Simulación De Una Cámara Contadora De Fotones Para La Adquisición De Imágenes Transitorias En Escenarios Sin Línea De Visión

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AGENDA

- 01 Introduction
- 02 Objectives
- 03 Proposed Method
- 04 Parameter Analysis
- 05 Validation
- 06 Conclusions

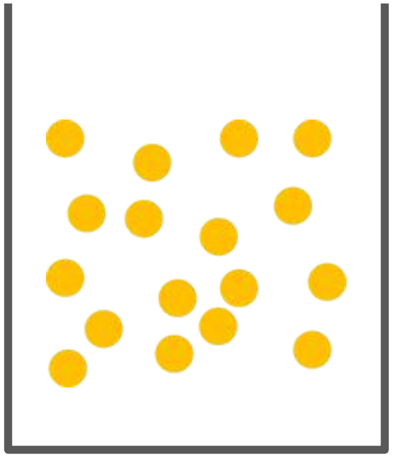
Introduction

Single-Photon Imaging

[1] Raskar et al. Femto-Photography: Visualizing Photons in Motion at a Trillion Frames Per Second. ACM Transactions on Graphics (TOG) 2013.

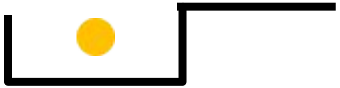
Single-Photon Imaging

~100-1000 photons



Conventional camera pixel

Single photon

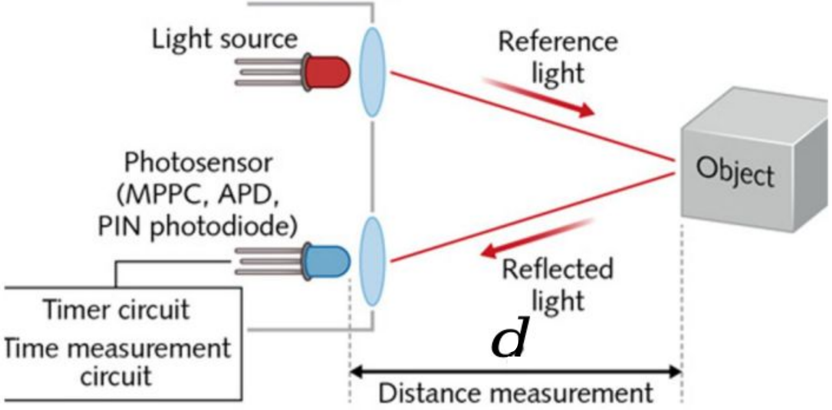


Single-photon camera pixel

Extreme sensitivity

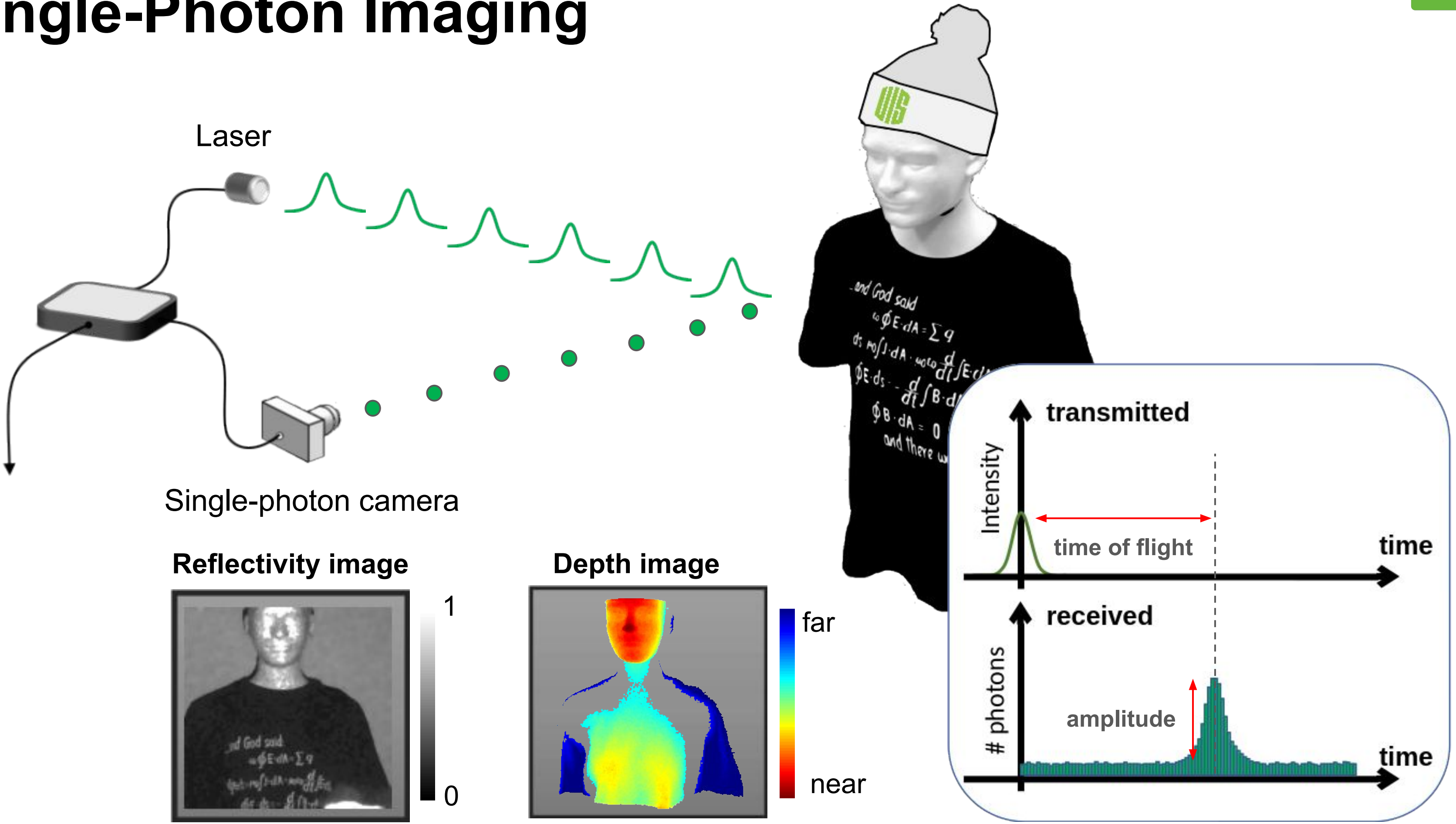
Single-Photon Imaging

Time of flight detectors



Distance to object: $d = \frac{ct}{2}$

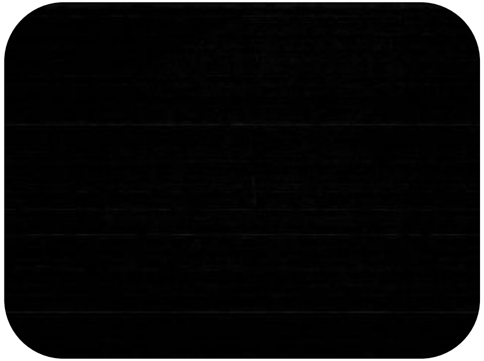
Single-Photon Imaging

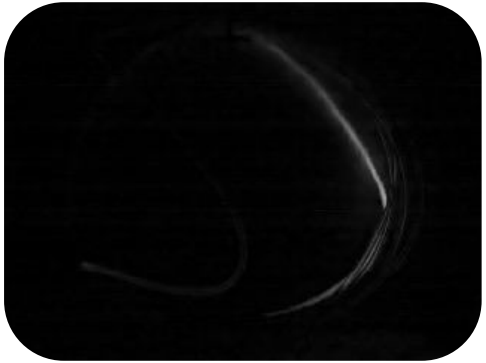


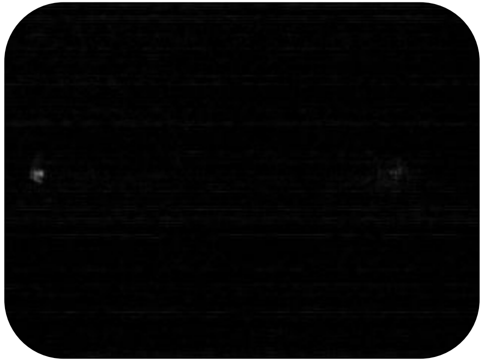
Transient Imaging

Color image

Transient image

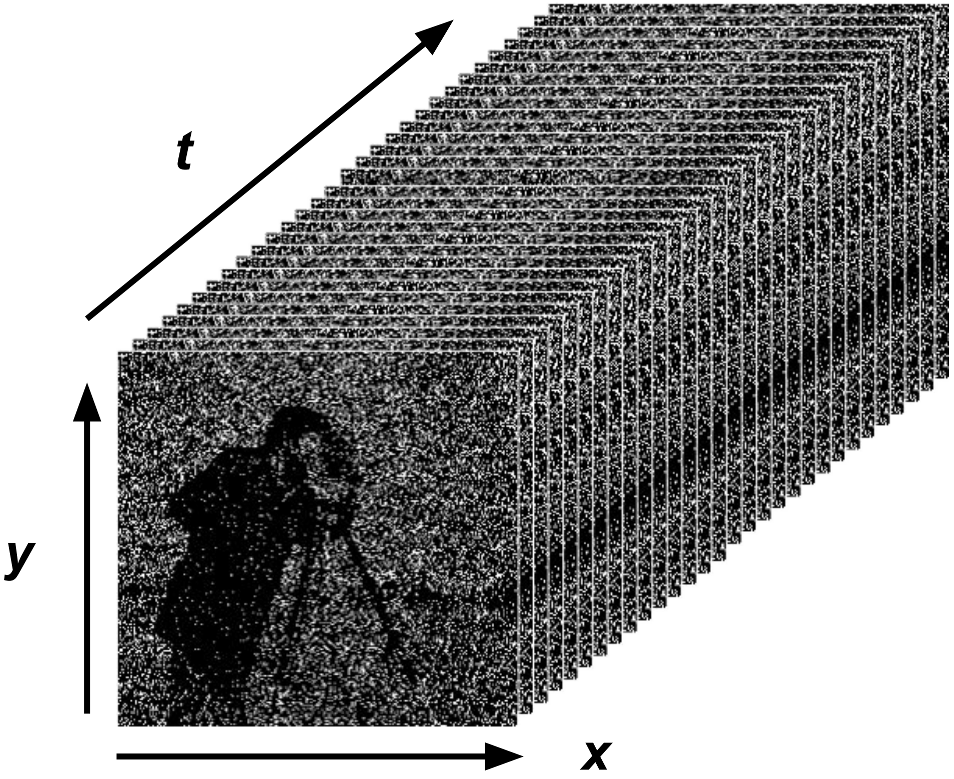






[2] O'Toole et al. Reconstructing transient images from single-photon sensors. CVPR 2017.

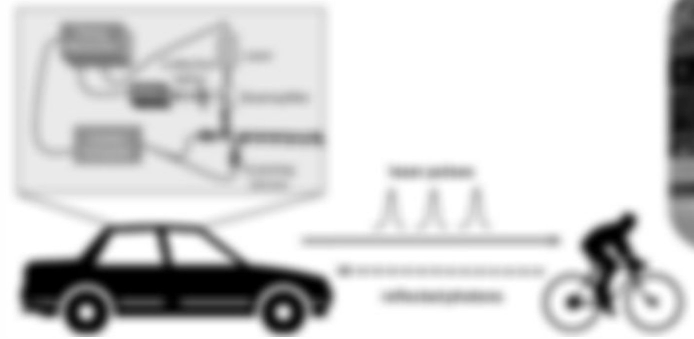
Transient Imaging



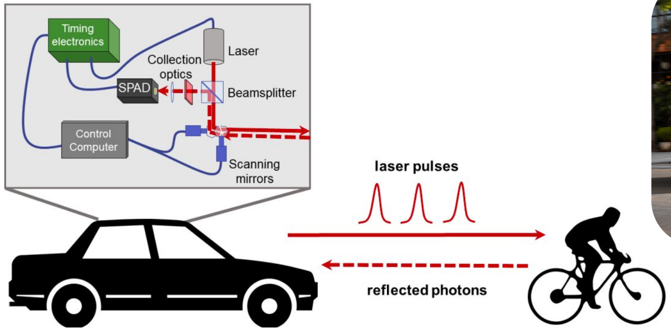
Spatio-temporal distribution of photon arrivals

I(x, y, t)

Applications of ToF Cameras



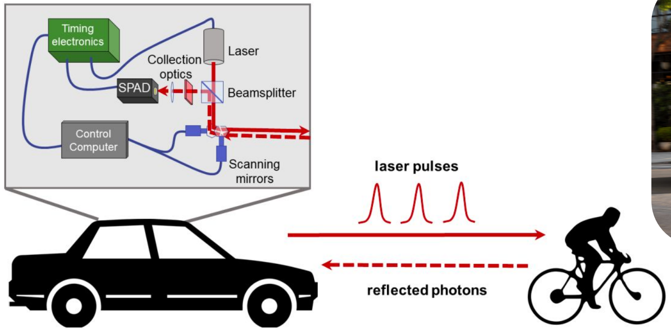
Applications of ToF Cameras



Autonomous Navigation [3]

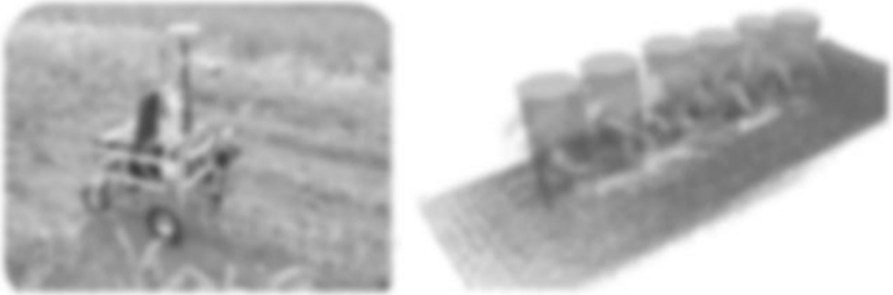
[3] Rapp et al. Advances in Single-Photon Lidar for Autonomous Vehicles: Working Principles, Challenges, and Recent Advances. IEEE Signal Processing Magazine 2020

Applications of ToF Cameras



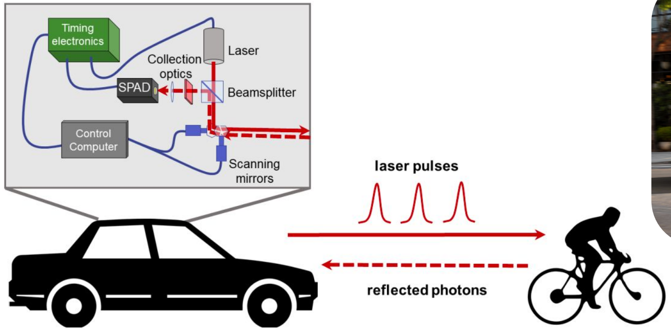
Electronic Devices [4]

Autonomous Navigation



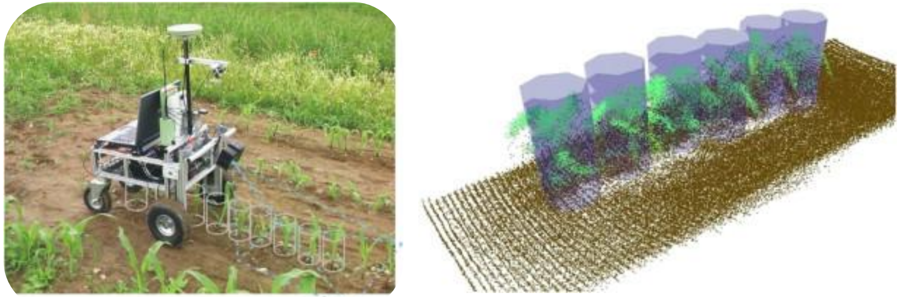
[4] Alessandra Spreafico, et al. "THE IPAD PRO BUILT-IN LIDAR SENSOR: 3D RAPID MAPPING TESTS AND QUALITY ASSESSMENT." ISPRS

Applications of ToF Cameras



Autonomous Navigation

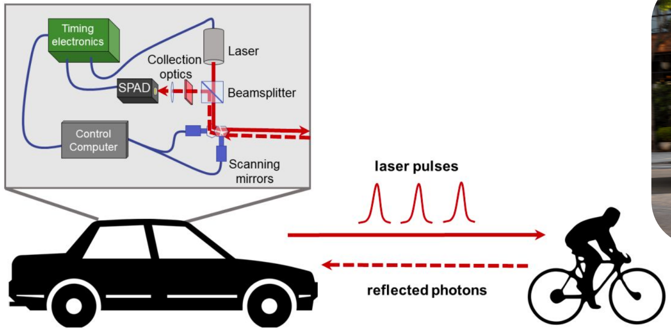
Electronic Devices



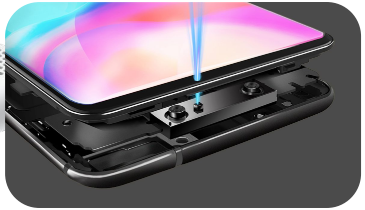
Robotics [5]

[5] Ulrich Weiss and Peter Biber. "Plant detection and mapping for agricultural robots using a 3D LIDAR sensor." Robotics and Autonomous Systems

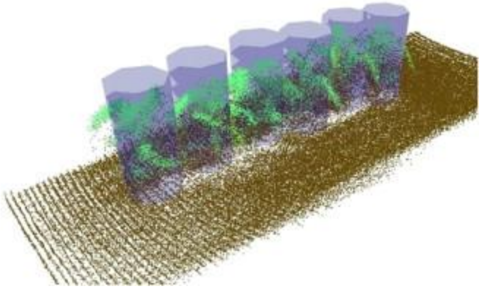
Applications of ToF Cameras



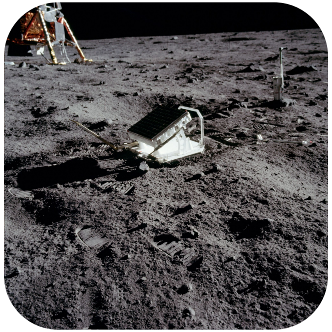
Autonomous Navigation



Electronic Devices



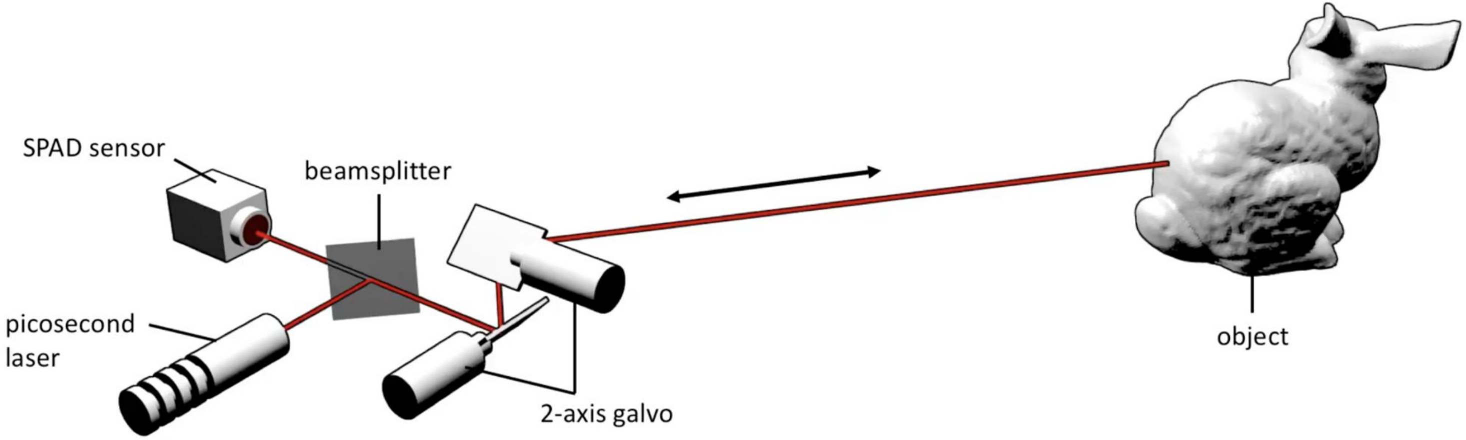
Robotics



Satellite Measurements [6]

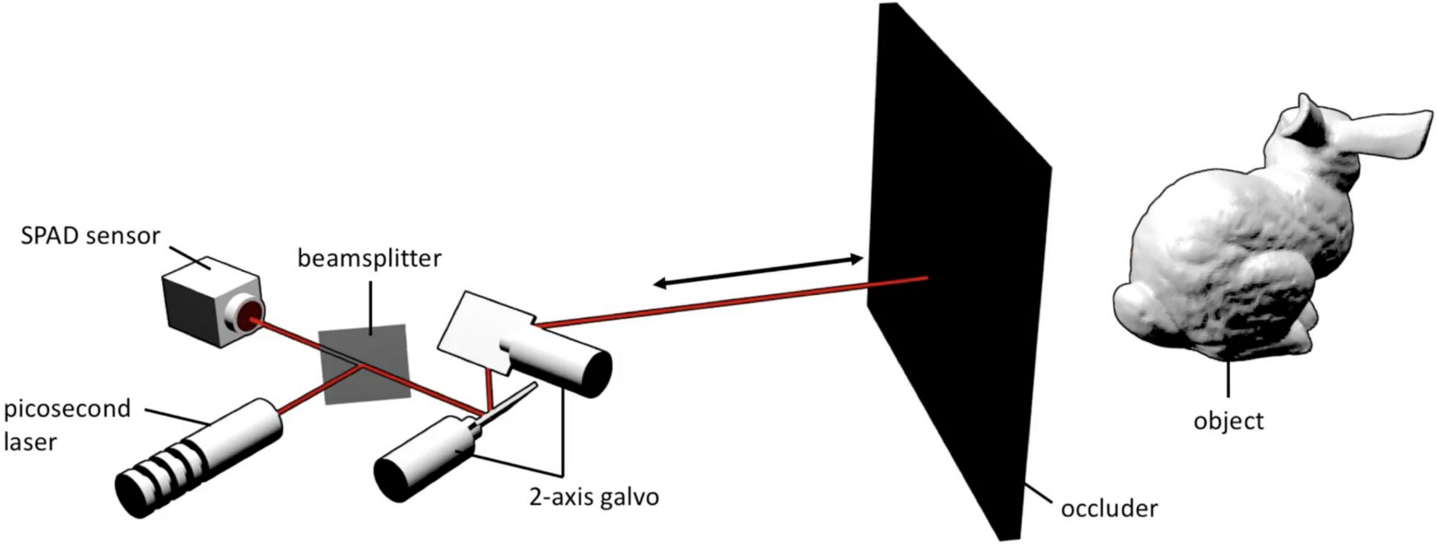
[6] Matthew Wilkinson, et al. "The Next Generation of Satellite Laser Ranging Systems." Journal of Geodesy, 2018. doi: 10.1007/s00190-018-1196-1.

