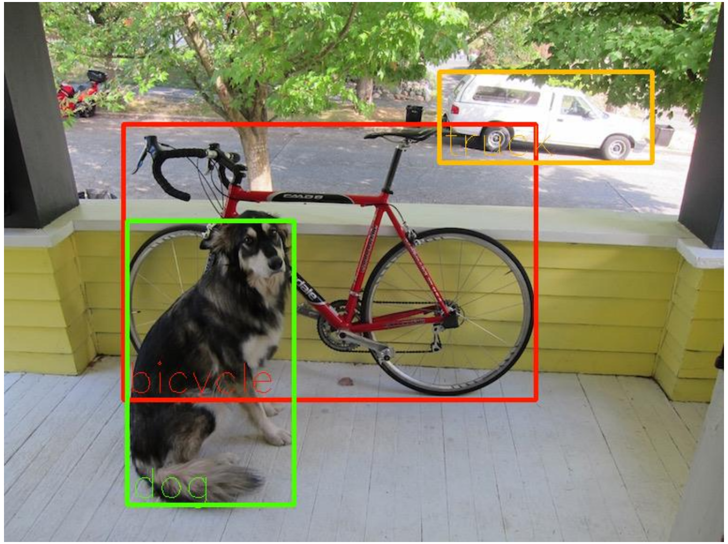
WHY USING VISION SYSTEMS SIMULATION

WHAT ABOUT MACHINE PERCEPTION ?

All this process relies on aberration minimization

Fitted for human perception

What about machine perception ?



- Can aberrations help scene understanding ?
- Can we tolerate more aberrations for designs dedicated to machine perception ?

We need to redefine the way we apply image quality indicators for machine perception

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WHY USING VISION SYSTEMS SIMULATION

IMPROVING VISION SYSTEMS DESIGN PROCESS

Main objective : assists the design process by creating simulated outputs dependant on various design parameters.

Principle: simulates all the steps implied in the image formation process, from the object space to the performance indicators measurements.

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CAMERA SIMULATION

HOW DO WE SIMULATE THE ENTIRE IMAGE FORMATION PIPELINE ?

CAMERA SIMULATION-GEOMETRICAL ASPECT

DISTORTION, FOV, SENSOR DIMENSION

Data collection

Shooting

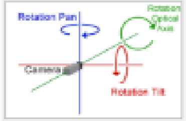
Stitching

=360° environment

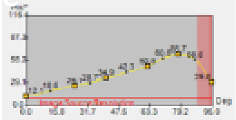
Simulation pipeline

Input Picture

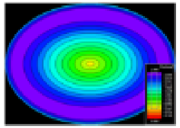
Camera Parameters
-Orientation
-Resolution
-FOV



Lens Parameters
-Distortion
-Anamorphosis

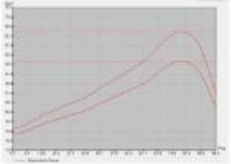


Curve Analyse



Simulation results

Optical Design Software



Simulated resulting image

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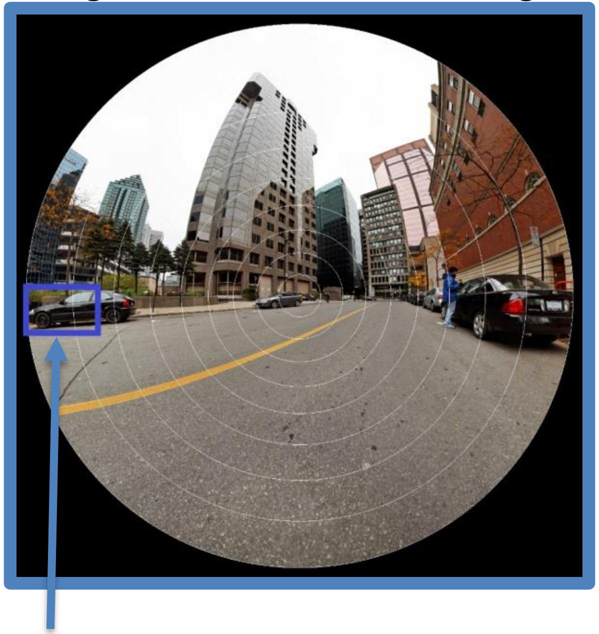
CAMERA SIMULATION-GEOMETRICAL ASPECT

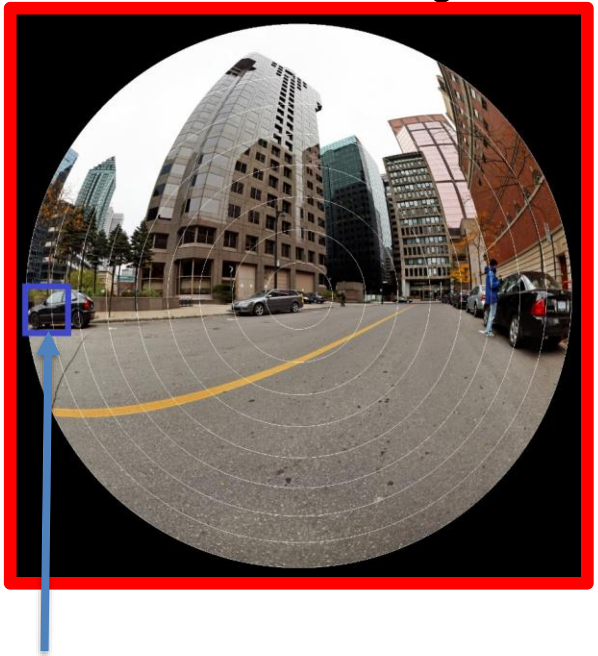
SMART PIXEL MANAGEMENT: INCREASE PIXEL DENSITY IN A REGION OF INTEREST

Targeted resolution wide-angle



≈23000 pixels *13 pixels/degree at the edge*

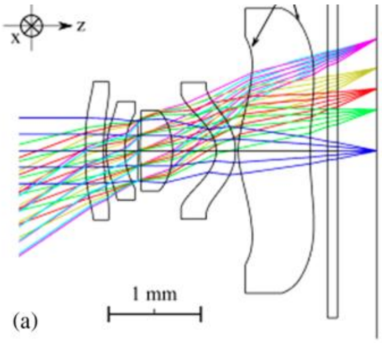
Traditional wide-angle



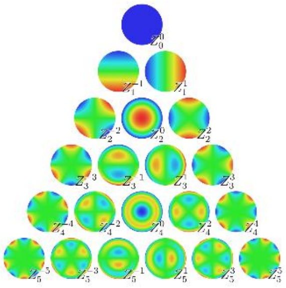
≈12000 pixels *6.5 pixels/degree at the edge*