Non-Line-Of-Sight Imaging



[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

Non-Line-Of-Sight Imaging



[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

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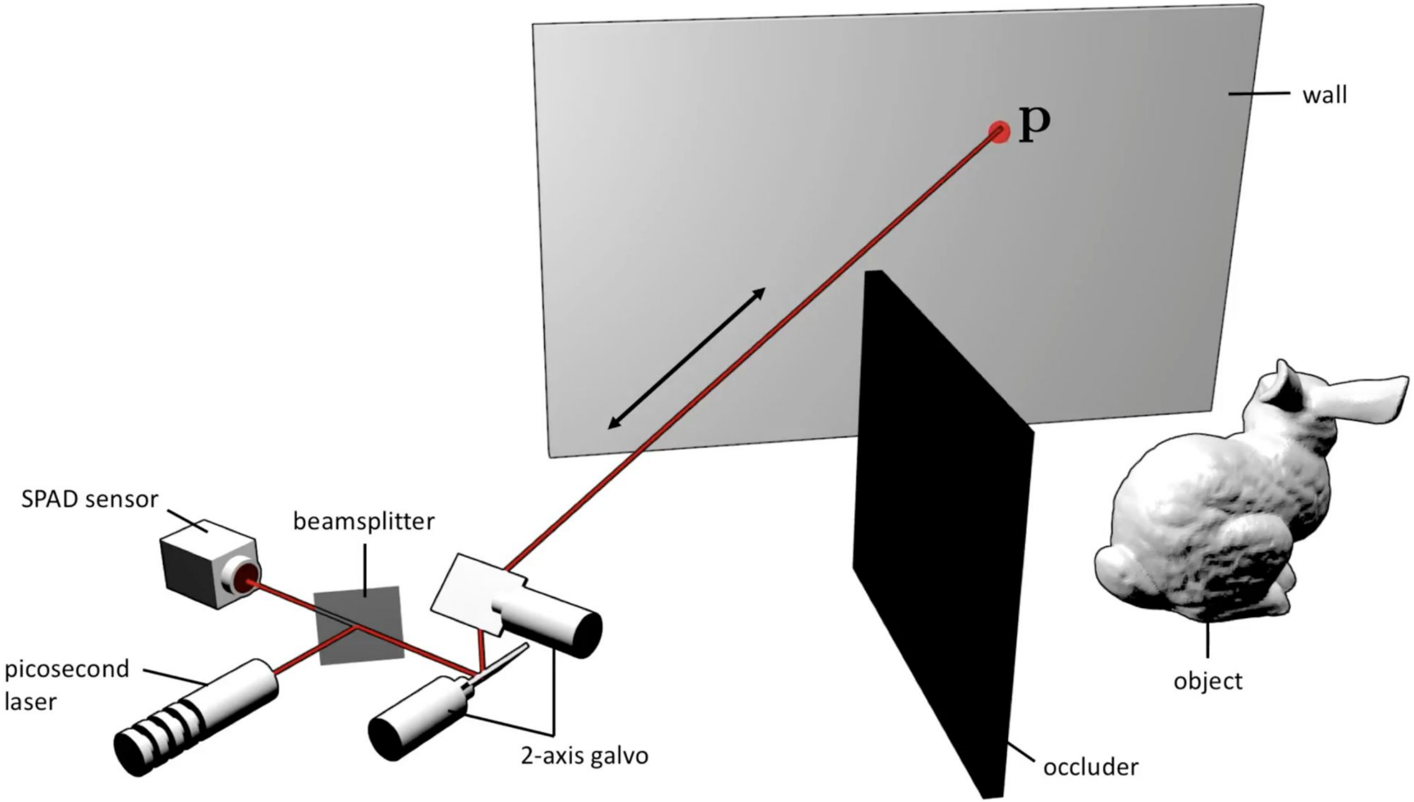

[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

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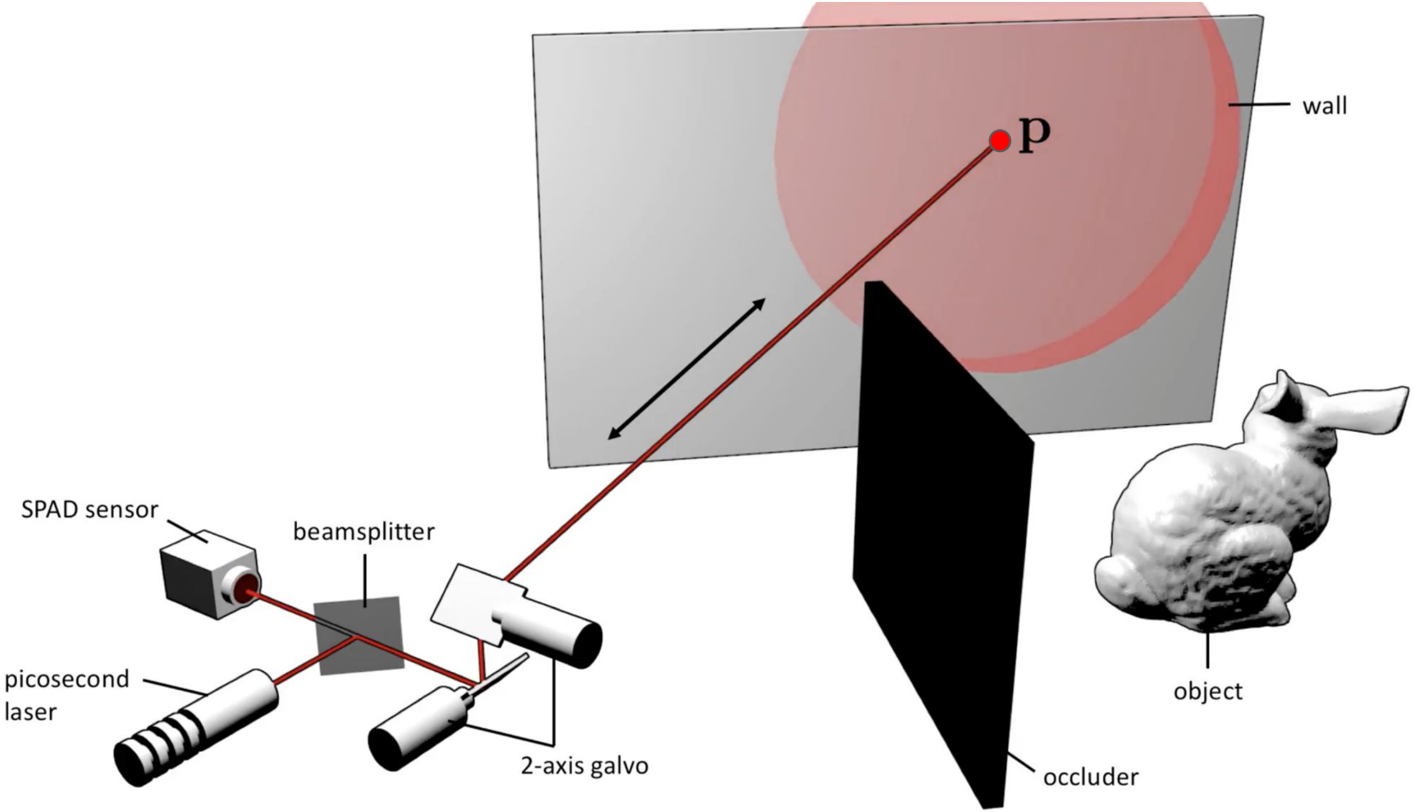

[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

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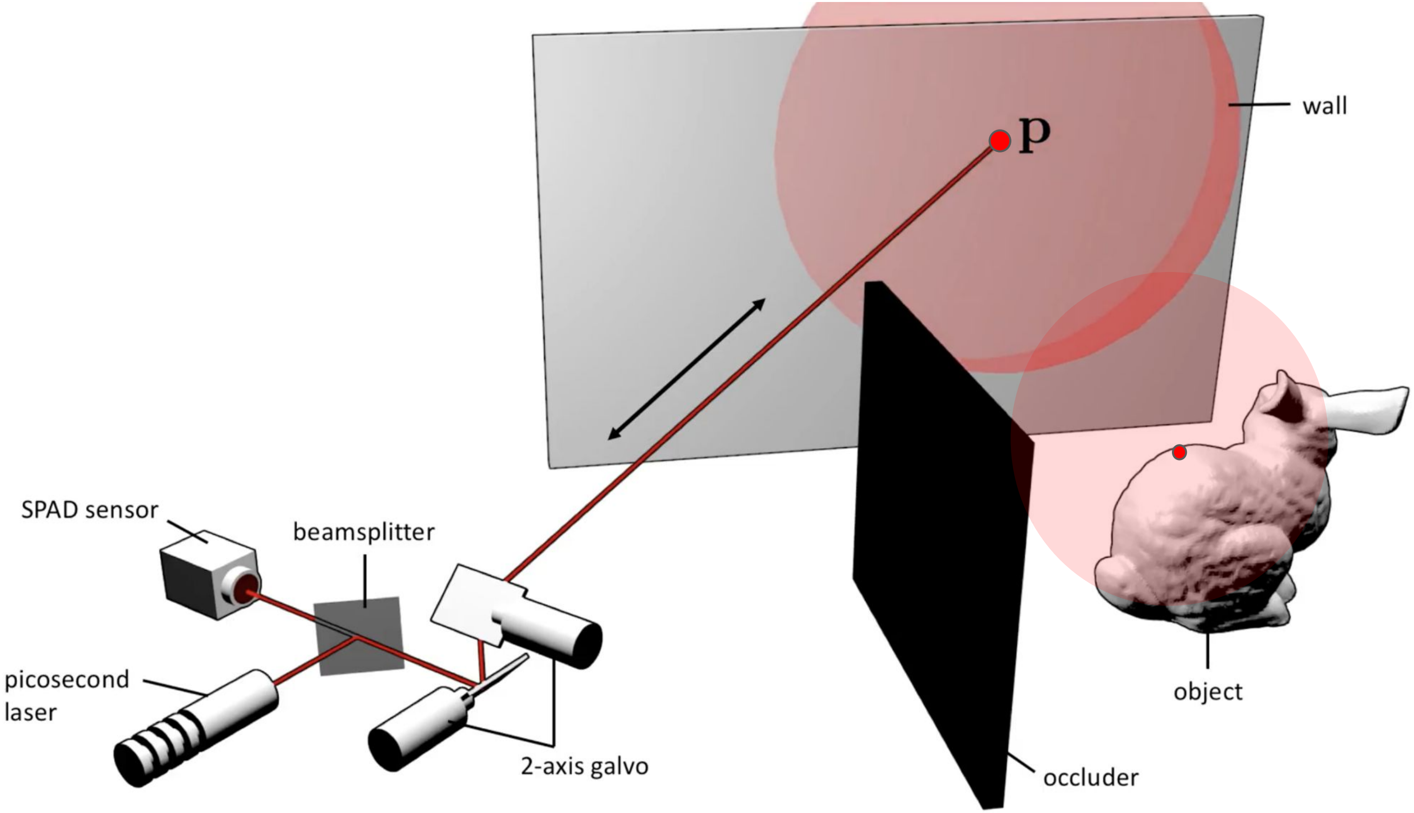
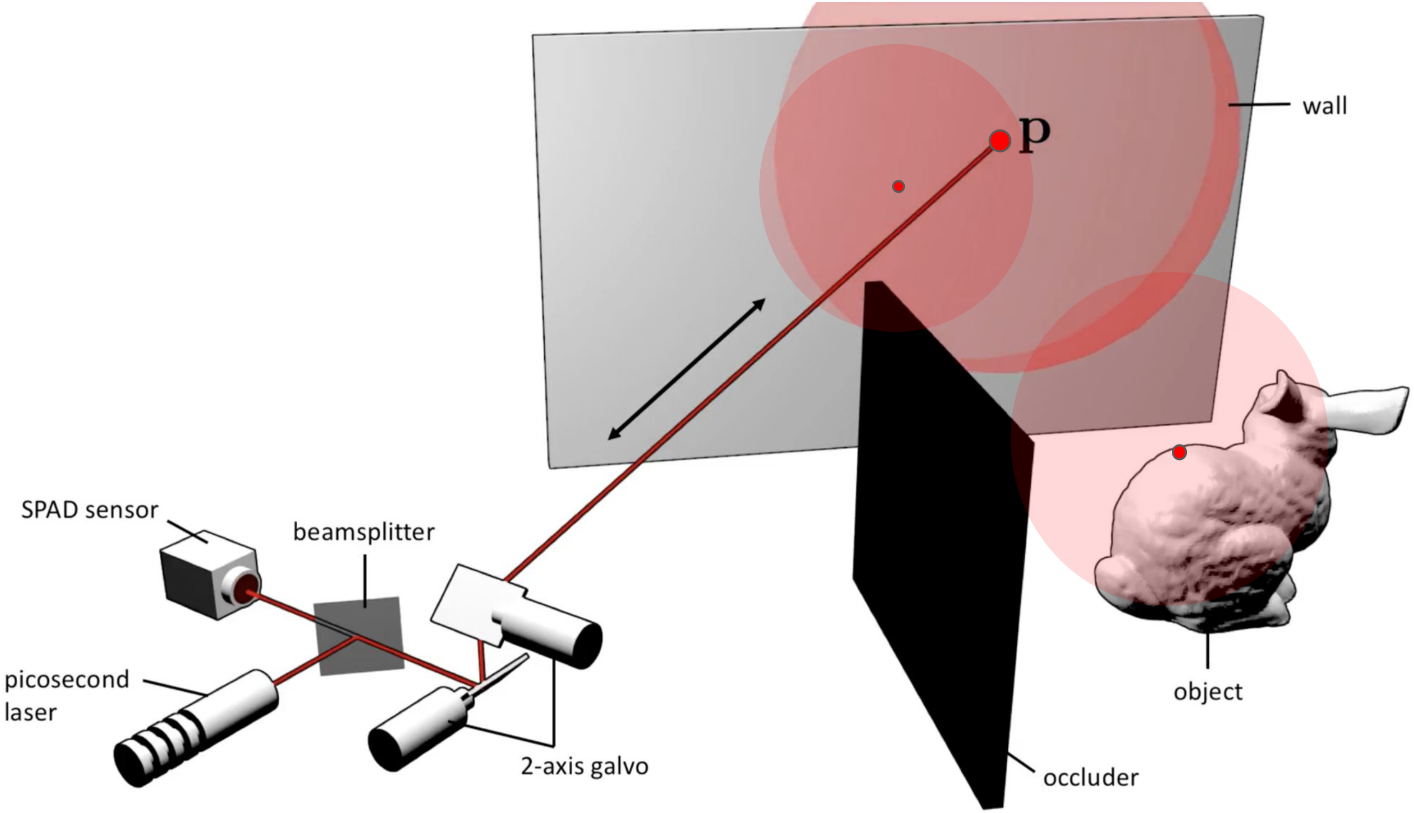


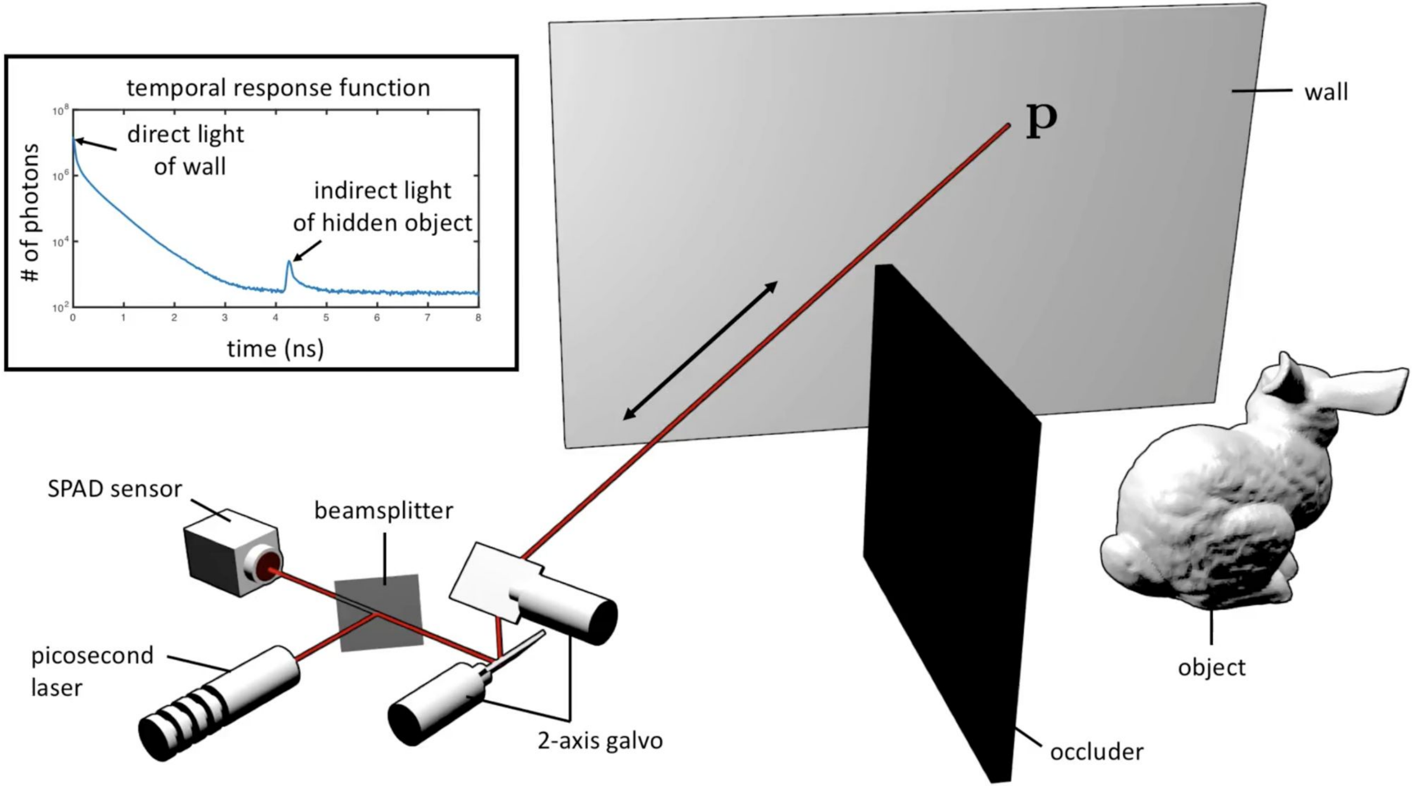
[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