CAMERA SIMULATION-OPTICAL ABERRATION

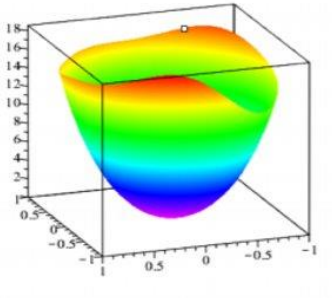
DIFFERENT WAY OF REPRESENTING OPTICAL ABERRATION



Design presenting aberrations

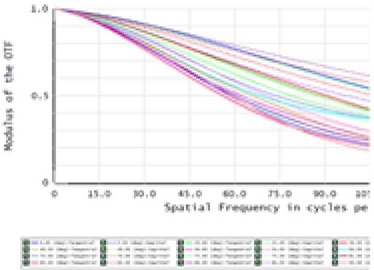


Zernike polynomial basis

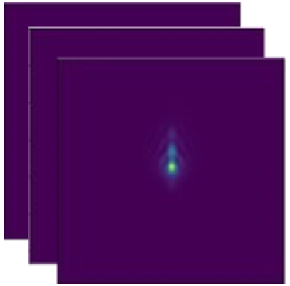


$$W(\rho,\varphi) = \sum_n \sum_m C_{nm} Z_n^m(\rho,\varphi)$$

Aberrated wavefront



MTF



Spatially varying PSF

Link for paper,
J. Buquet, R. Larouche, J. Parent, P. Roulet, S. Thibault, "Accurate camera performance prediction using optical and imaging simulation pipeline for super wide-angle lens," Proc. SPIE 12217, Current Developments in Lens Design and Optical Engineering XXIII, 122170B (3 October 2022);

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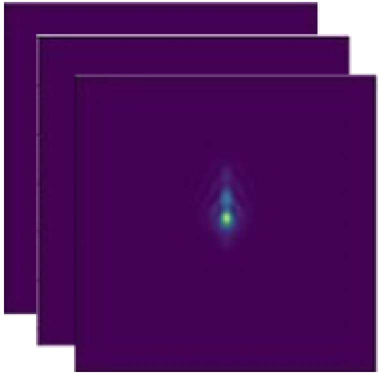
CAMERA SIMULATION-OPTICAL ABERRATION

RENDER ABERRATION ON IMAGES USING SPATIALLY VARYING PSF



*

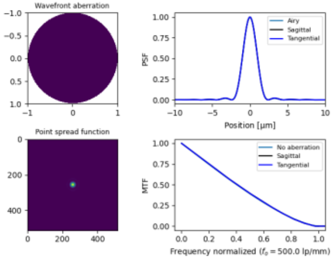
Aberration free image

Aberrated image

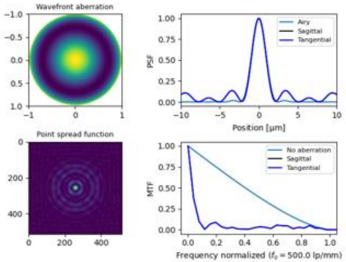
CAMERA SIMULATION-OPTICAL ABERRATION

EXAMPLE OF DIFFERENT OPTICAL ABERRATION RENDERED

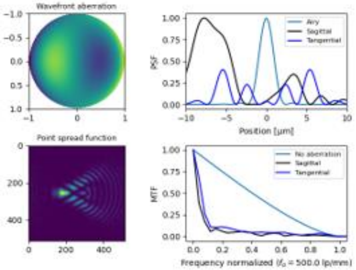
Aberration-free image
PSF represented as a point