Non-Line-Of-Sight Imaging



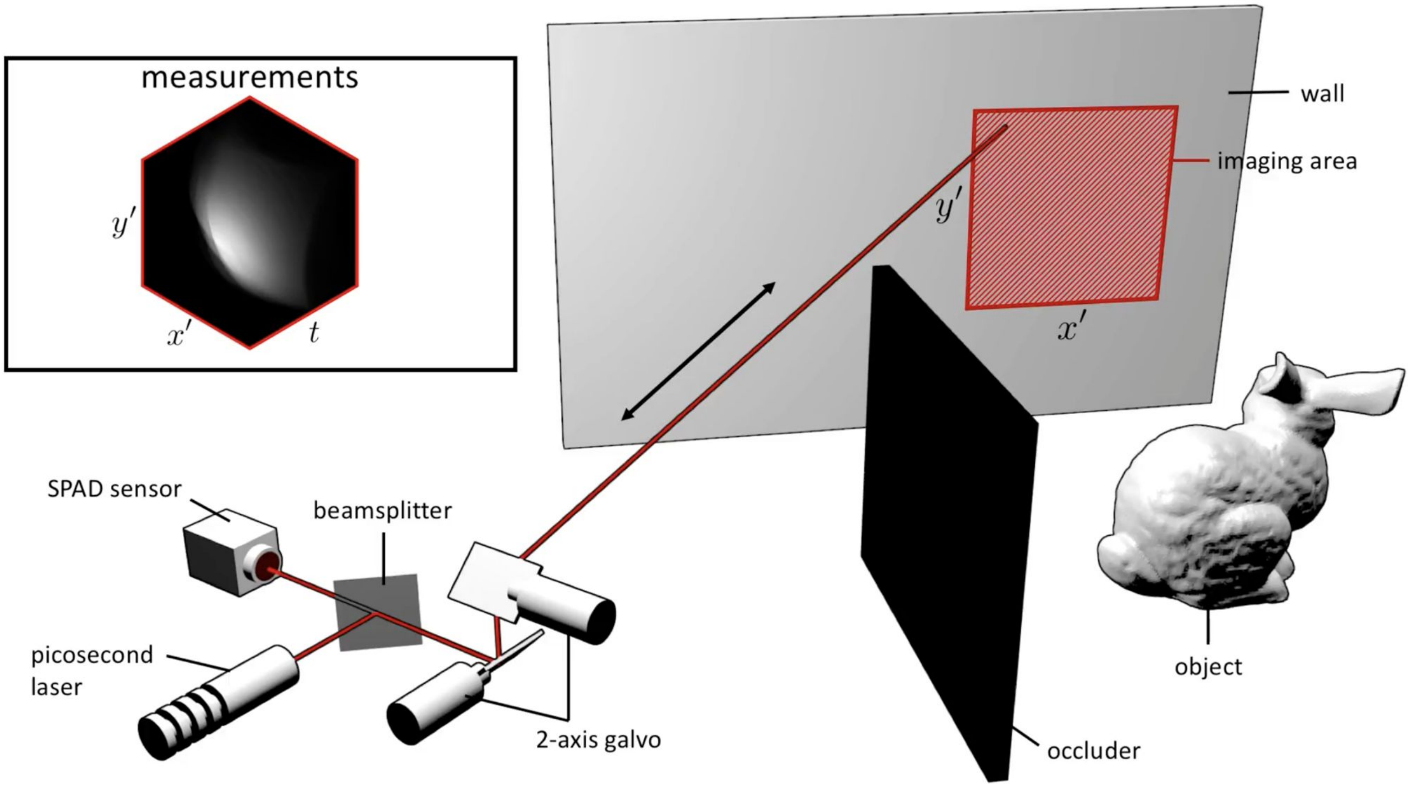
[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

Non-Line-Of-Sight Imaging



[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

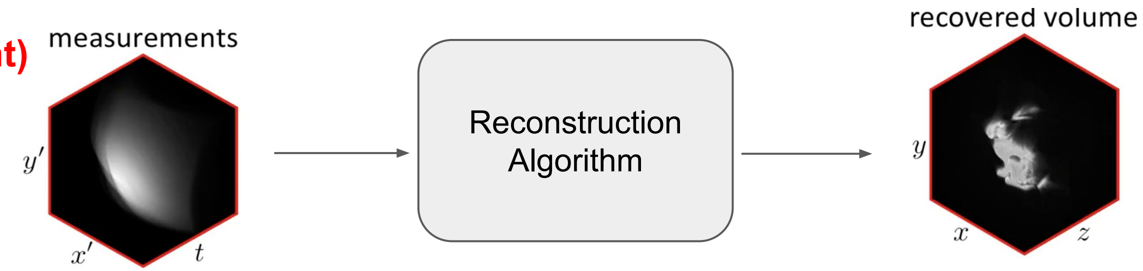
Non-Line-Of-Sight Imaging



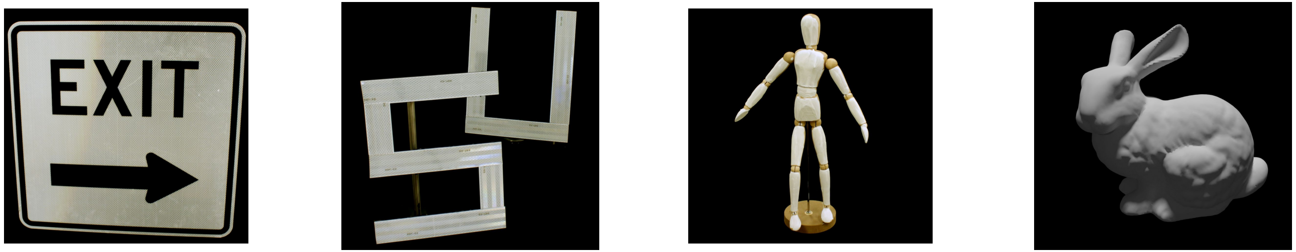
[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

Non-Line-Of-Sight Imaging

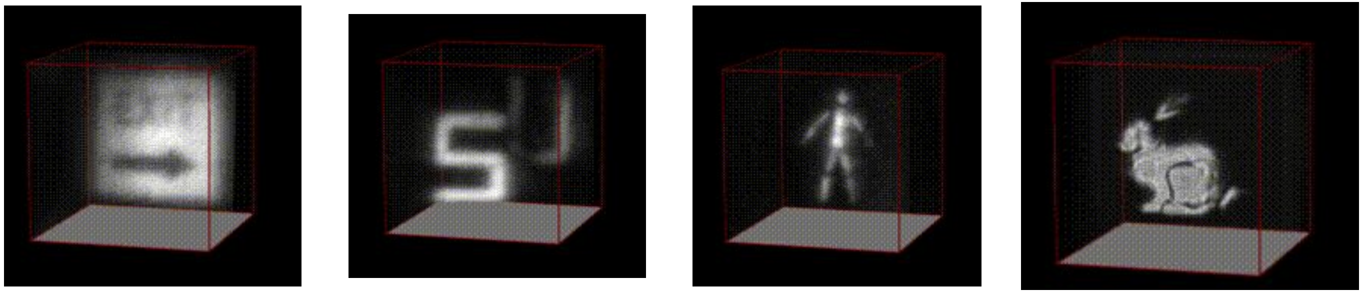
(Transient)



Hidden scene

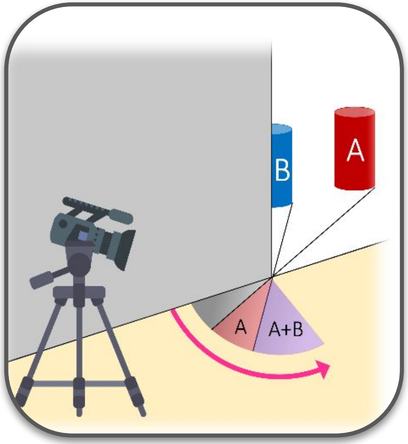


Reconstruction

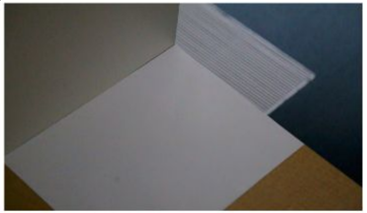


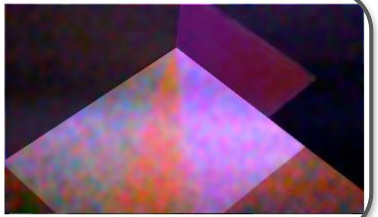
[7] O'Toole, Lindell, Wetzstein. Confocal non-line-of-sight imaging based on the light-cone transform Nature 2018

Corner (Edge-Resolved) Camera

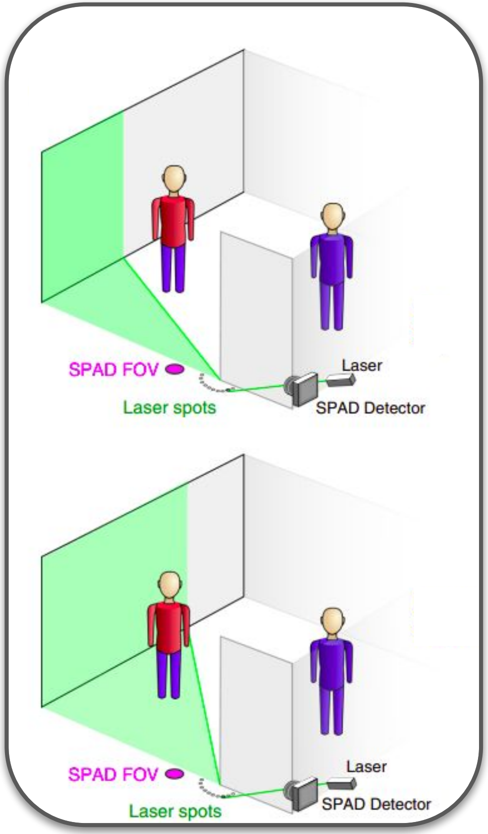


Passive methods





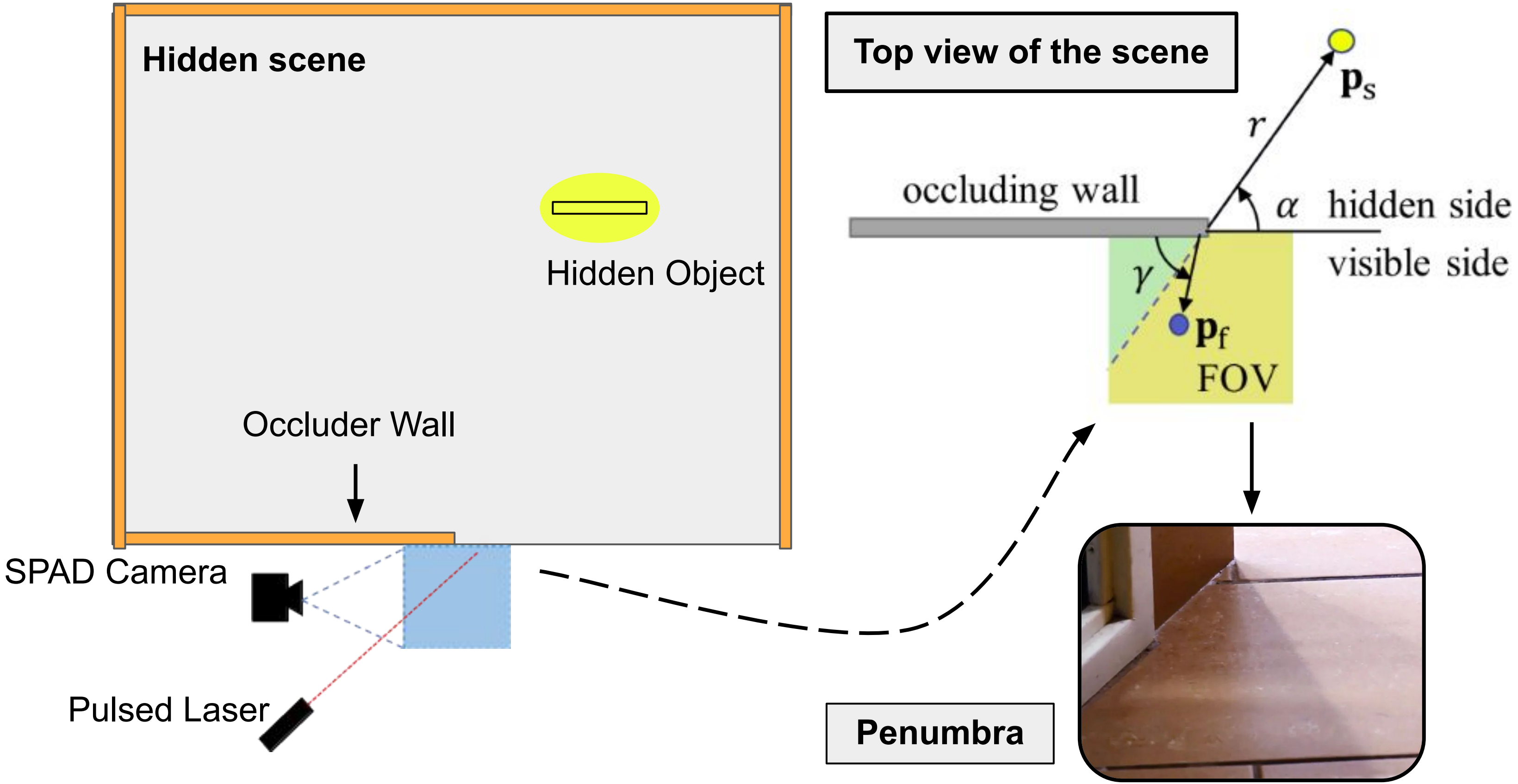
Original Frame | **Color Magnified**



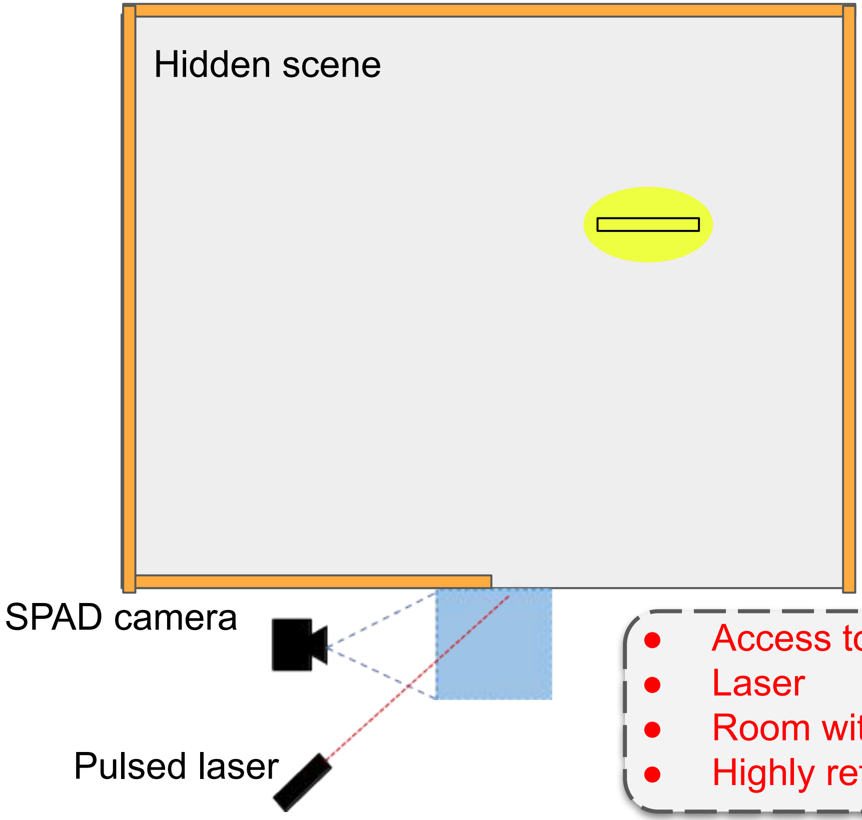
Active methods

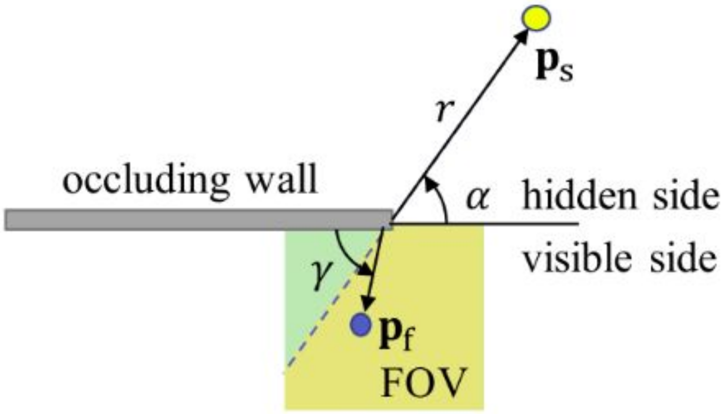
[7] Bouman, et al. Turning corners into cameras: Principles and methods. Proceedings of the IEEE International Conference on Computer Vision (ICCV), 2017.

Corner (Edge-Resolved) Camera



Corner (Edge-Resolved) Camera





- Access to single photon camera
- Laser
- Room with good conditions
- Highly reflective objects

Difficulty in generating measurements in real environments

Objectives

Objetivo General

Desarrollar un simulador en Python que emule el funcionamiento de una cámara contadora de fotones para la adquisición de imágenes transitorias en escenarios sin línea de visión directa de los objetos generados de manera sintética.

Objetivos Específicos

1. Modelar matemáticamente la propagación de la luz en escenarios sin línea de visión y su detección a través de una cámara contadora de fotones.

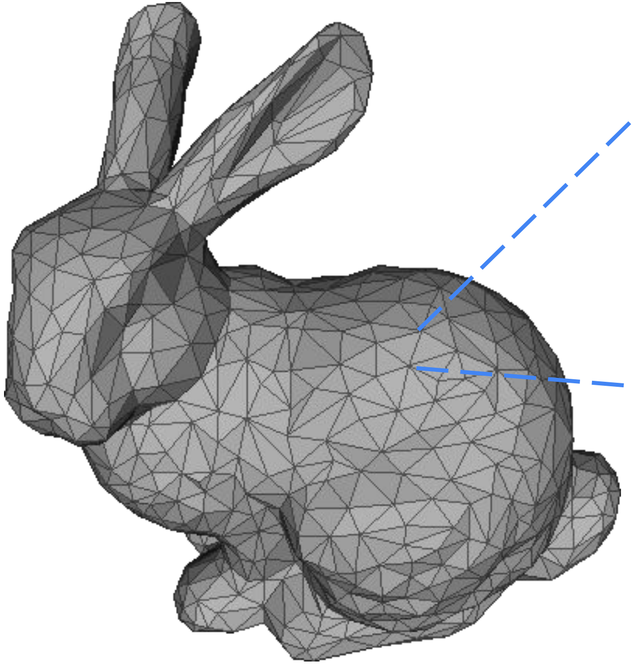
2. Diseñar y simular escenas que incluyan objetos en una configuración sin línea de visión directa de la cámara.

3. Simular el proceso de conteo de fotones generados por una fuente de iluminación pulsada, por medio de una cámara parametrizada en términos del número de píxeles y resolución temporal.

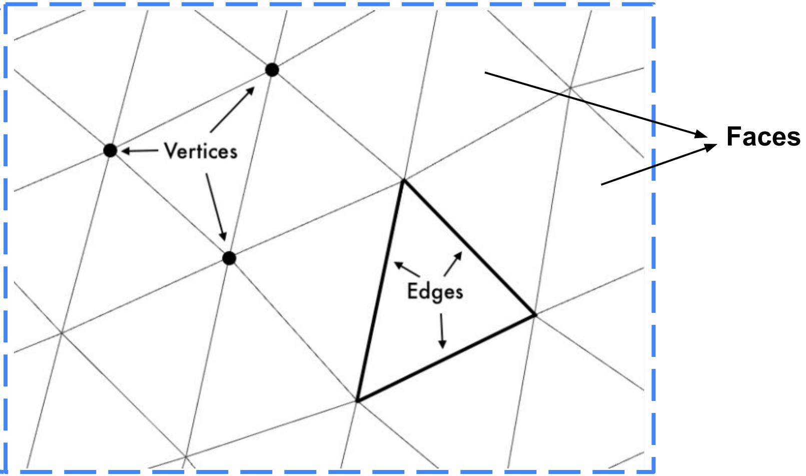
4. Diseñar una interfaz para la visualización de las escenas sin línea de visión y de las imágenes transitorias obtenidas de la simulación del proceso de conteo de fotones.

Proposed Method

Modeling of NLOS scenarios



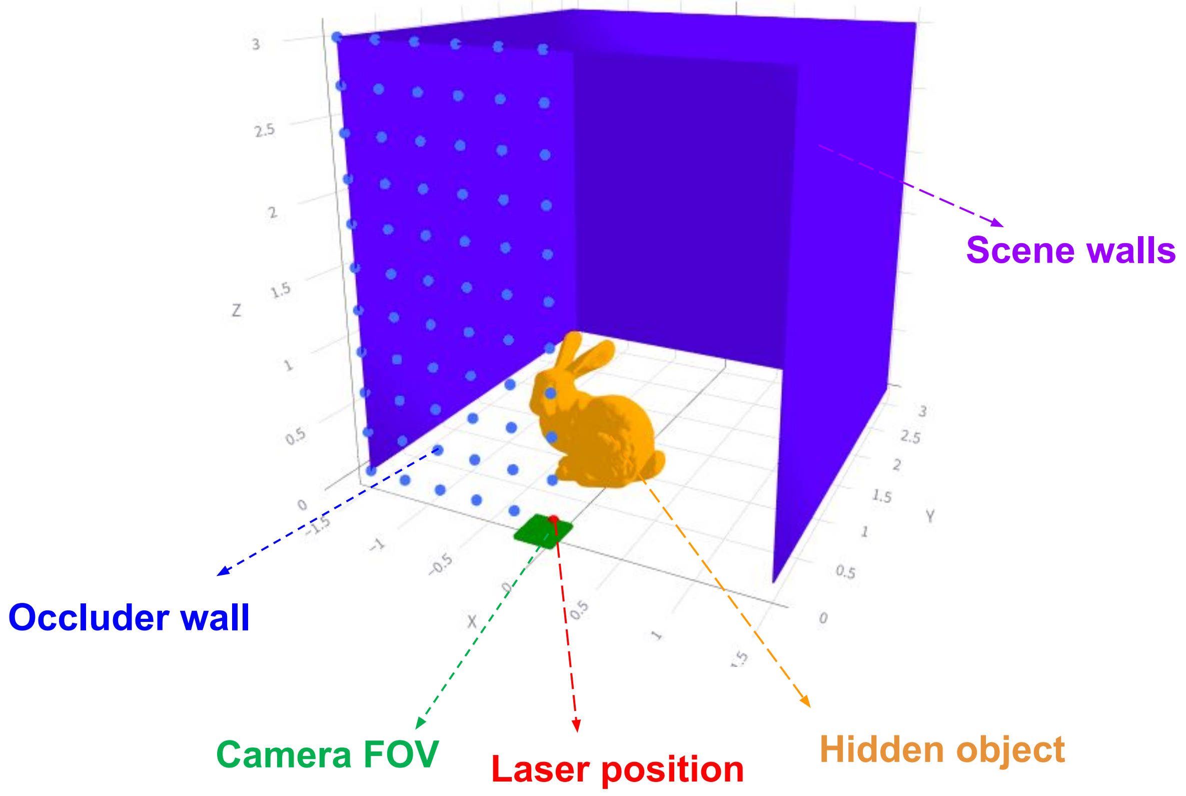
Triangular Mesh



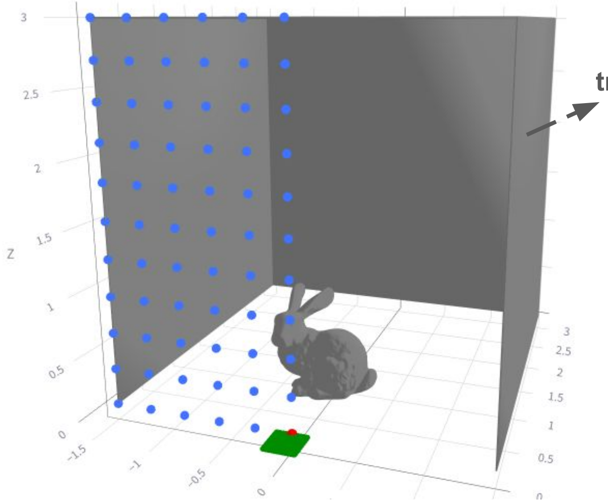
$$\mathcal{M} = (\mathcal{V}, \mathcal{F}) \quad \mathcal{F} \subseteq \{f_1, \ldots, f_{\mathcal{F}}\}$$

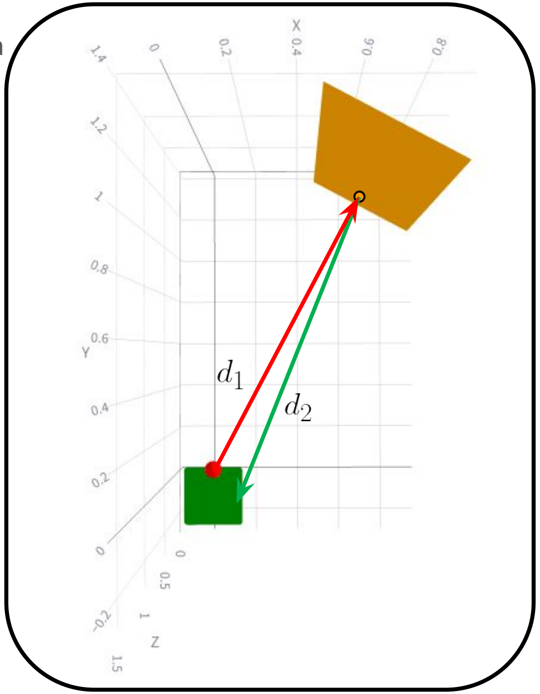
$$f_n \in \mathcal{V} \times \mathcal{V} \times \mathcal{V}$$

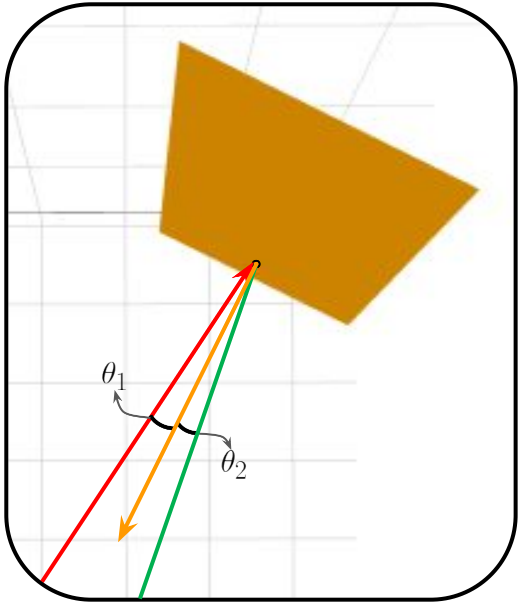
Modeling of NLOS scenarios



Light propagation modeling for NLOS scenarios



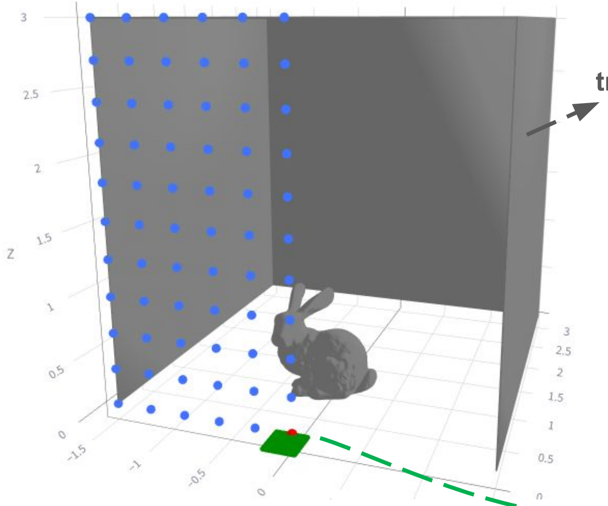




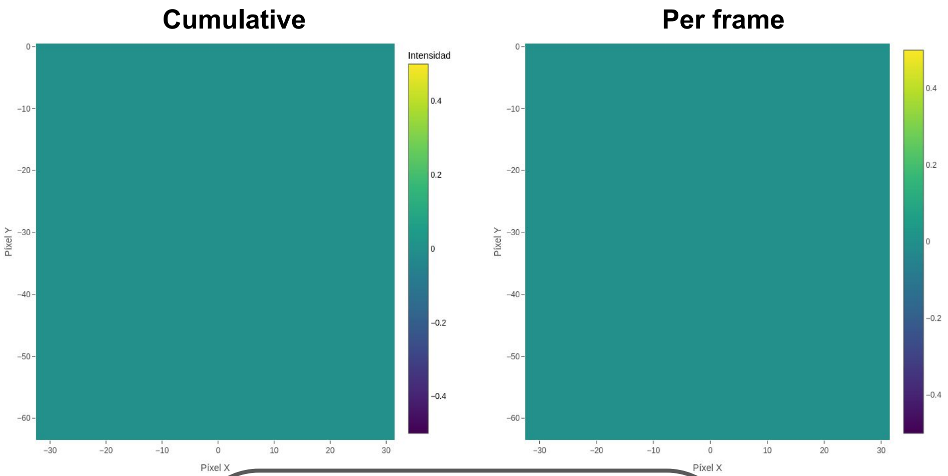
$$i^{x,y,t} = \frac{P_{Laser} \cdot A \cdot \cos\theta_1 \cdot \cos\theta_2}{4\pi(d_1^2 \cdot d_2^2)}$$

$$bin = \left\lceil \frac{d_1 + d_2}{c \cdot \Delta_t} \right\rceil$$

Light propagation modeling for NLOS scenarios



Combined triangular mesh



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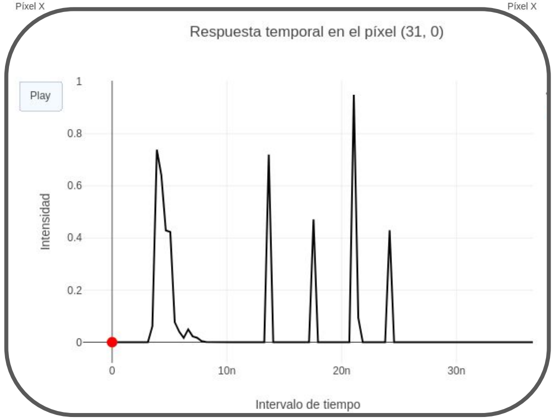
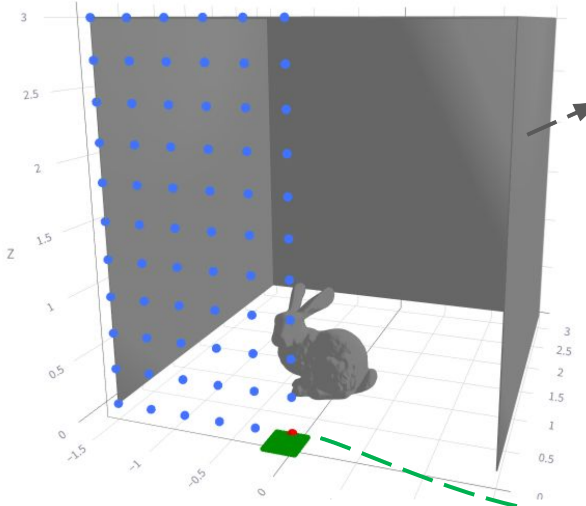
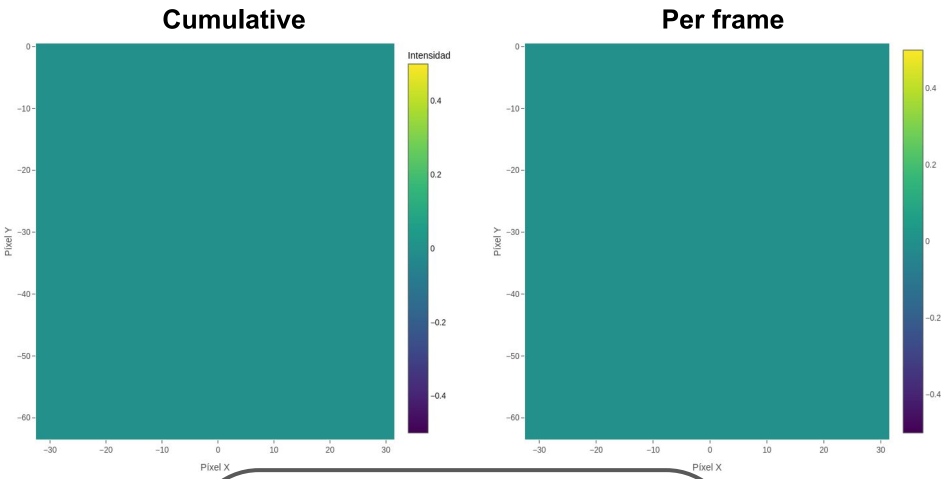
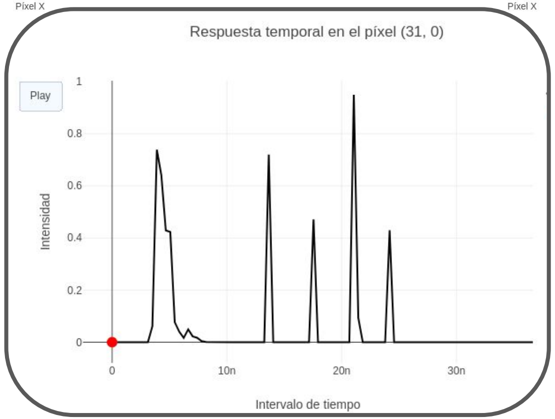


Light propagation modeling for NLOS scenarios



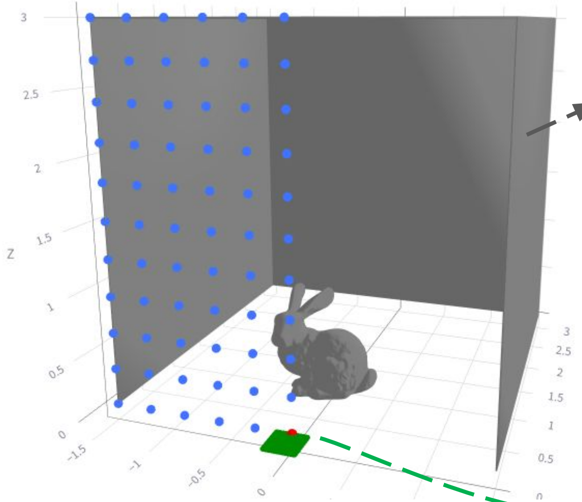
Combined triangular mesh



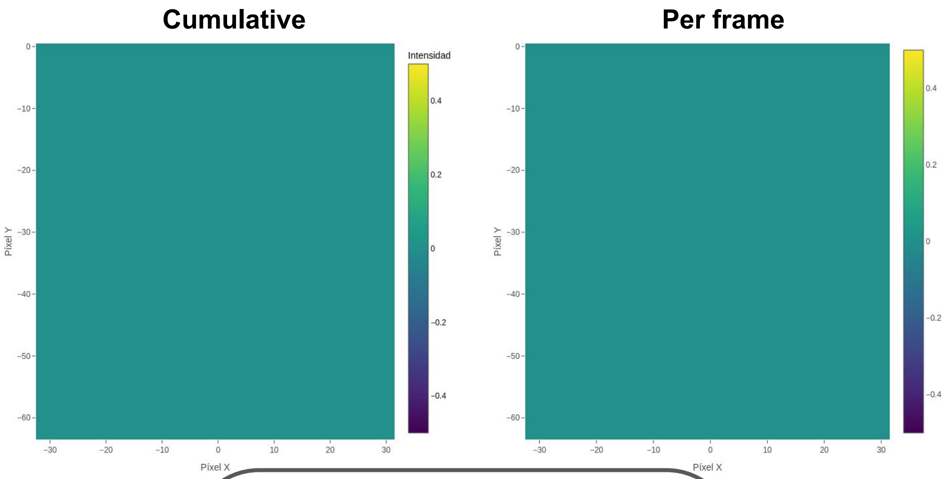


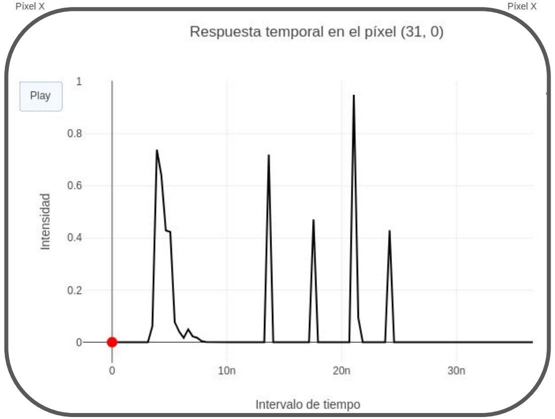
Camera pixel dimension: 64 x 64 pixels
Bin size: 3.9e-10 s
Laser intensity: 1000 mW
Camera FOV: 0.25 m
Room dimensions: 3m x 3m x 3m
Object position: [0, 1.25, 0]

Light propagation modeling for NLOS scenarios



Combined triangular mesh





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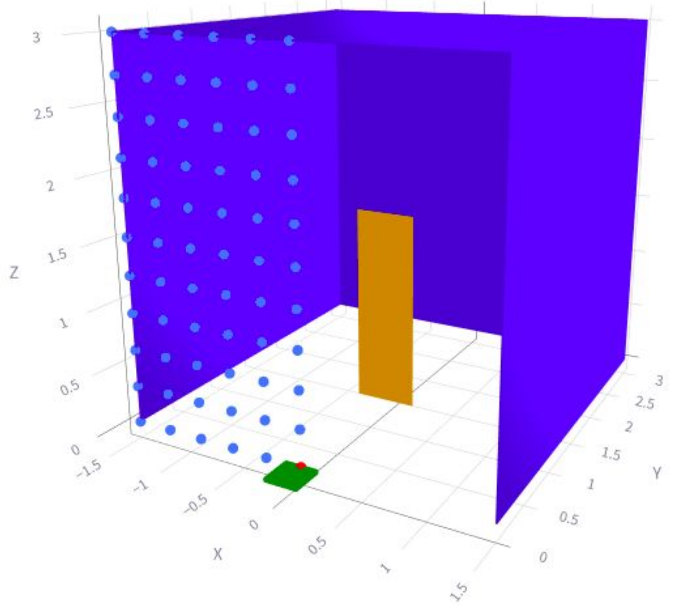
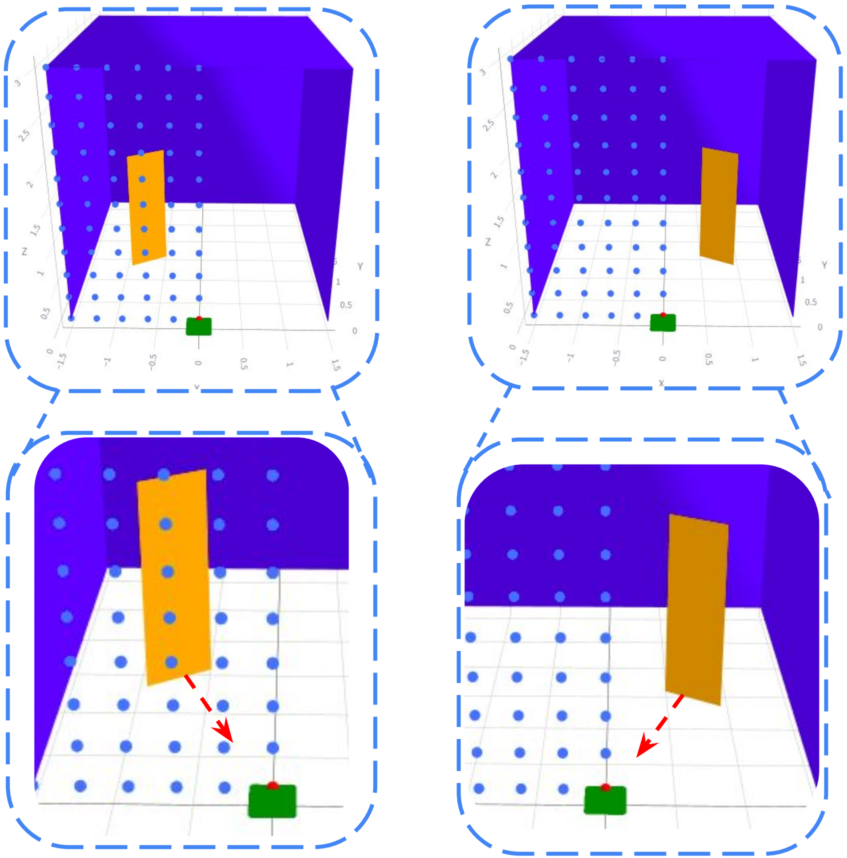
Modeling of NLOS scenarios