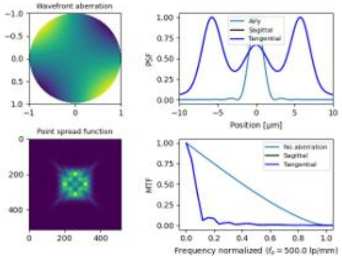
Spherical



Coma



Astigmatism

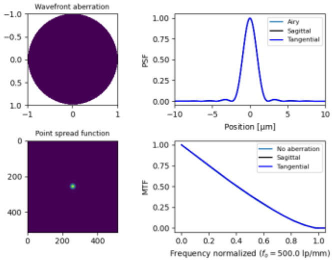


CAMERA SIMULATION-OPTICAL ABERRATION

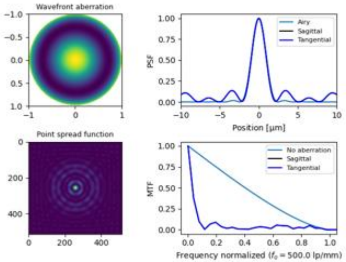
EXAMPLE OF DIFFERENT OPTICAL ABERRATION RENDERED- ZOOM-IN

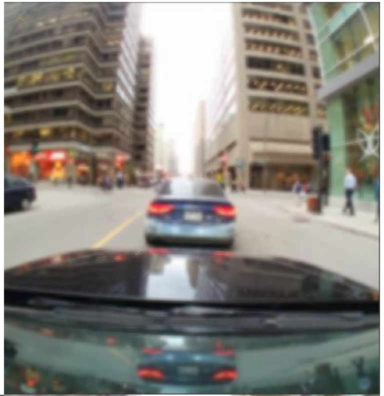
Aberration-free image

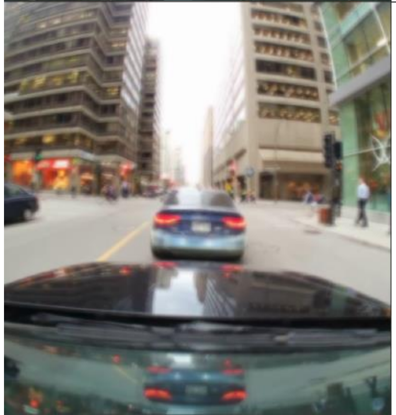
PSF represented as a point



Spherical







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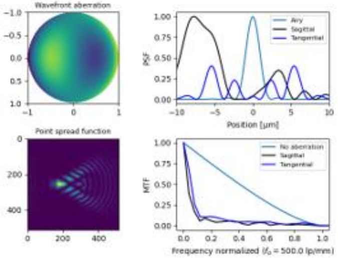
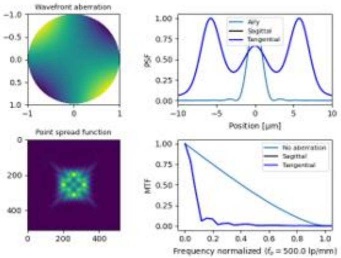
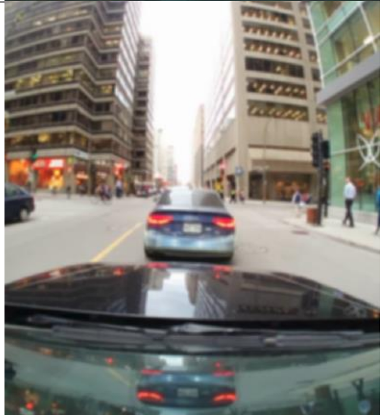


Astigmatism





CAMERA SIMULATION-SENSOR

SENSOR RESOLUTION, NOISE AND SNR SIMULATION

Dark noise (thermal + reading noises) :

fluctuation of the signal in the absence of light

$\eta_d \sim \mathcal{N}(0, \sigma_d^2)$ and $\sigma_d = QSE \times N_{dark}$

N_{dark} *is the dark noise in digital values*

Quantization noise :

digitization into integers of the electrons generated by the photons

$$\eta_q \sim \mathcal{N}(0, \sigma_q^2) \ and \ \sigma_q = \frac{QSE}{\sqrt{12}}$$

$QSE = \frac{N_{well}}{N_{dr}}$ N_{well} *(e-) is the full well capacity of a pixel and* N_{dr} *(ADU) is the dynamic range of the digital counts*

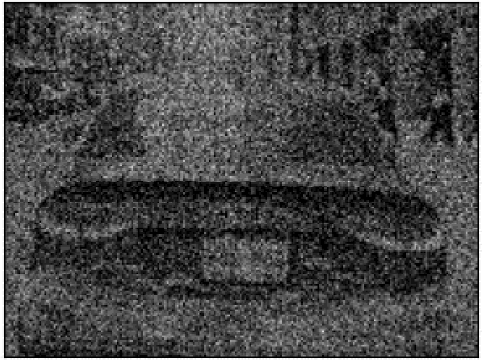
Shot noise :

discontinuity of photo-electrons numbers in a certain time interval

$\eta_s \sim POIS(\lambda)$ λ *being the average signal on a pixel*

Original image

SNR average: 7.6 dB



Number of photons per pixel increases

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DESIGN OPTIMIZATION

AUTOMOTIVE ULTRA-WIDE-ANGLE CAMERA FOR IN-CABIN MONITORING

OBJECTIVE

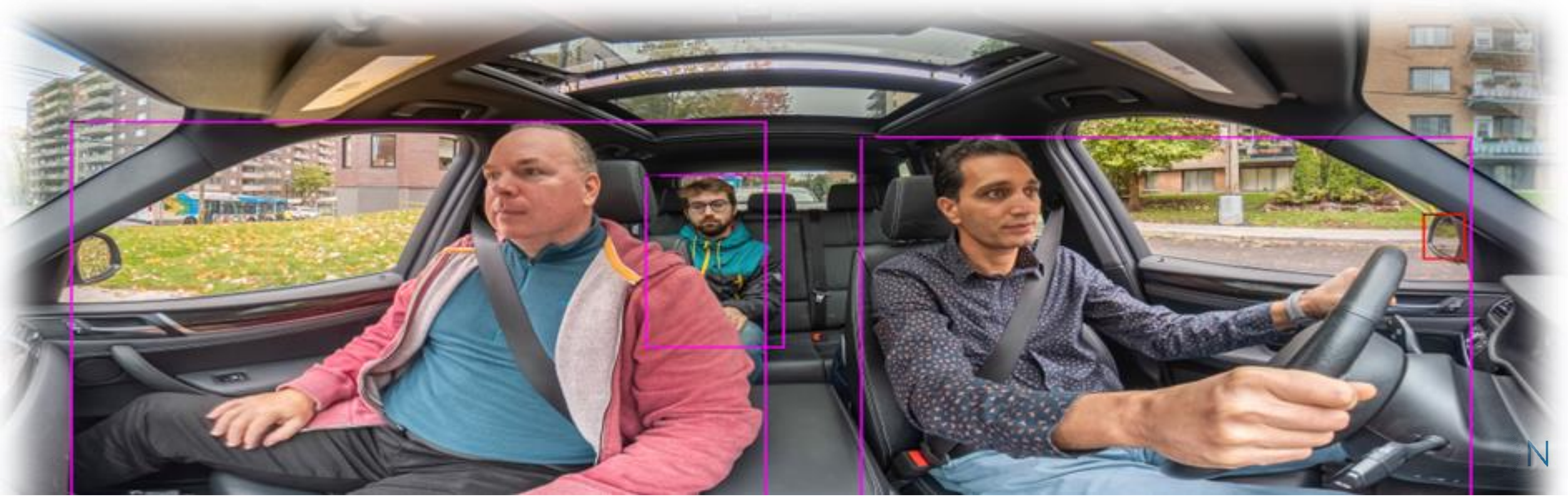
- **Design an ultra-wide-angle camera design for in-cabin monitoring**
- **The FoV needs to enable imaging the entire cabin**
- **The vision system needs to perform well enough to capture features of interest allowing for In-Cabin and Driver monitoring**
- **The camera has to perform well in various range of illuminations to cover most scenarios**

PRACTICAL CASE 1-OBJECTIVE

MULTIPLE APPLICATIONS BEHIND IN CABIN MONITORING

Seat Occupancy (OMS)
Video Surveillance and Black Box
Passenger Classification (OMS)

Driver Monitoring (DMS)
Video Chat/Conference
Identification



PRACTICAL CASE 1-WIDE ANGLE IN-CABIN PROBLEM STATEMENT

APPLICATIONS REQUIREMENTS:

- **Driver monitoring:**
  - gaze tracking => high pix/deg. in IR
  - hands on wheel => high pix/deg
  - posture recognition => medium pix/deg
- **Driver identification** => high pix/deg. in IR
- **Passenger seat occupancy** => low pix/deg
- **Back seat occupancy** => low pix/deg
- Video chat/conference => 1080p in RGB
- Video surveillance => low pix/deg RGB and IR

Problem : With traditional wide angle, the driver and occupants have same resolution while application requirements in pixel are different

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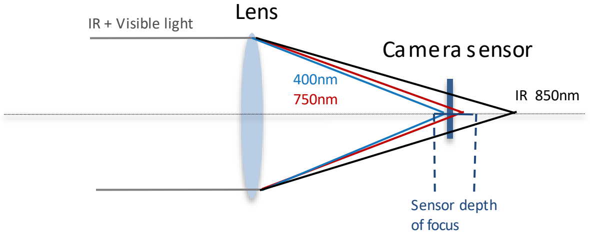
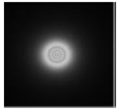
PRACTICAL CASE 2-MTF AND PSF FOR RGB AND IR

BROADER BAND NEEDED TO COVER ALL SCENARIOS

Lens optimized for narrow band (**visible OR IR**)

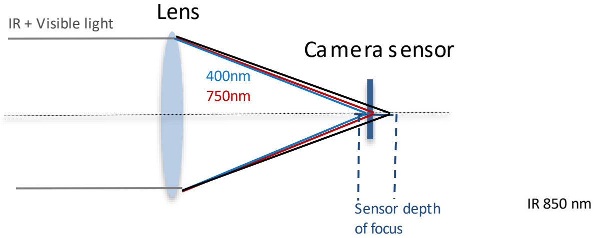




Visible on focus

IR not in focus

Lens optimized for broadband (**visible AND IR**)



Visible and IR on focus

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PRACTICAL CASE 2-ADJUSTMENT OF THE DISTORTION

Standard Fisheye lens

Immervision OTS lens

Standard Fisheye lens

Immervision OTS lens

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USING IMAGE SIMULATION TOOL TO REDEFINE KPI FOR MACHINE PERCEPTION

IMPACT OF THE DEFOCUS ON OBJECT DETECTION

OBJECTIVE

- **Predict camera degradation during its lifespan**

  (defocus can be induced when a camera is exposed to temperature changes)

- **Define tolerances threshold to relax the design requirement without affecting an algorithm performance**.

- **Knowing the amount of defocus tolerated for a vision application in advance constitutes a substantial saving in time and cost**

Link for paper J. Buquet, R. Larouche, J. Parent, P. Roulet, S. Thibault, "Optical characteristics optimized for machine perception using learning-based losses backpropagation through optical simulation pipeline," Proc. SPIE 12227, Applications of Machine Learning 2022, 122270B (3 October 2022);