Foreshortening

$$\cos\theta = \frac{a \cdot b}{||a||\,||b||}$$

Simulation of signal noise

Sensor noise

$$SNR_{linear} = 10^{\frac{SNR_{dB}}{10}}$$

$$P_{signal} = \frac{1}{N}\sum_{k=1}^{N} \left|{i_k}^2\right|$$

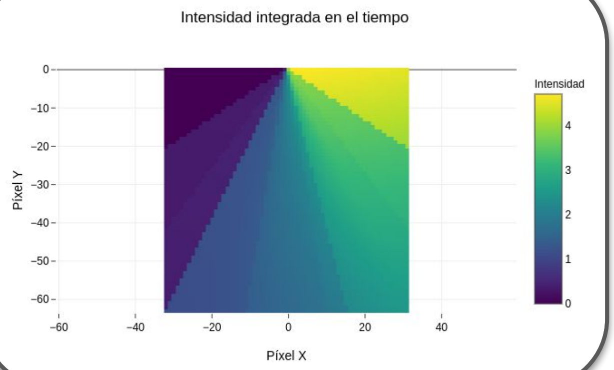
$$P_{noise} = \frac{P_{signal}}{SNR_{linear}}$$

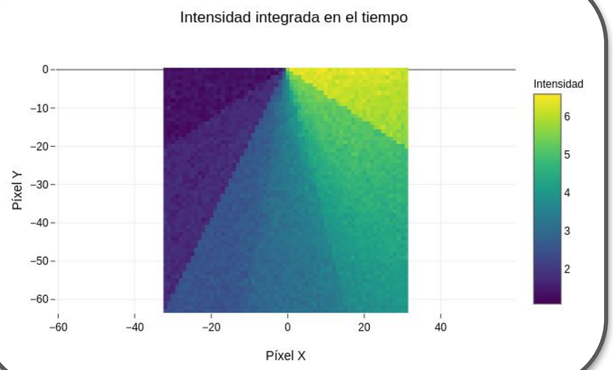
$$\sigma_{noise} = \sqrt{P_{noise}}$$

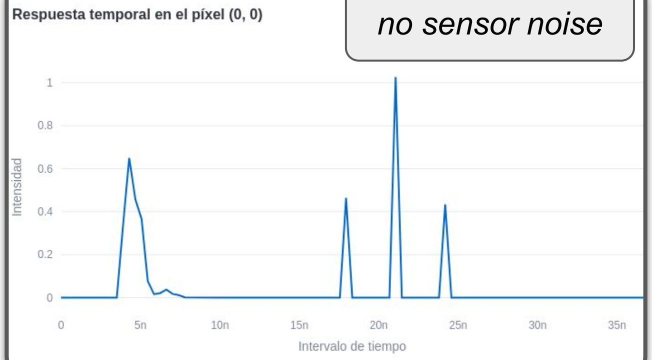
$$\hat{n} \sim \mathcal{N}(0, \sigma^2_{noise})$$

$$\hat{i_k} = i_k + |\hat{n_k}|$$

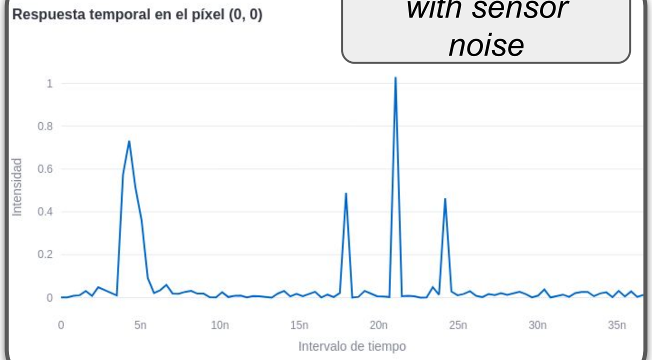
$$SNR_{db} = 15$$







no sensor noise



with sensor noise

[8] Felipe Gutierrez-Barragan, et al. "Compressive Single-Photon 3D Cameras." CVPR 2022

Simulation of signal noise

Background noise

$$i_b = \frac{i_t}{SBR}$$

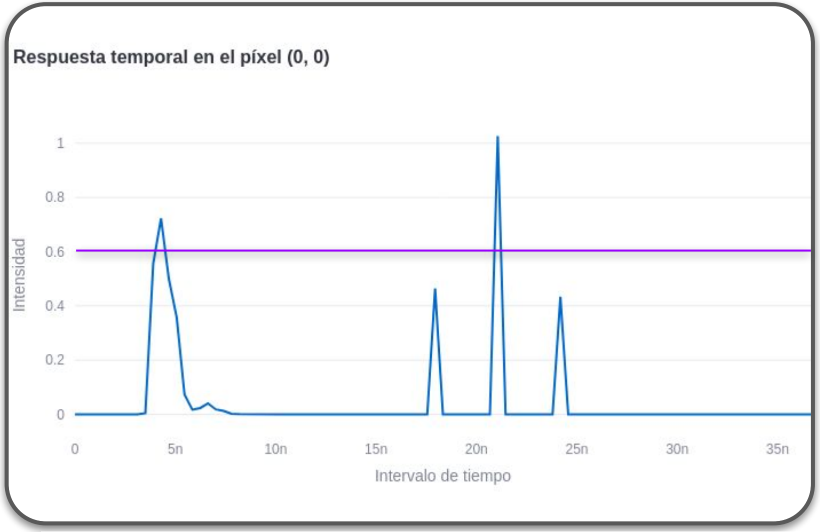
$$\tilde{n} = \frac{i_b}{N_b}$$

$$\tilde{i} = i + \tilde{n}$$

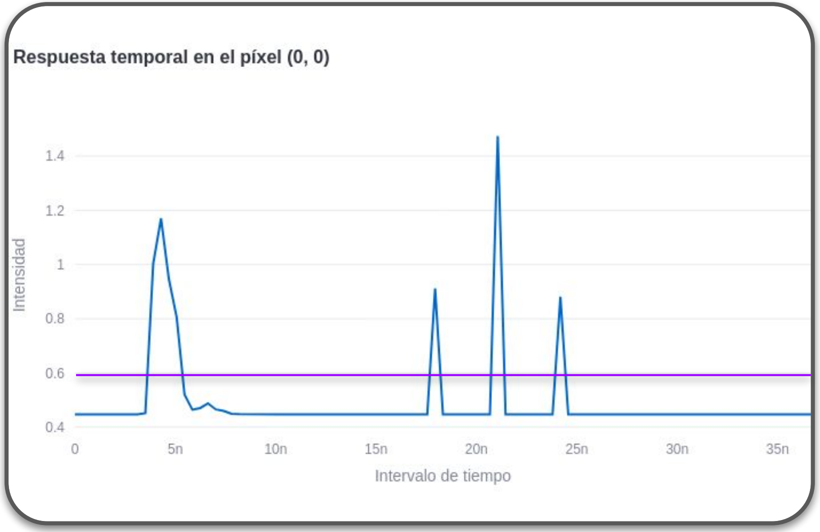
no background noise

$$SBR_{db} = 0.1$$

with background noise



vertical shift



[8] Felipe Gutierrez-Barragan, et al. "Compressive Single-Photon 3D Cameras." CVPR 2022

Simulation of signal noise

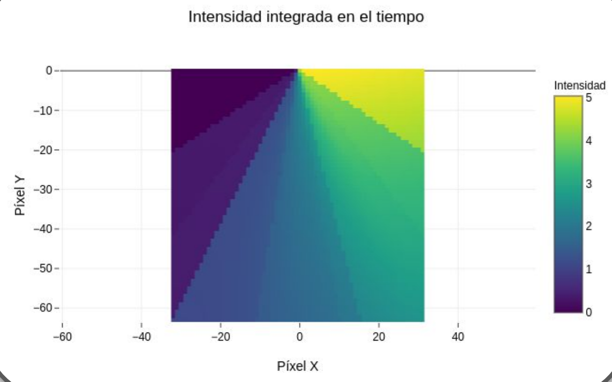
Shot noise

$$i_{scaled} = i \cdot K$$

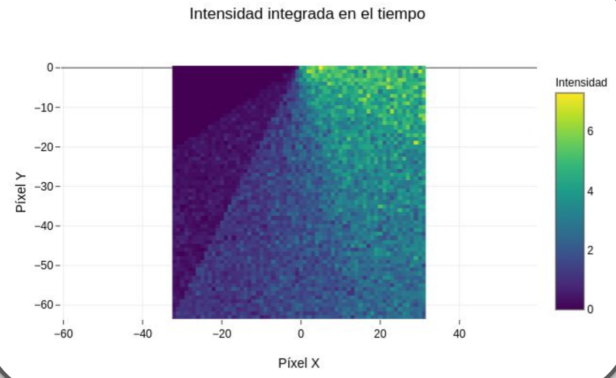
$$n_p \sim Poisson(\lambda = i_{scaled})$$

$$\bar{i} = \frac{n_p}{K}$$

no shot noise



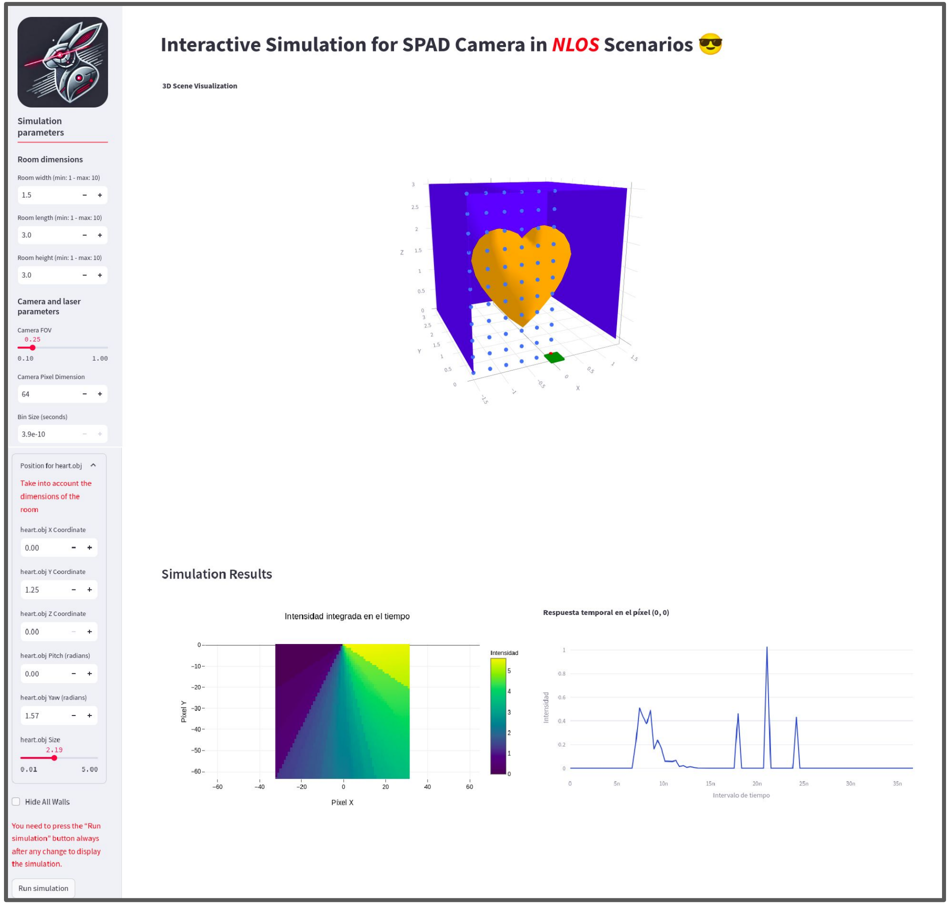
$$K = 10$$



with shot noise

[8] Felipe Gutierrez-Barragan, et al. "Compressive Single-Photon 3D Cameras." CVPR 2022

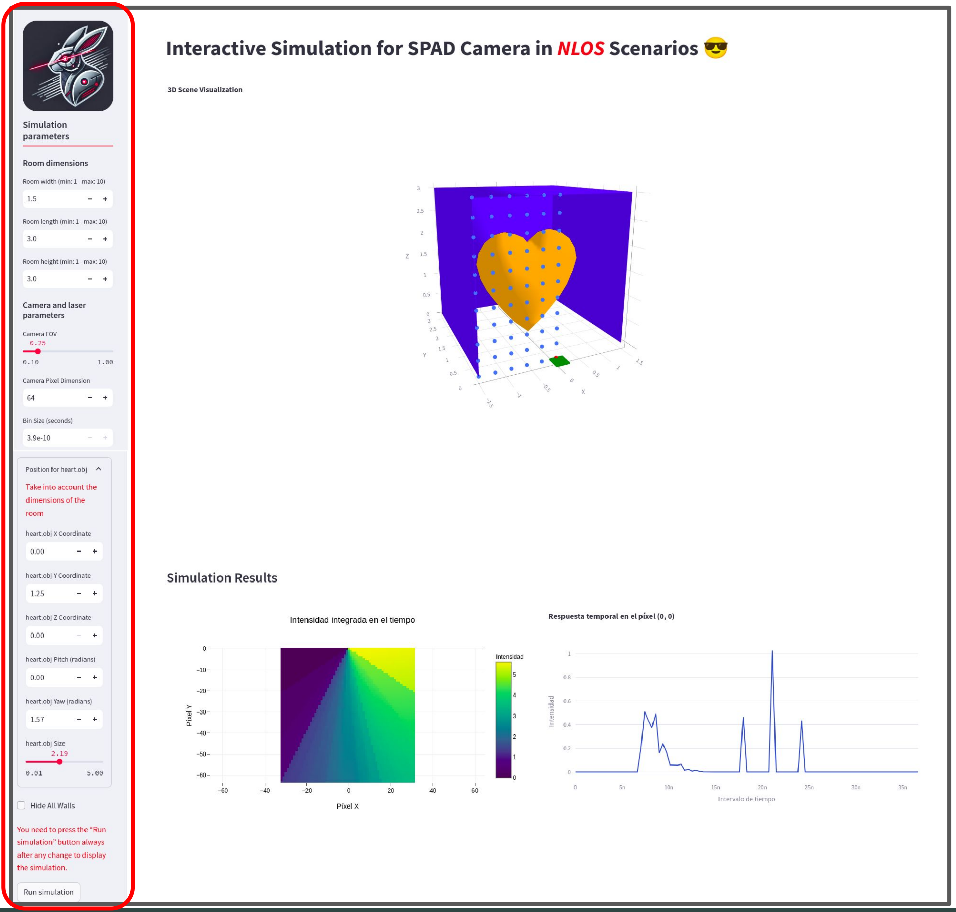
Graphical User Interface



Streamlit

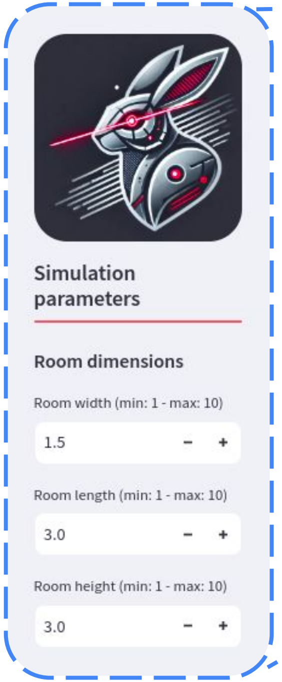
Graphical User Interface

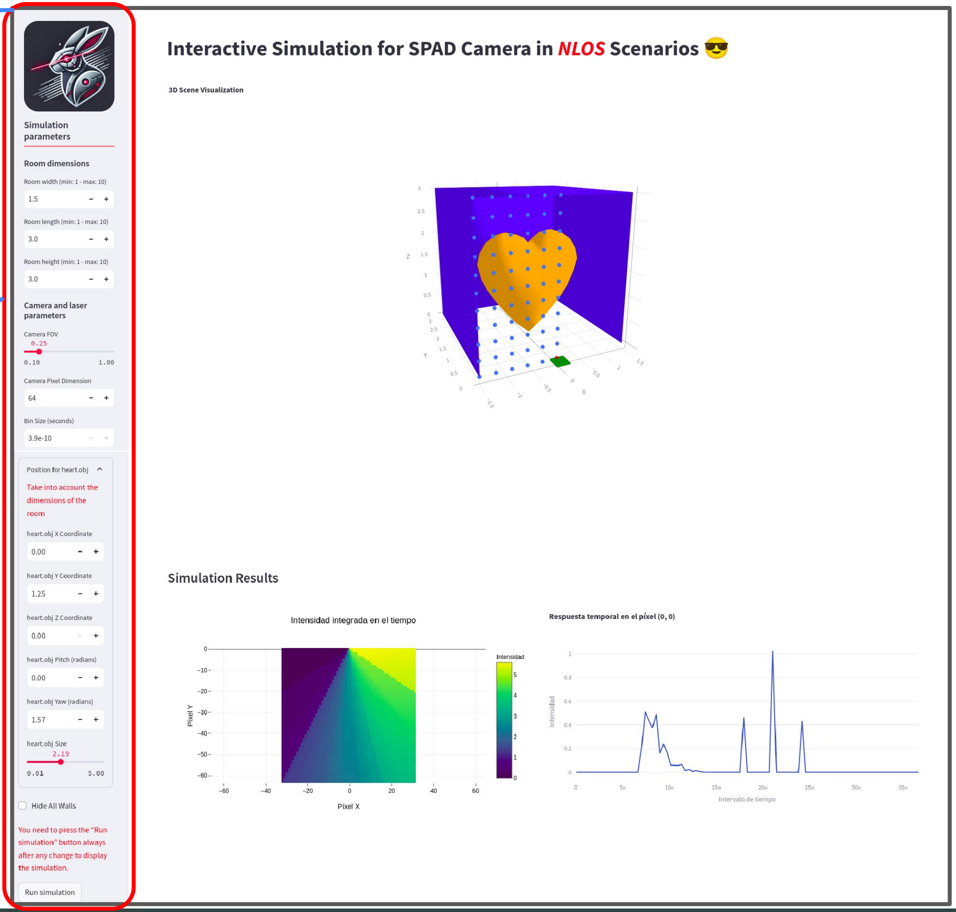
Universidad Industrial de Santander



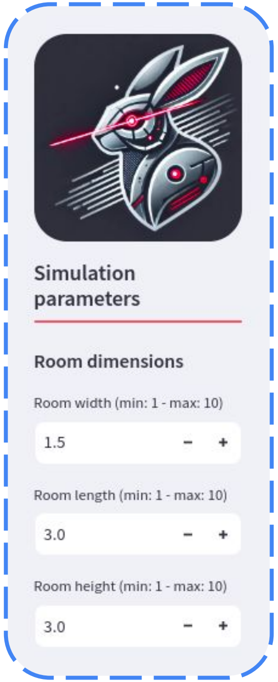
Sidebar with Simulation Parameters

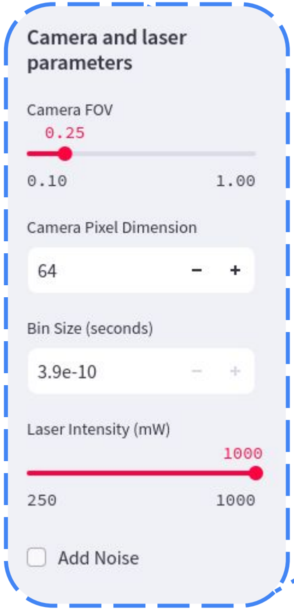
Graphical User Interface

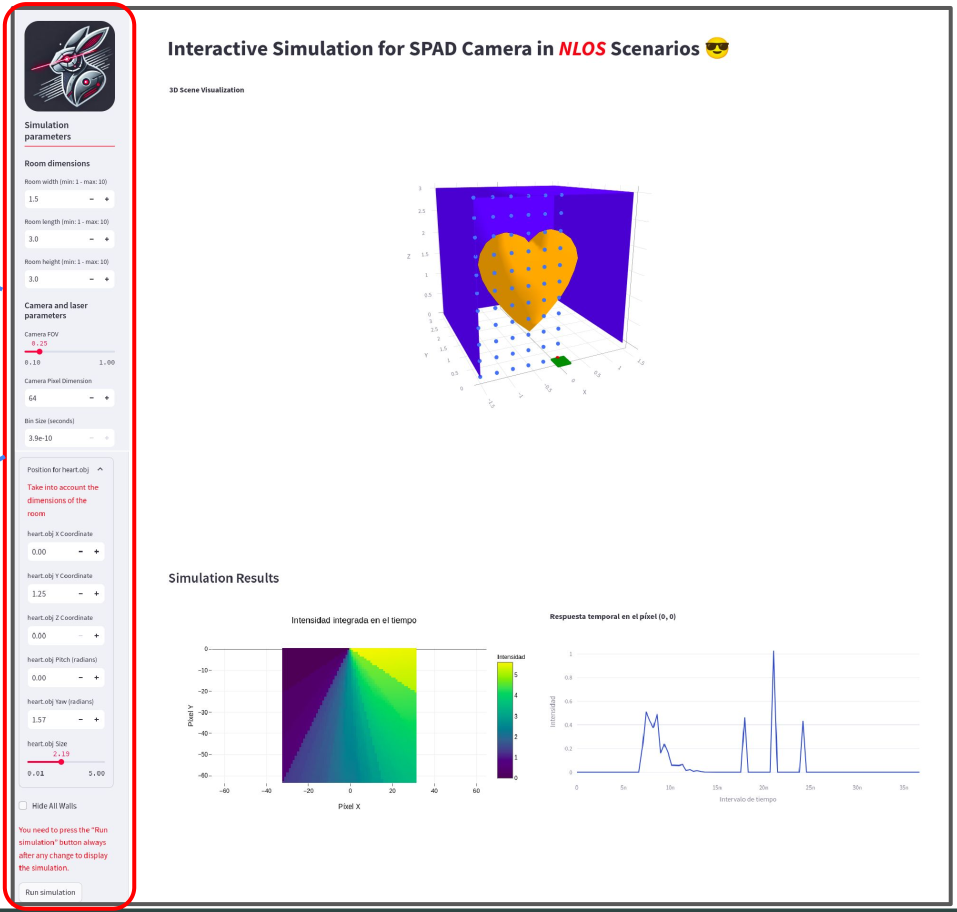




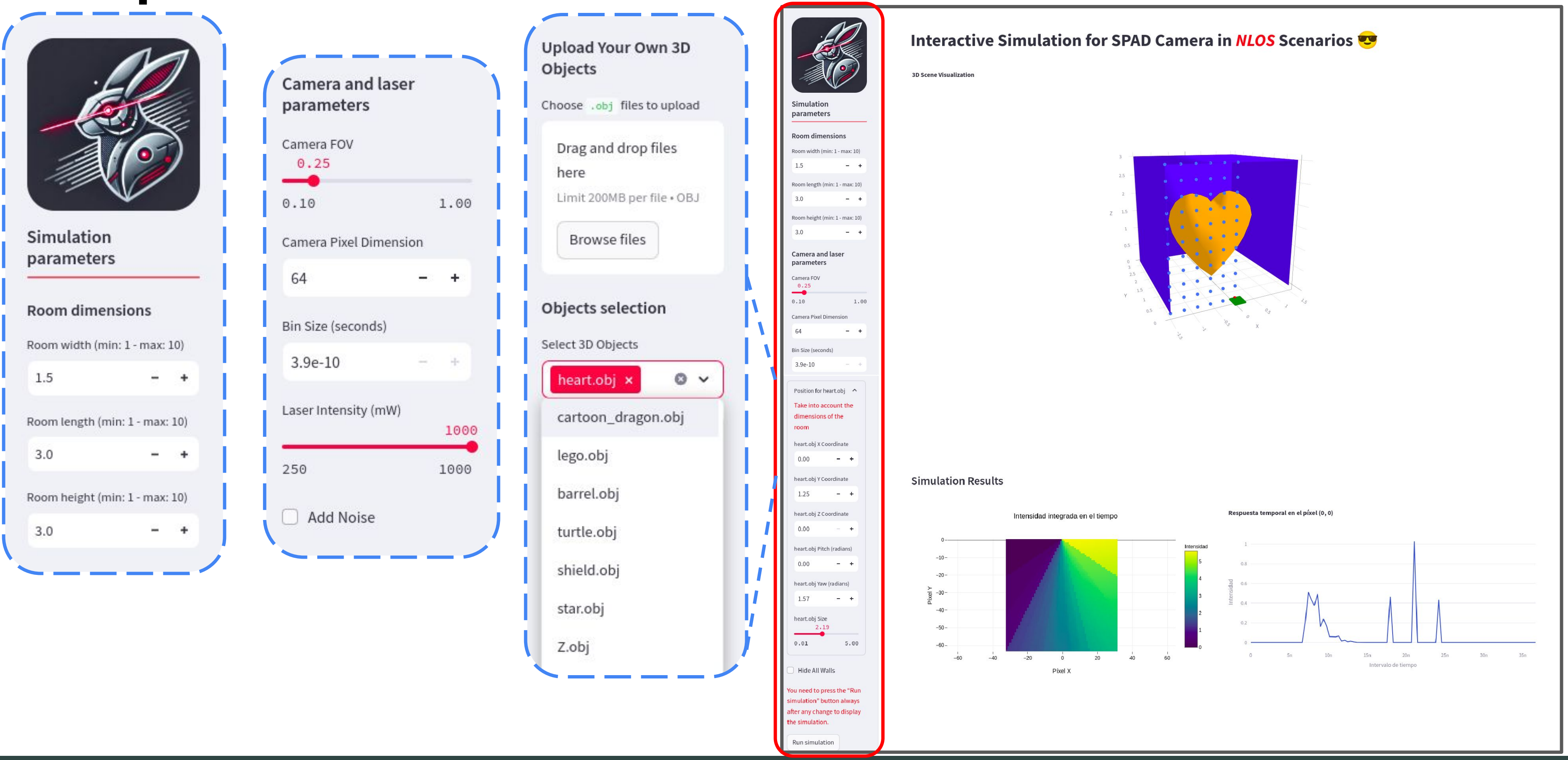
Graphical User Interface



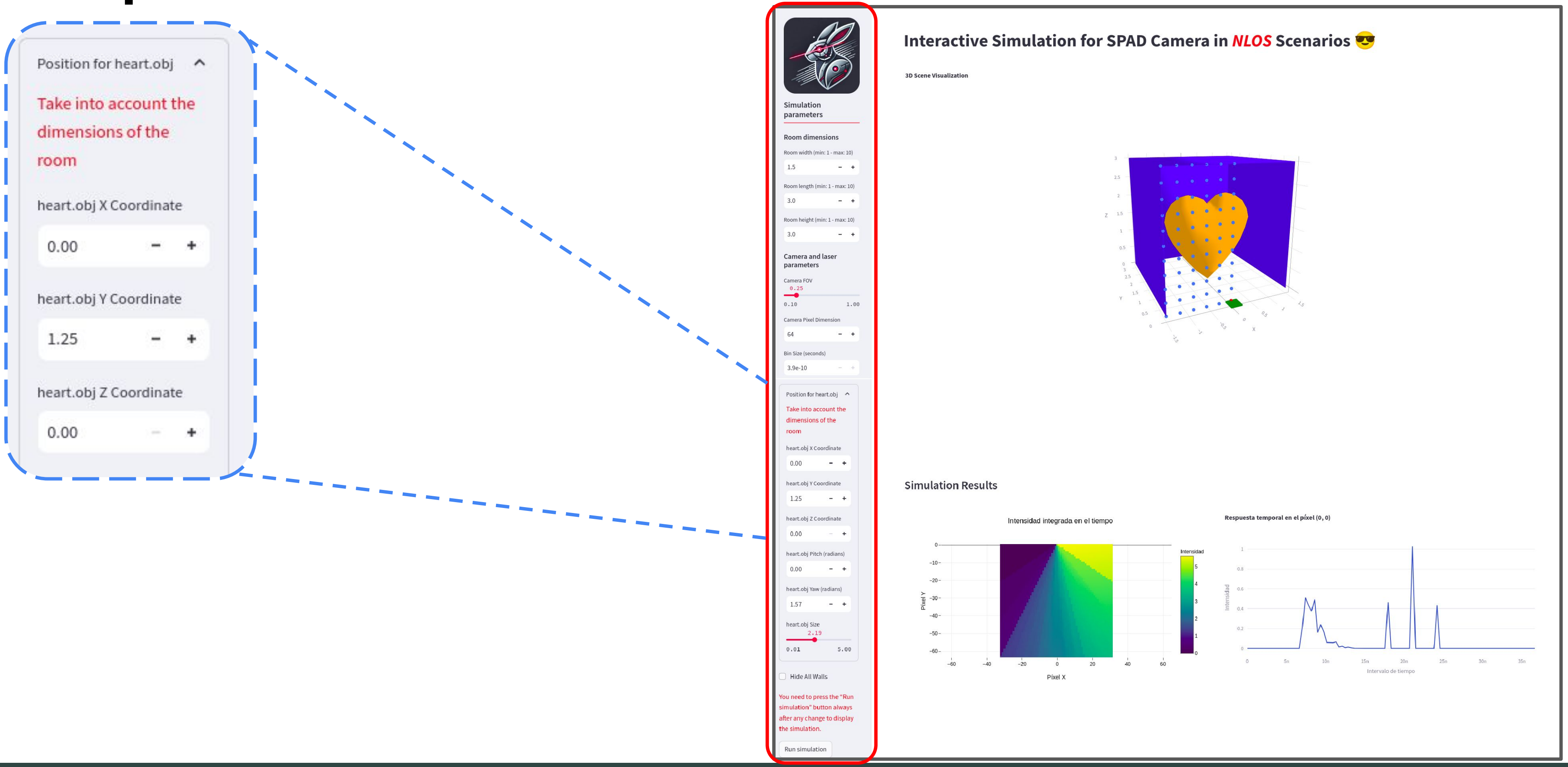




Graphical User Interface



Graphical User Interface



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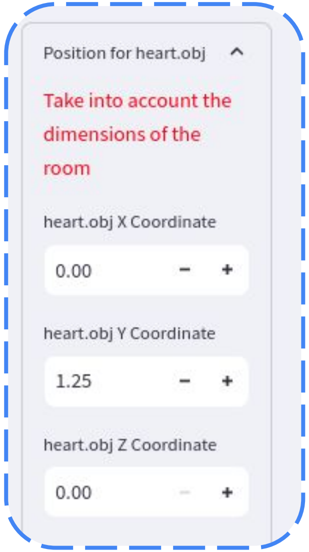

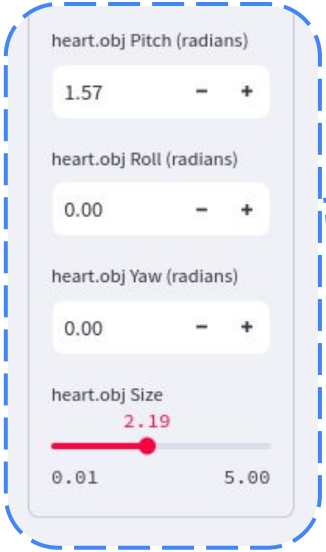

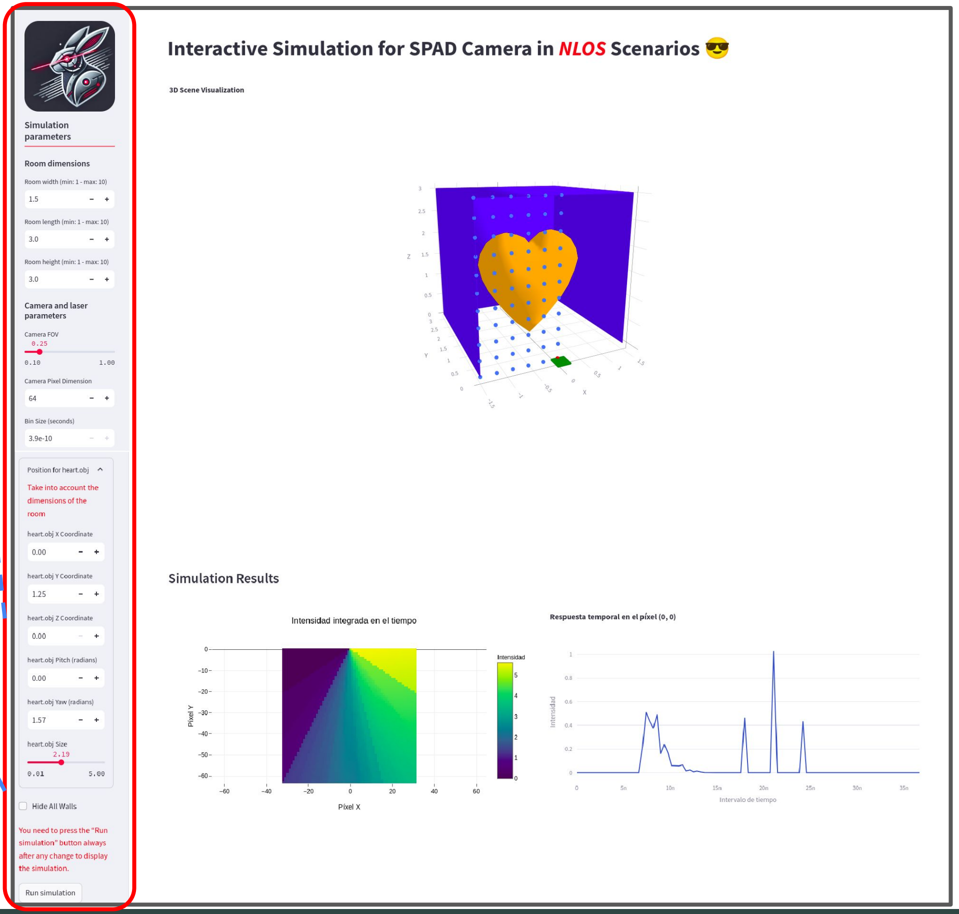

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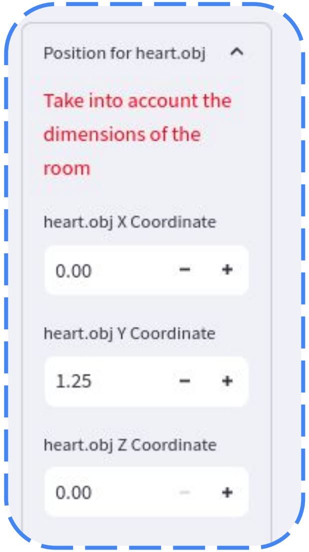
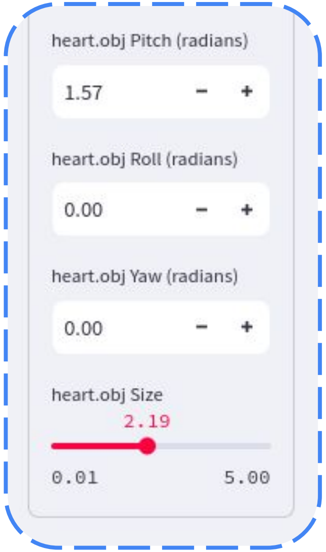
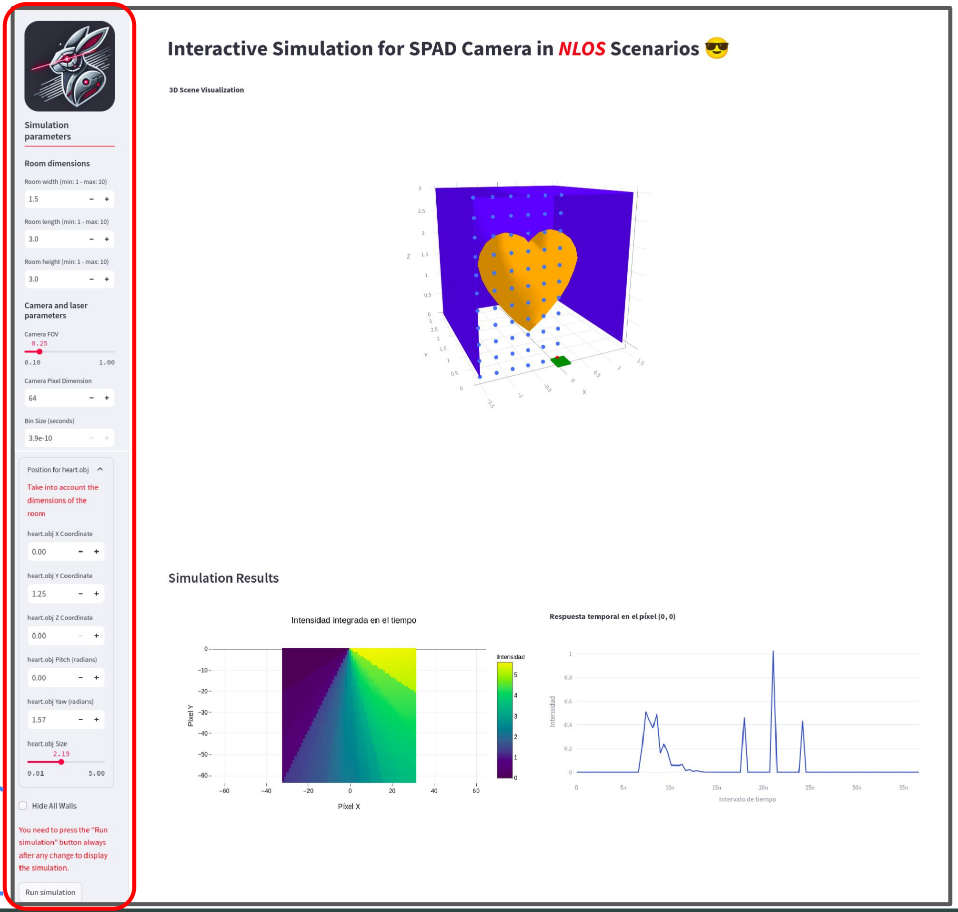
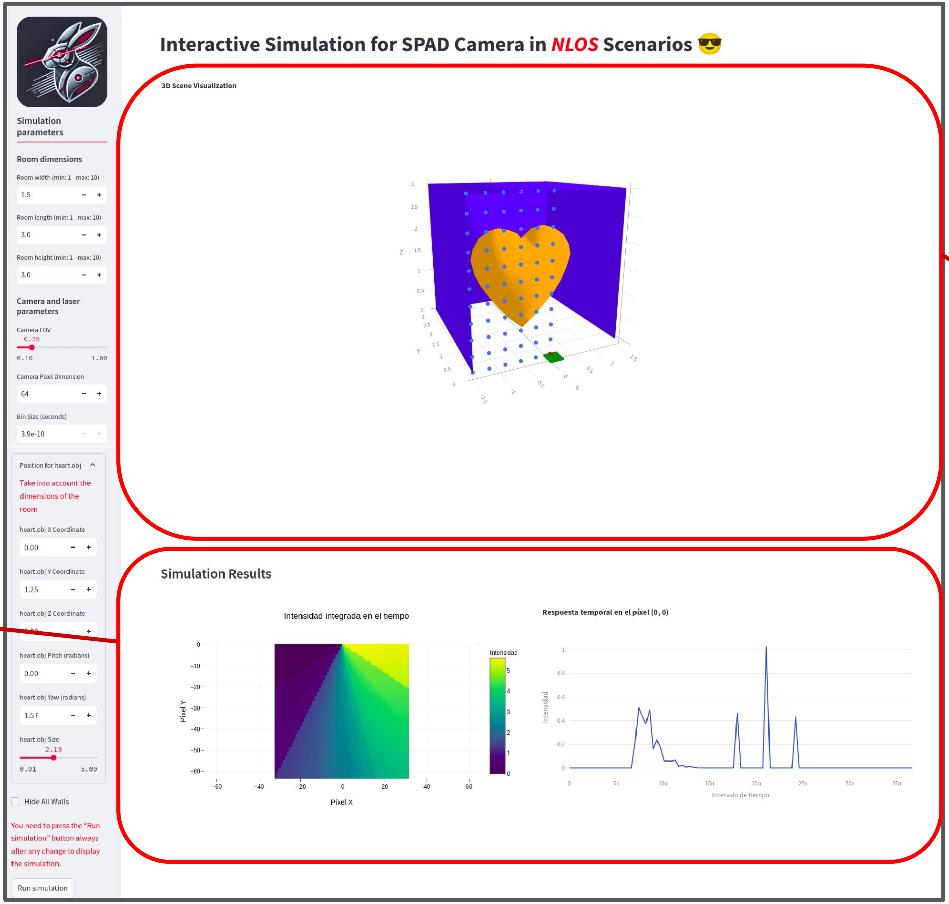