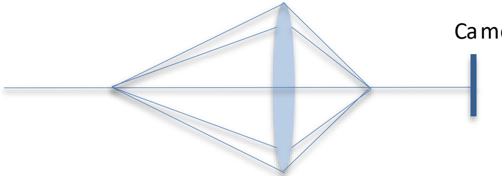
PRACTICAL CASE 2-SIMULATION OF DIFFERENT AMOUNT OF DEFOCUS

EFFECT OF DEFOCUS ON IMAGE SPOT SIZE

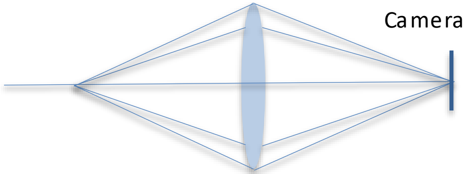
Positive defocus

0

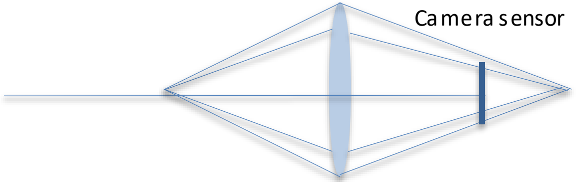
Negative defocus



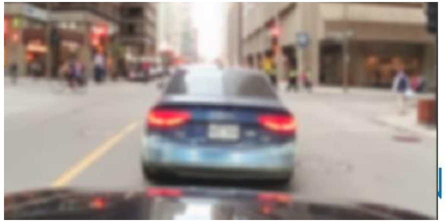
Front focus



In focus system

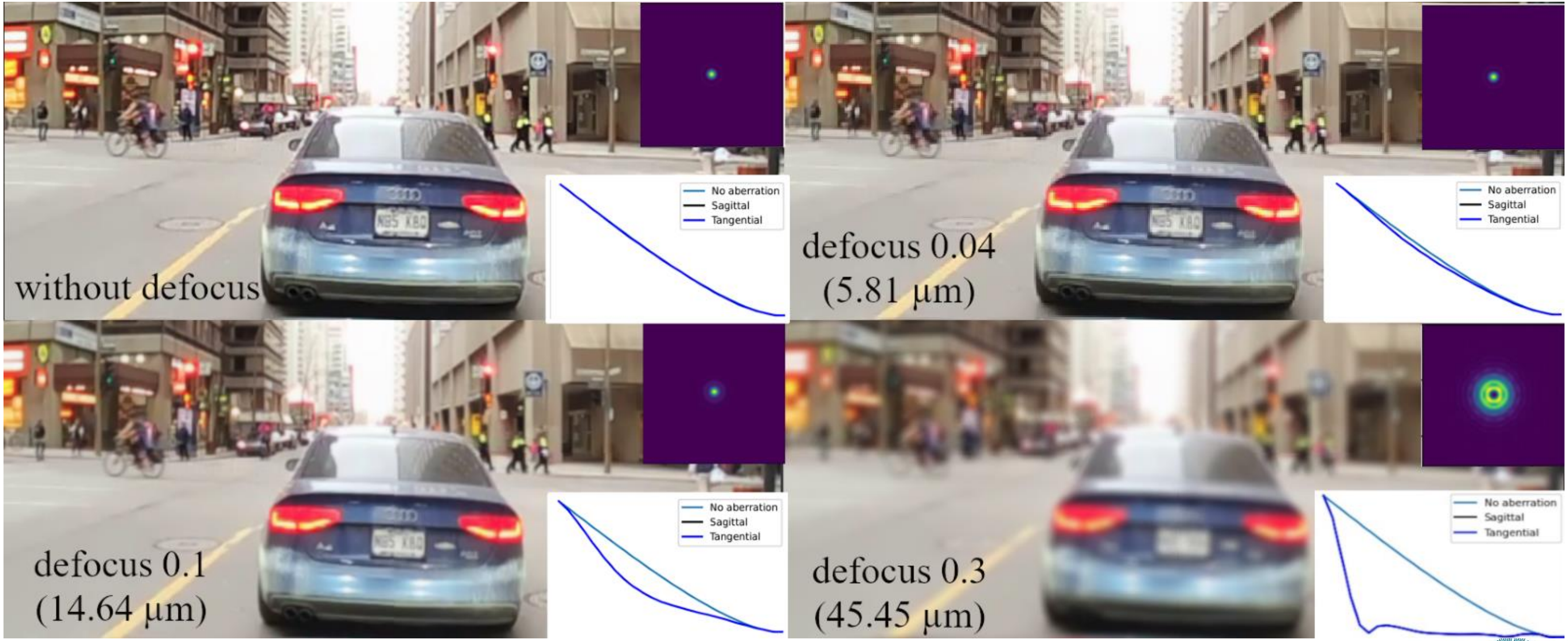


Rear focus



PRACTICAL CASE 2-SIMULATION OF DIFFERENT AMOUNT OF DEFOCUS

USING A DESIGN WITH A F-NUMBER 4



PRACTICAL CASE 2-EXPERIMENTAL PROCEDURE

NETWORK

- Yolov4: 2D Object identification (Pretrained on MsCOCO dataset)
- Light architecture
- Works in real-time

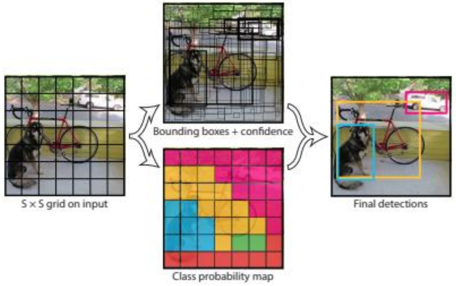


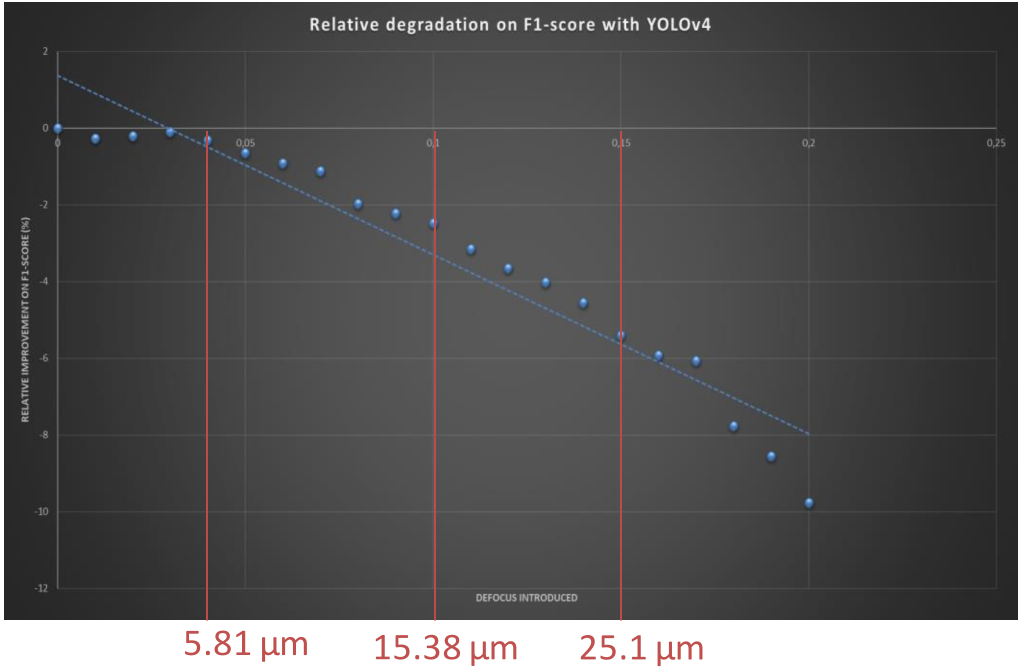
Figure 2: The Model. Our system models detection as a regression problem. It divides the image into an $S \times S$ grid and for each grid cell predicts B bounding boxes, confidence for those boxes, and C class probabilities. These predictions are encoded as an $S \times S \times (B * 5 + C)$ tensor.

LENS SPECIFICATION

- Effective focal length of 1.3mm
- F# 4
- Defocus in µm computed with optical design software simulation [0,35]

PRACTICAL CASE 2-RESULTS

PRECISION, RECALL AND F1 SCORE AS A FUNCTION OF THE DEFOCUS INTRODUCED



- Stationary results below 5 µm of defocus (only 2.5 % drop on F1-score)
- Slow drop until reaching 5% at 15.38 µm

A defocus of 15 µm can be tolerated with a relative drop of 5% in the F1-score

At λ=550nm a **drop of 2%** in the performances :

5.81 µm / **23.19 °C**

RESULTS

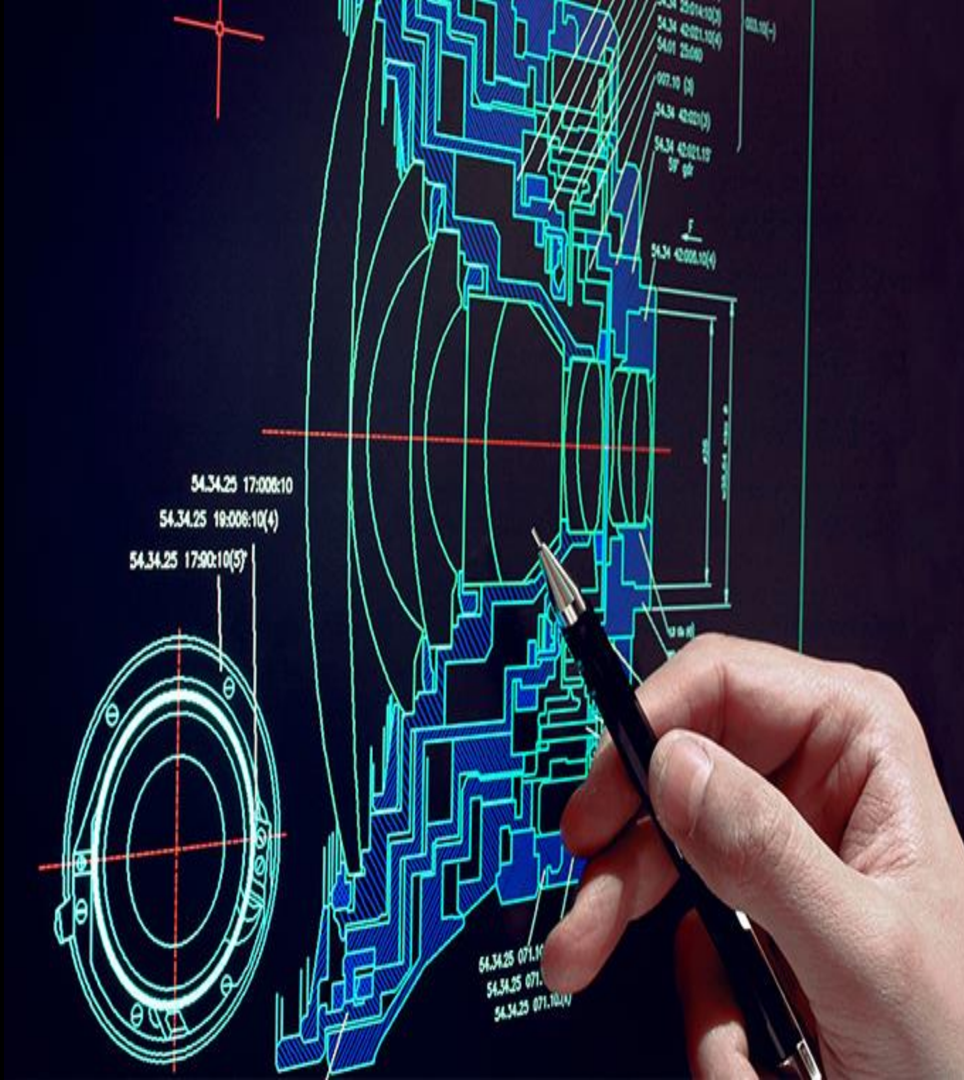
Object detection algorithm accuracy is quite invariant up to a certain level of defocus.

Large defocus reduces the accuracy of object detection algorithm.

Defocus increases from upper left to bottom right.

TAKE AWAY

- **Entire vision system simulation enables redefining performance indicators for machine perception**
- **It helps translating requirements from machine vision to optical parameters**
- **Optical design can be optimized before investing in the prototyping phase**
- **Optimizing the entire vision system is beneficial to leverage the strength of each component**



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WHY USING CAMERA SIMULATION

USE CASES

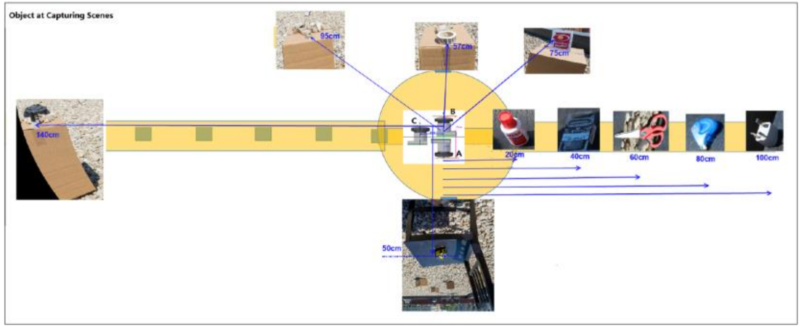
Some examples of Immervision past projects where PGMS contribution was key for success:

During the design of a vision lens for autonomous robot based on object recognition, the customer was able to test the recognition algorithms (eyes of humans nearby at various distances) and confirm the optical system parameters.

WHY USING CAMERA SIMULATION

USE CASES

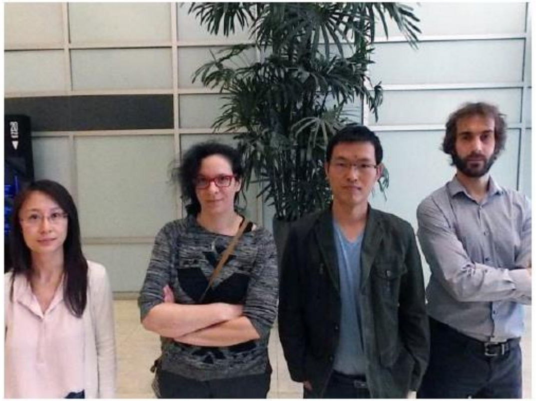
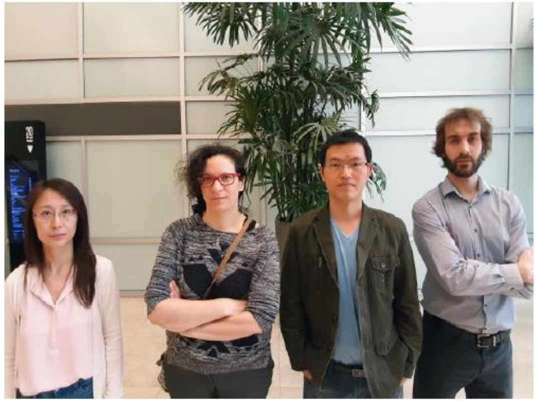
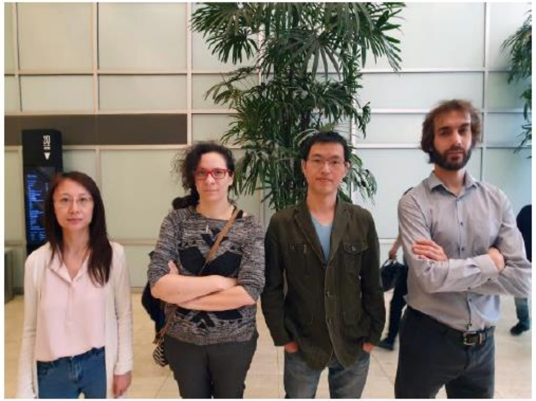
2. During the design of a back-to-back 360 camera, with two lenses having different entrance pupil positions, the simulation allowed to test multiples separations between the lenses and make sure the stitching algorithms were working fine before starting production with the selected distortion profile. It also allowed the customer to better understand what will be visible and what will not be visible around the camera after stitching.