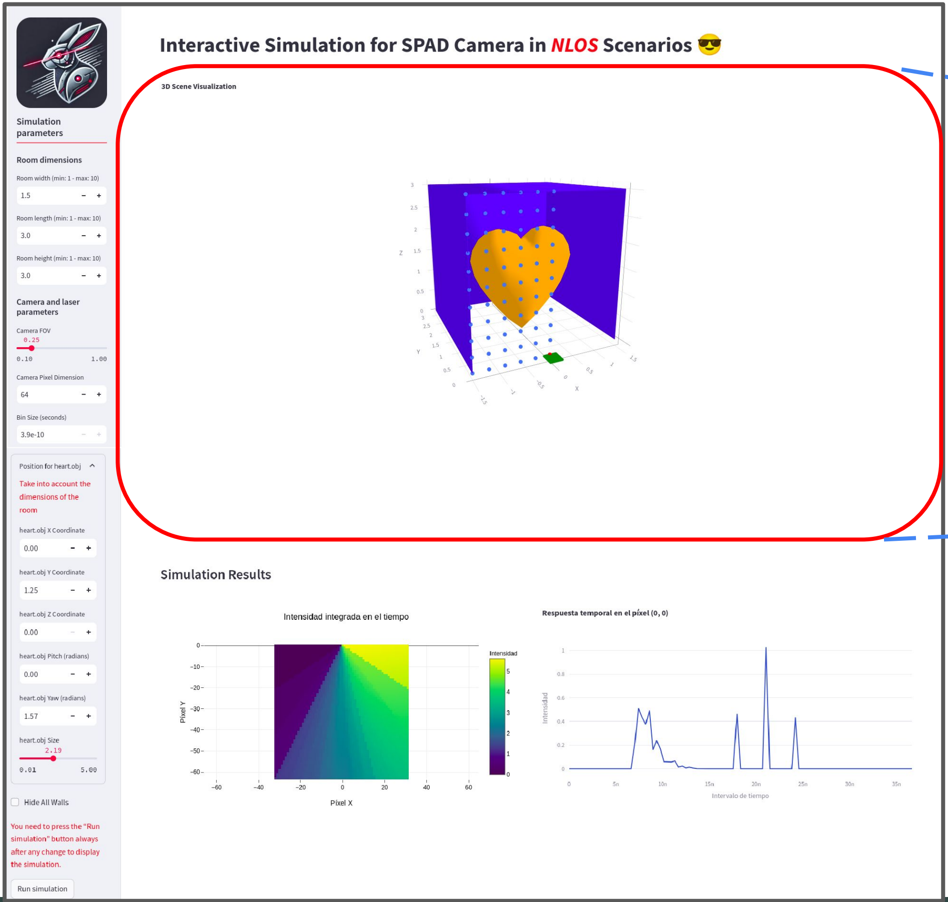
Graphical User Interface

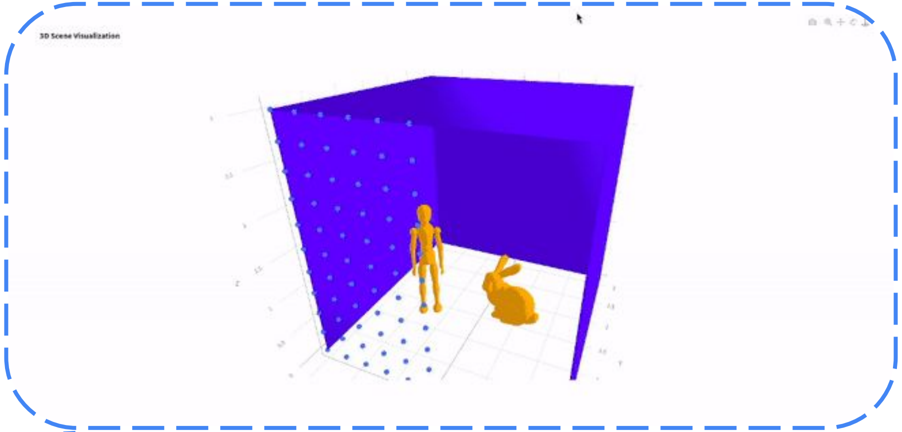


3D Scene Visualization

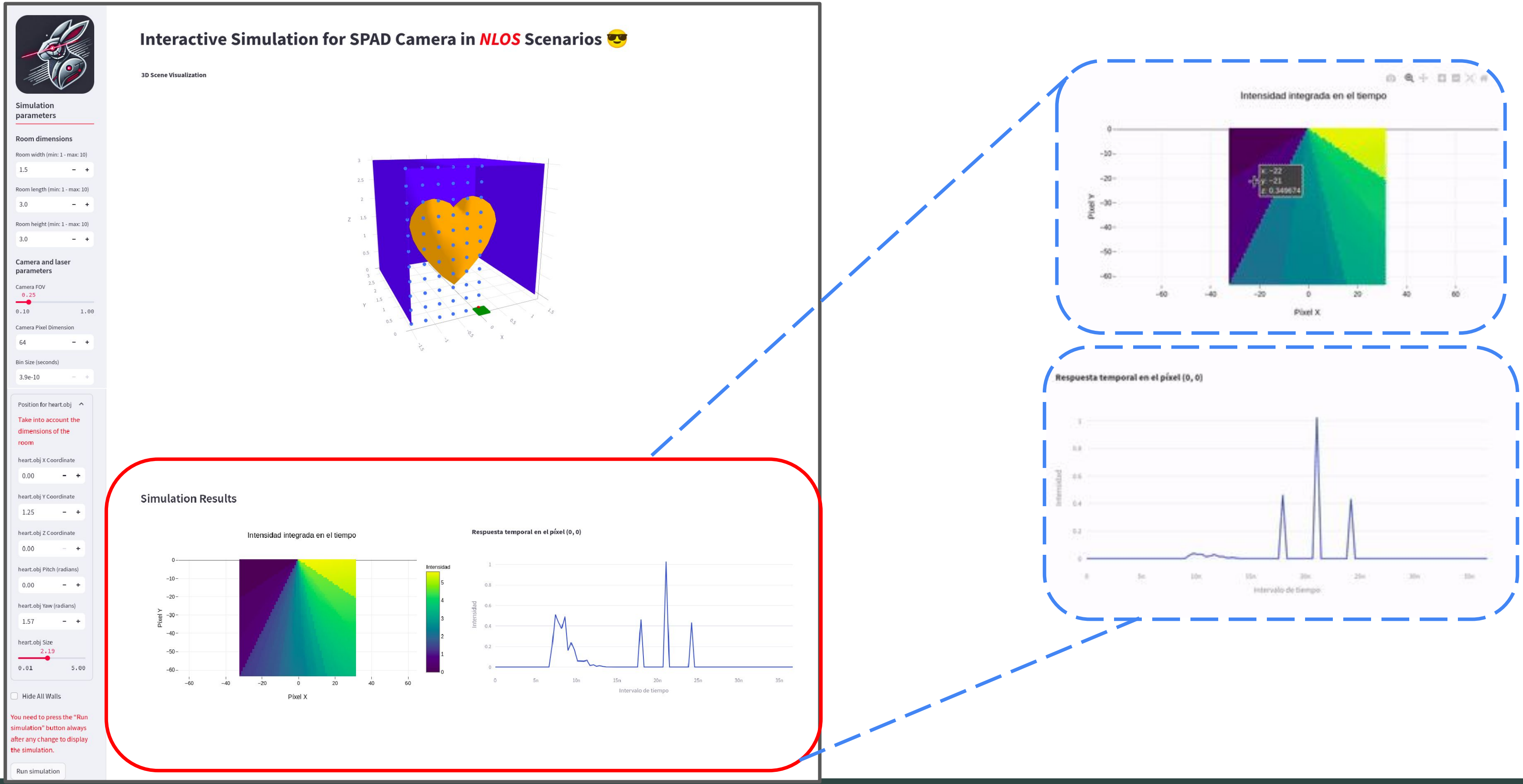
Simulation Results

Graphical User Interface

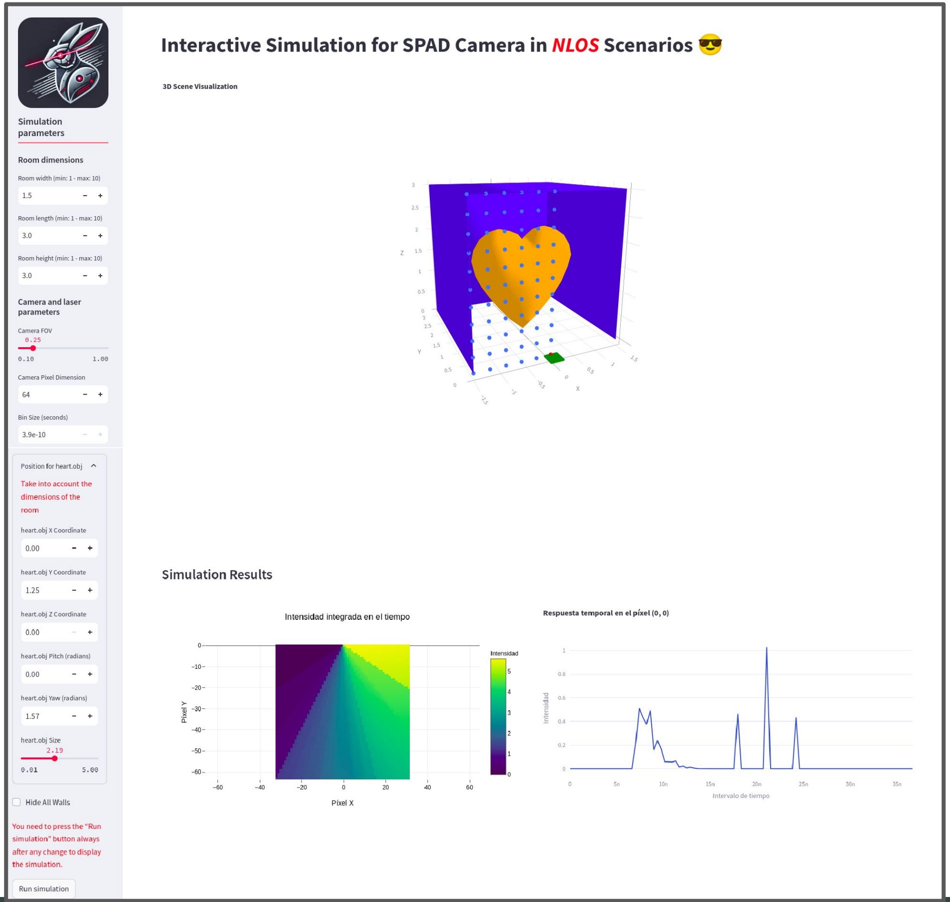




Graphical User Interface



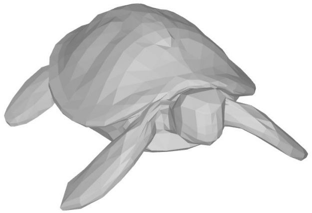
Graphical User Interface

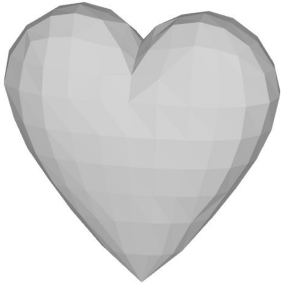


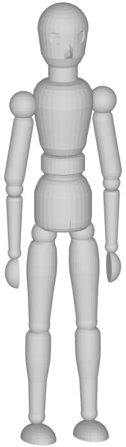
4. Diseñar una interfaz para la visualización de las escenas sin línea de visión y de las imágenes transitorias obtenidas de la simulación del proceso de conteo de fotones.

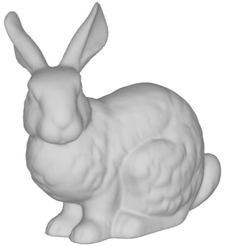
Parameter Analysis

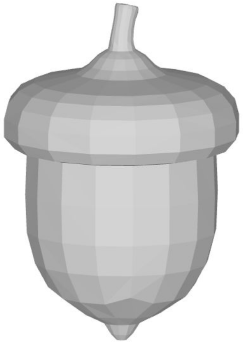
Data

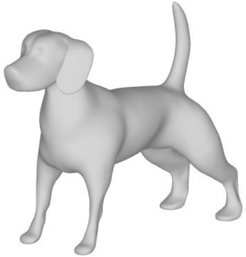






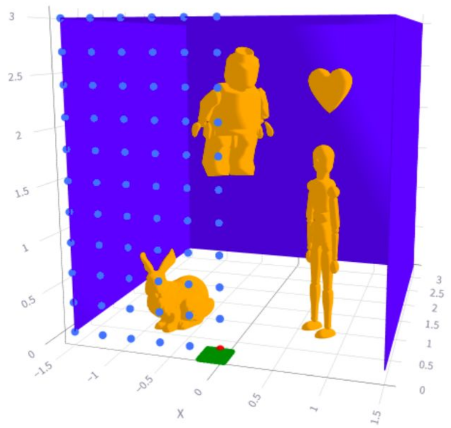


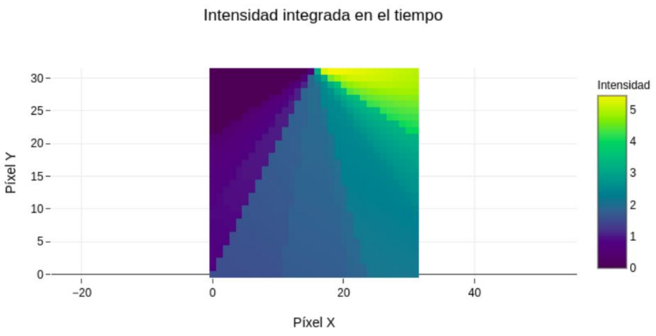


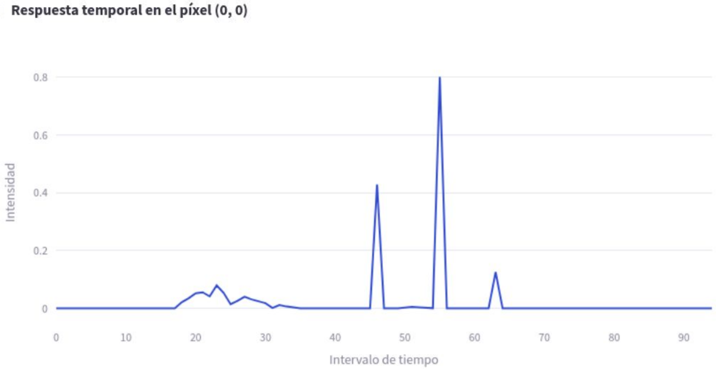


[9] Jiaxiang Tang, et al. "EdgeRunner: Auto-regressive Auto-encoder for Artistic Mesh Generation." arXiv preprint arXiv:2409.18114, 2024.

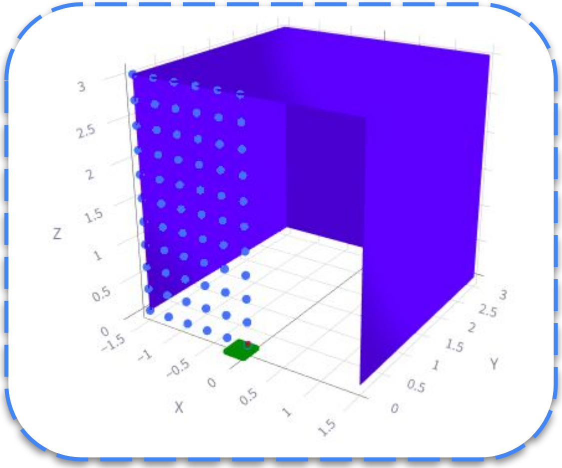
Analysis of Objects Parameters



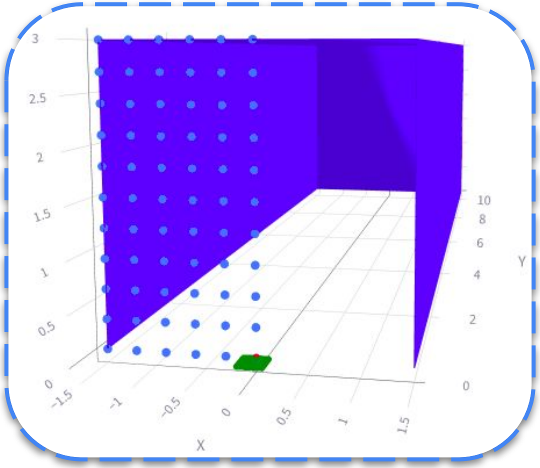




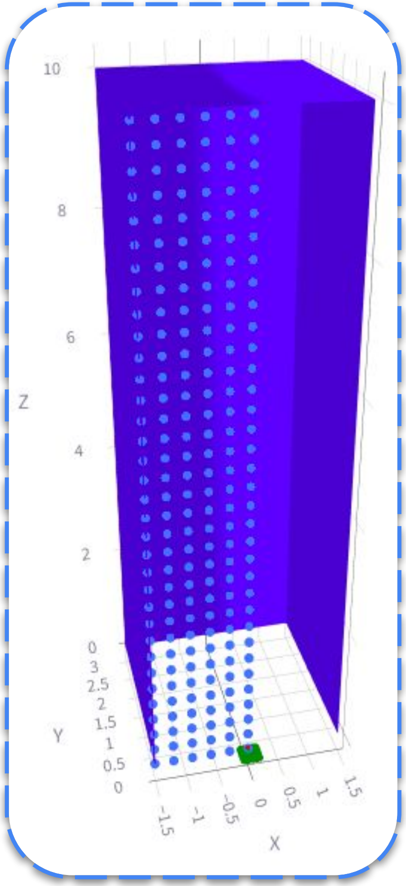
Analysis of Scene Parameters



3m x 3m x 3m

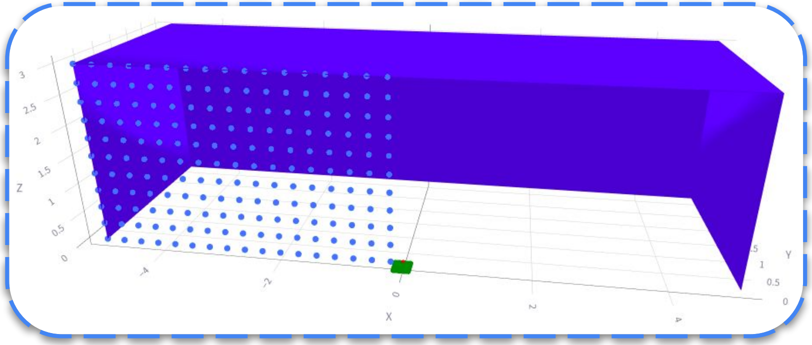


3m x 10m x 3m



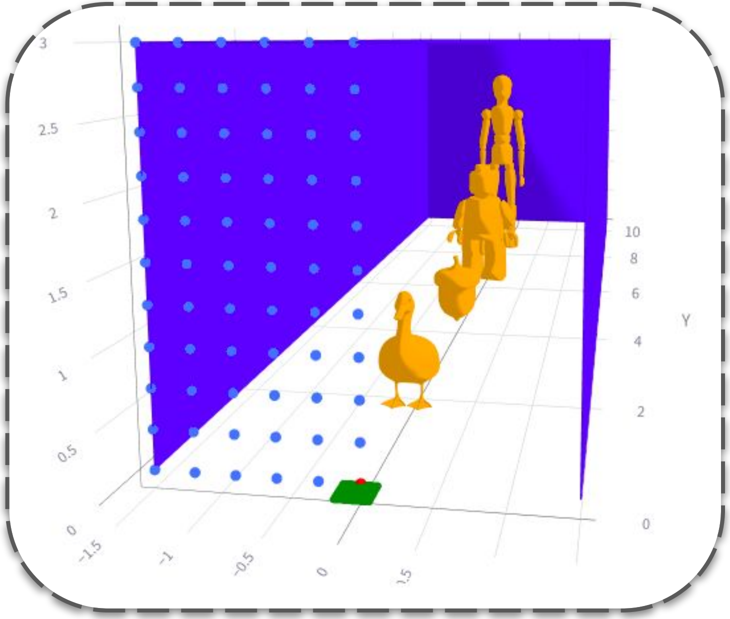
3m x 3m x 10m

Default Range: (min: 1 - max: 10)