WHY USING CAMERA SIMULATION

USE CASES

For laptop and for mobile phone lenses around 120°, we used the simulation tool to generate multiples distortion profiles and test with focus group users which one they preferred. This helped to define a balance of how straight the lines should be and how much body and face deformation are allowed by this wide-angle lens.

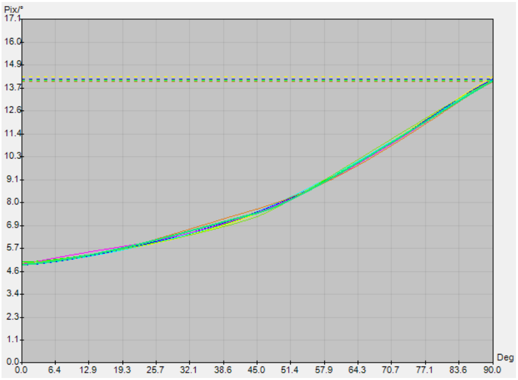




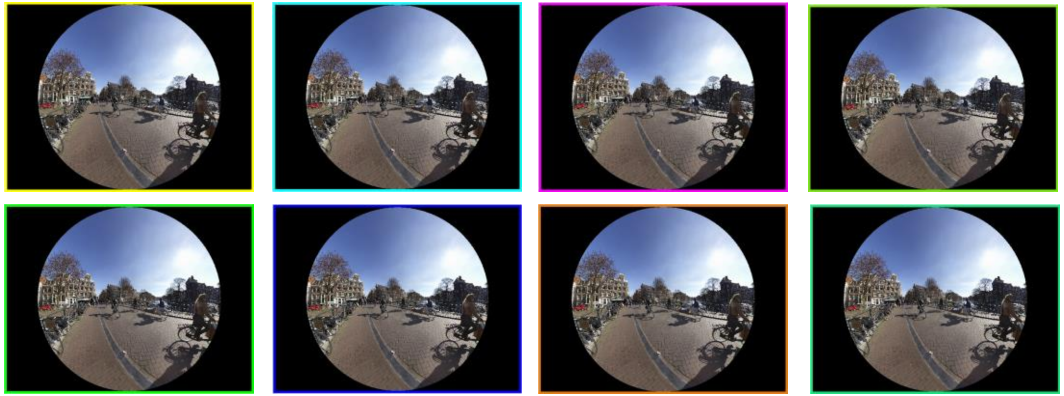
IMMERVISION

WHY USING CAMERA SIMULATION

USE CASES

For a system in which the glass molded element had high tolerances and impacting the distortion from system to system, the simulation tool was used to generate hundreds of images based on Monte-Carlo systems generated in optical design software with the manufacturing tolerances. These simulated images allowed to confirm if the distortion changes from lens to lens would affect the algorithms or not.

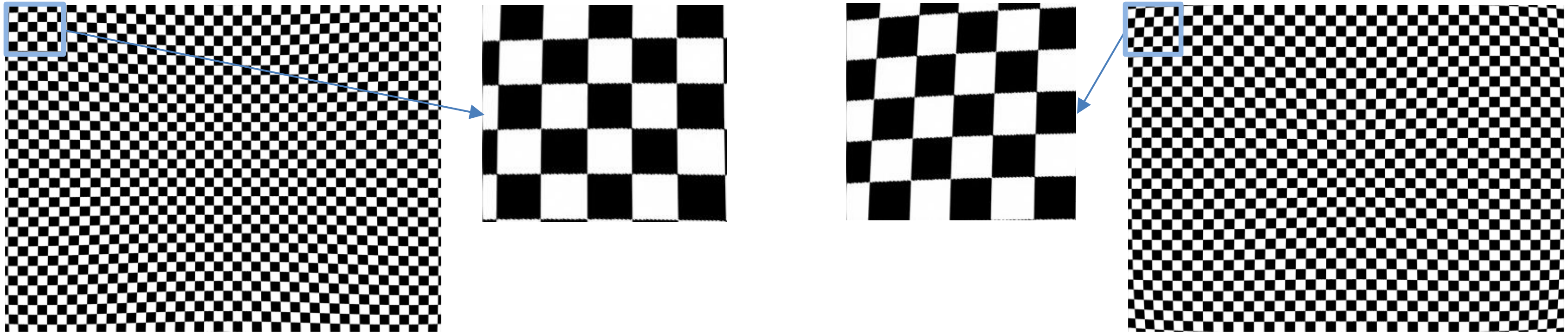




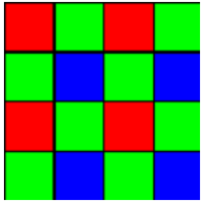
WHY USING CAMERA SIMULATION

USE CASES

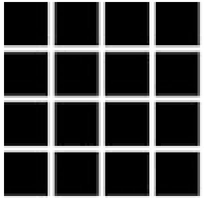
6. During a project, the lens distortion was higher than the original specification from the customer who was unsure of the impact. Simulations allowed the customer to really understand the impact of the distortion and release the specification, simplifying the overall design and reducing the costs.



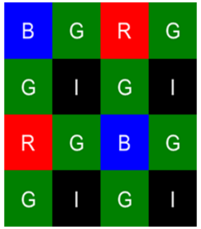
PRACTICAL CASE 1-SENSOR MODALITIES VS. EFFECTIVE RESOLUTION



RGB Sensor => complete resolution is in visible with 2x more weight in green



IR Sensor => complete resolution is in IR



RGB IR Sensor => (simplistic assumption) ¾ of resolution in visible and ¼ in IR

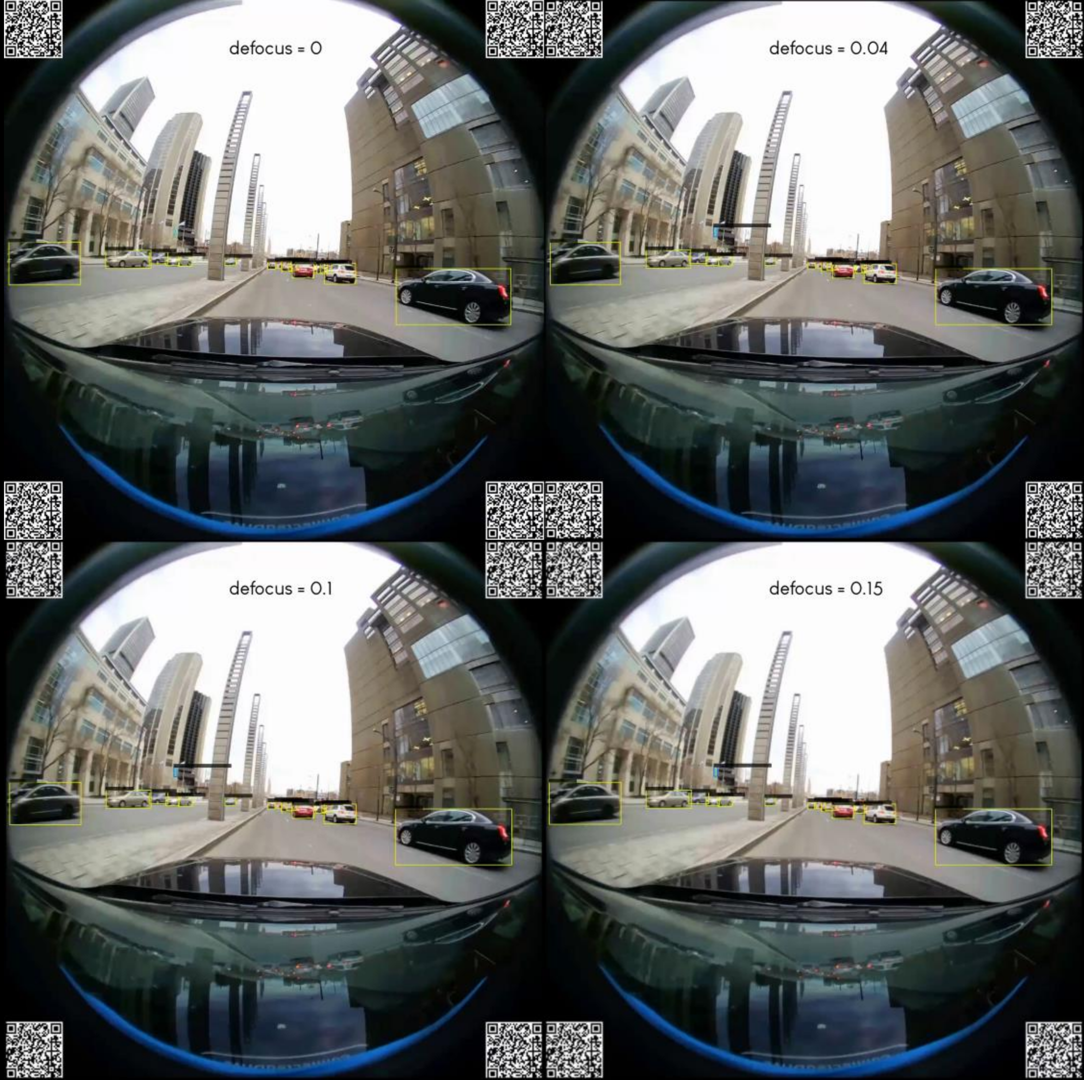
PRACTICAL CASE 2-EXPERIMENTAL PROCEDURE

DATASET PIXSET

- 29 000 images taken on Canadian Roads (urban environment)
- Different weather and light condition (day/night)
- Road Facing 180° road facing camera placed on the rear-view mirror
- Generation of 21 datasets with varying defocus on an identical subset of PixSet (150 images)

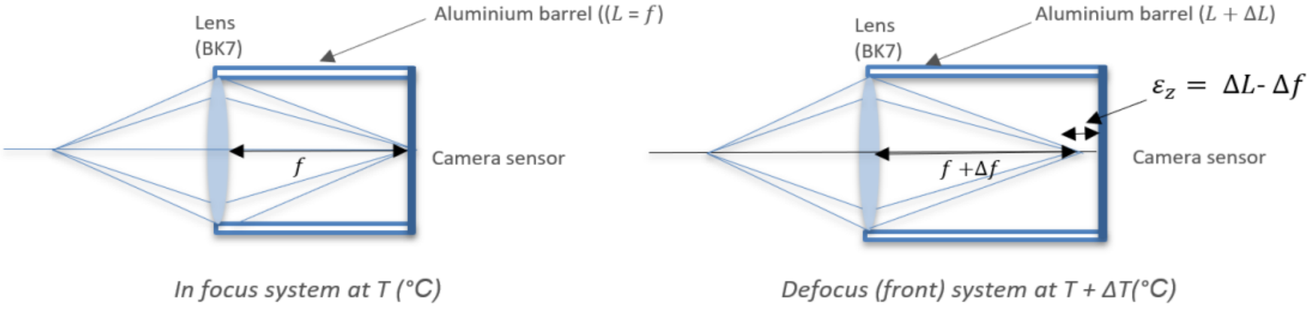
RESULTS

Defocus increases from upper left to bottom right video.



PRACTICAL CASE 2-CORRESPONDING TOLERATED CHANGES IN TEMPERATURE

IS THE TOLERANCE FOR DEFOCUS SUFFICIENT FOR AN OUTDOOR USECASE (AUTOMOTIVE) ?



$$\Delta f = \delta_G f \Delta T$$

$$\Delta L = \beta f \Delta T$$

At λ=550nm a **drop of 2%** in the performances :

$f_{\#} = 4$: 5.81 µm / **23.19 °C**

$f_{\#} = 2$: 10.94 µm / **43.67 °C**

PRACTICAL CASE 1-WIDE ANGLE IN-CABIN PROPOSITION

PROPOSITION : ENTIRE VISION SYSTEM TO MEET ALL REQUIREMENTS

Wide angle lens:

- Wide-angle to capture driver and occupants
- Magnification on the driver eyes, face and hands
- Broadband: High Image quality in RGB and IR
- Low F# for optimal low light performances
- Miniature to ease the integration
- Designed for 5Mpx RGBIR

Image processing:

- Adaptive Dewarping: correct distortion for human vision use cases
- Region of Interest Dewarping: extract features for computer vision and AI

Immervision smart pixel management lens concept

Lens with Smart Pixel Management increases resolution on the driver while maintaining good resolution on occupants

IMMERVISION