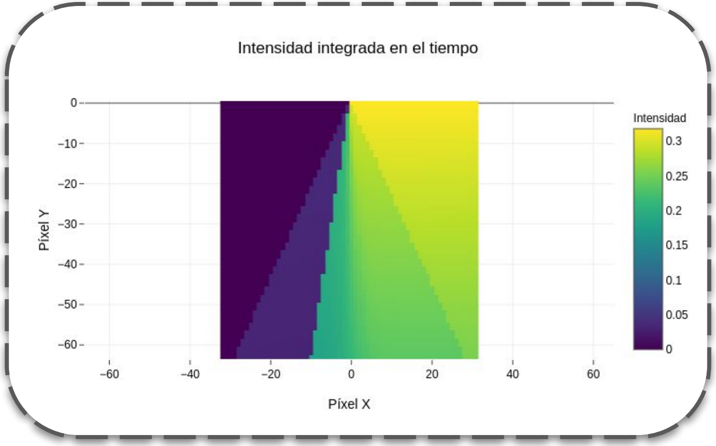


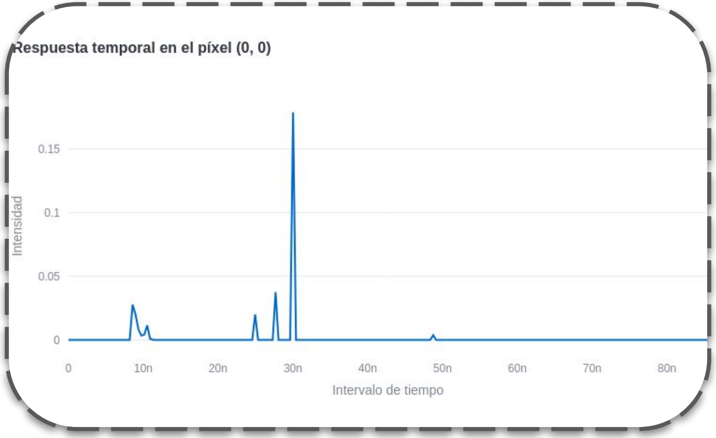
10m x 3m x 3m

Analysis of Scene Parameters

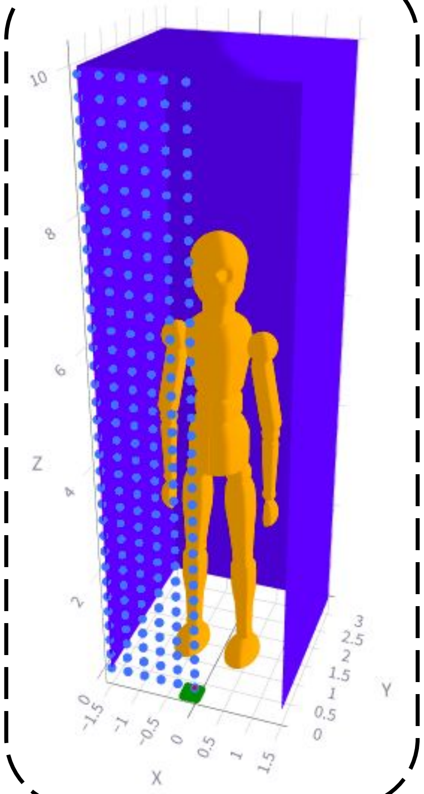


3m x 10m x 3m

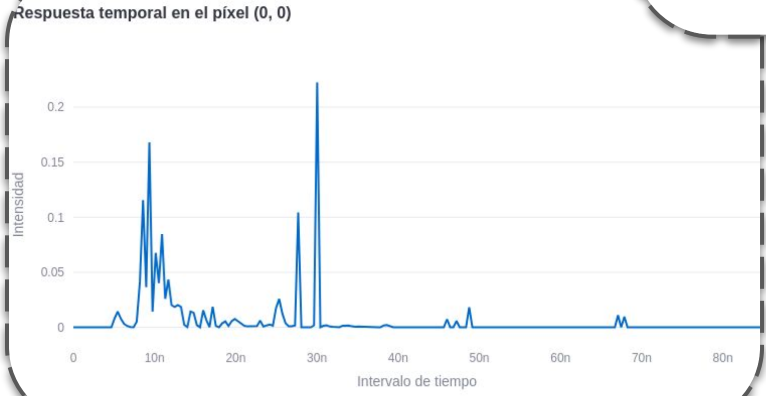


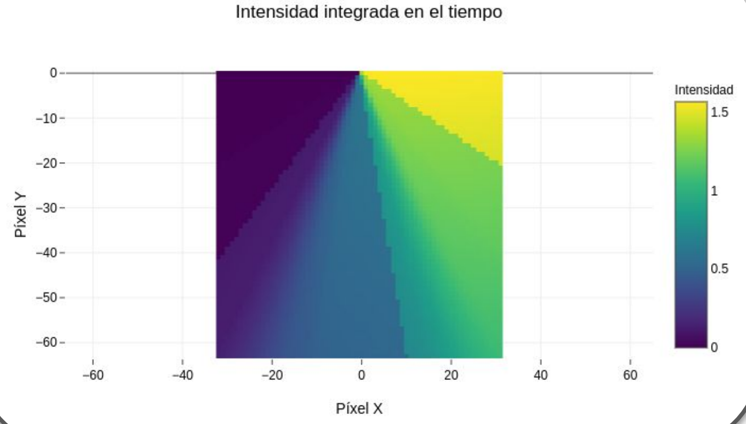


Analysis of Scene Parameters



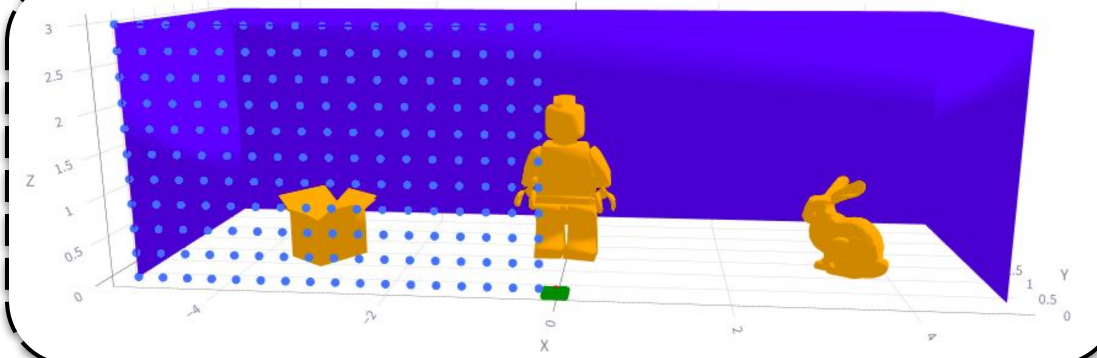
3m x 3m x 10m

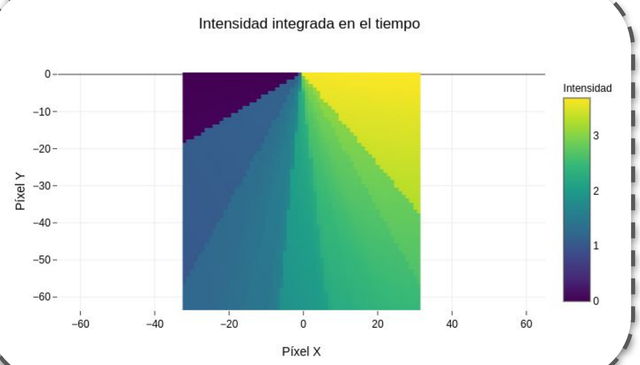


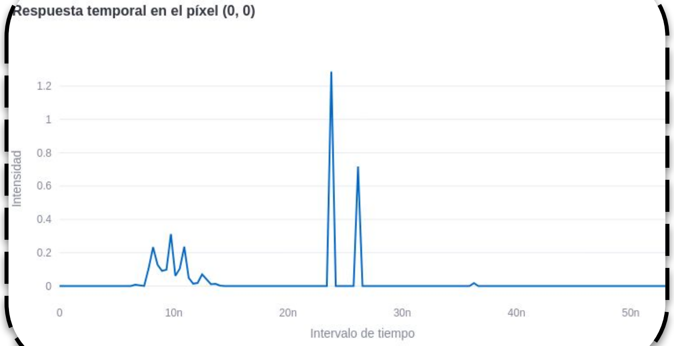


Analysis of Scene Parameters

10m x 3m x 3m

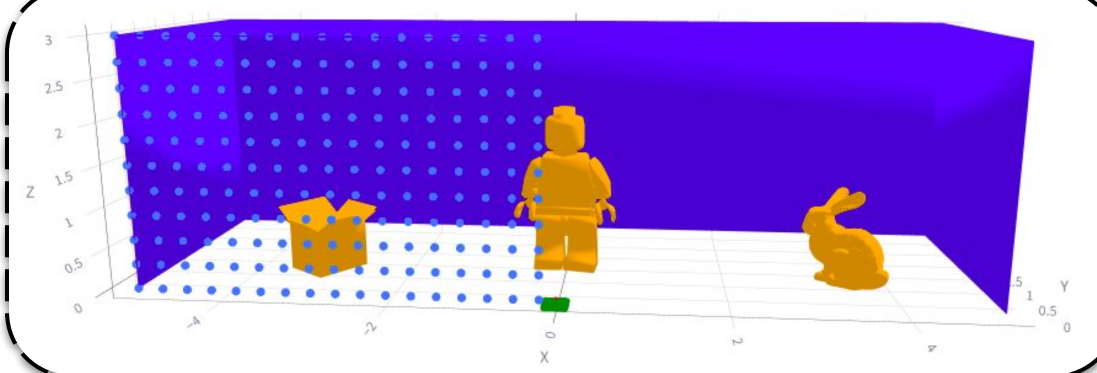






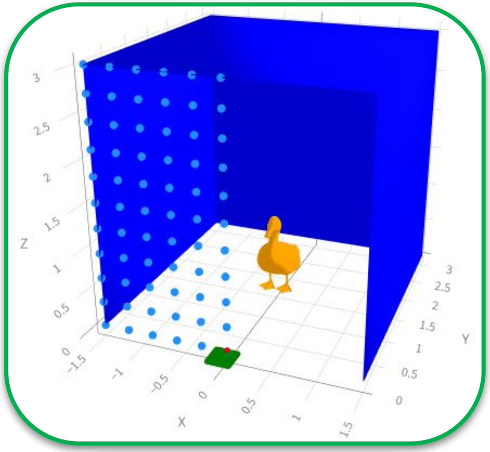
Analysis of Scene Parameters

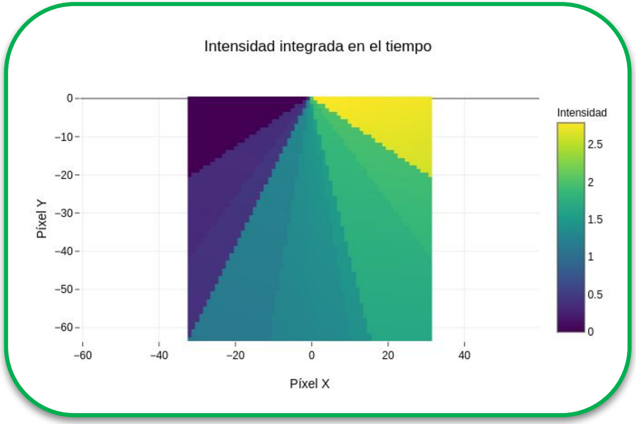
10m x 3m x 3m

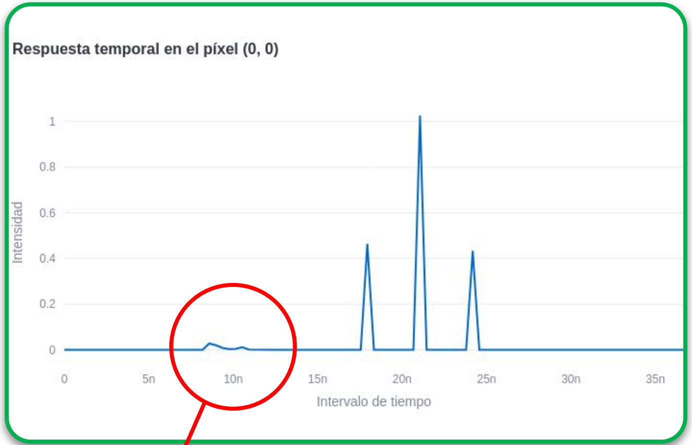


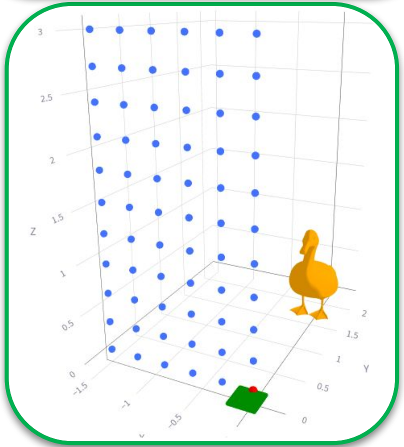
2. Diseñar y simular escenas que incluyan objetos en una configuración sin línea de visión directa de la cámara.

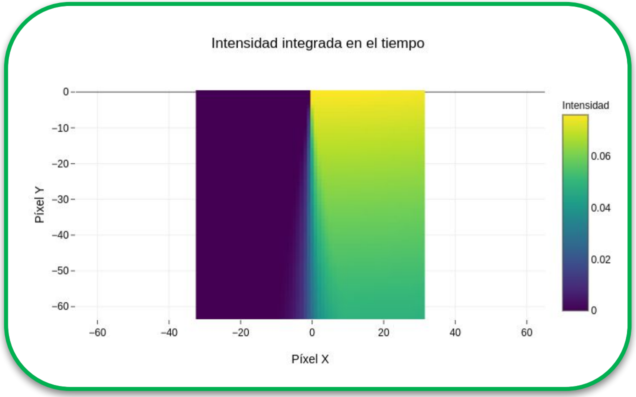
Option to remove the walls

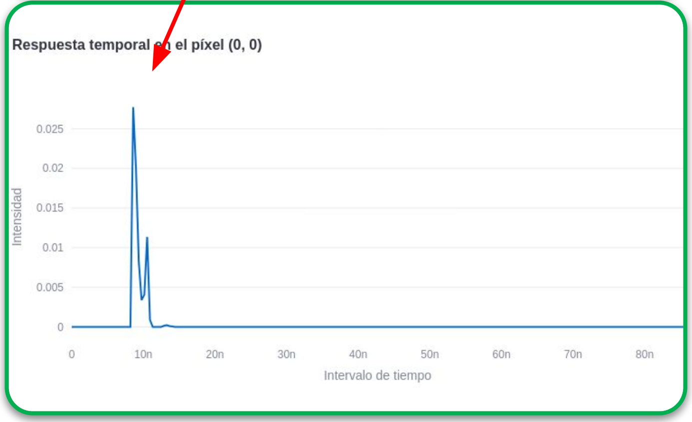




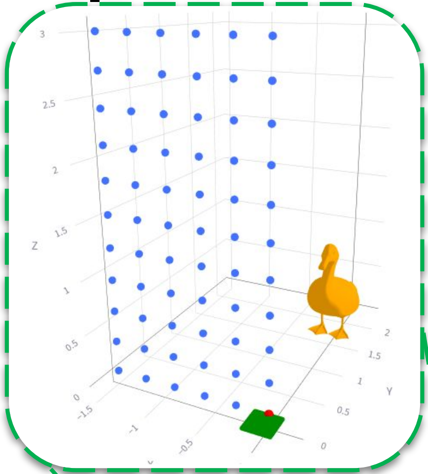


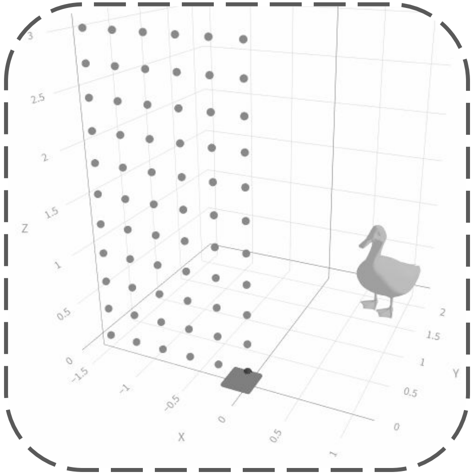


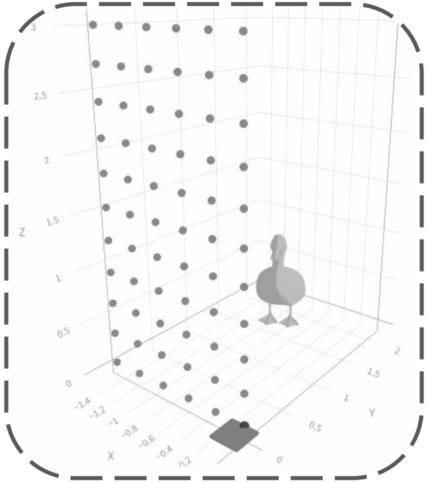


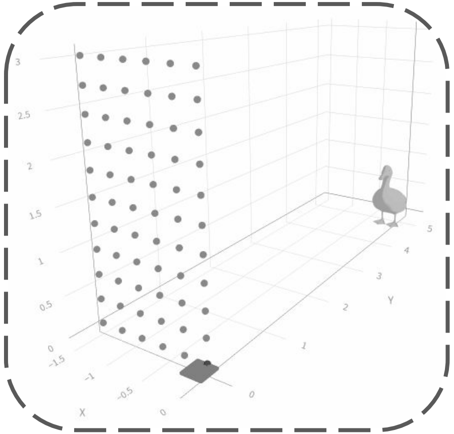


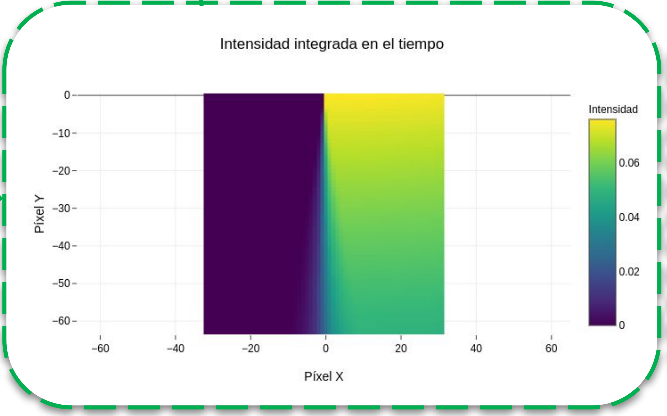
Option to remove the walls

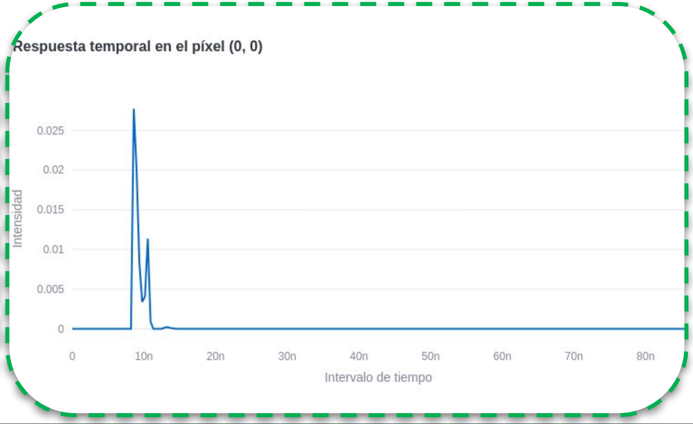




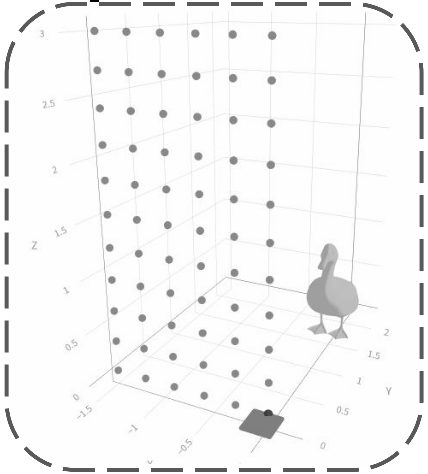


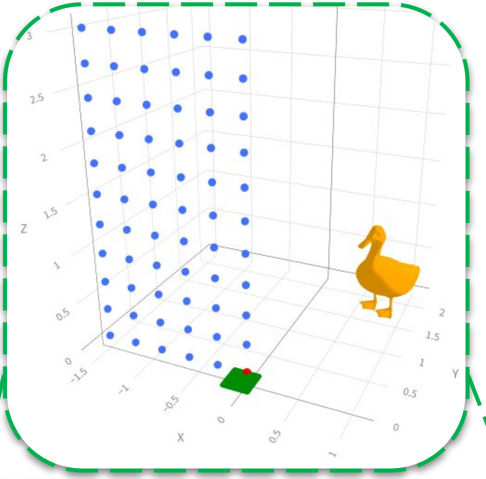


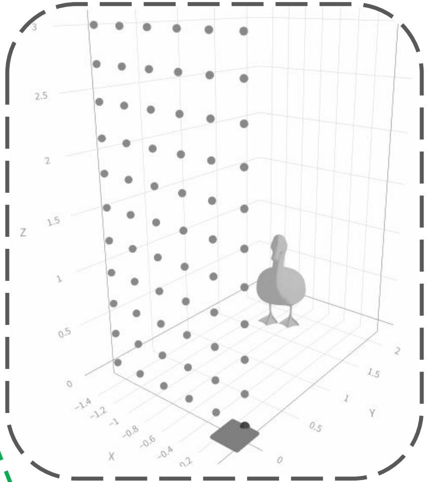


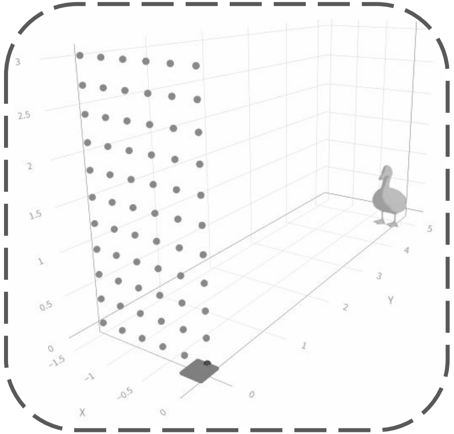


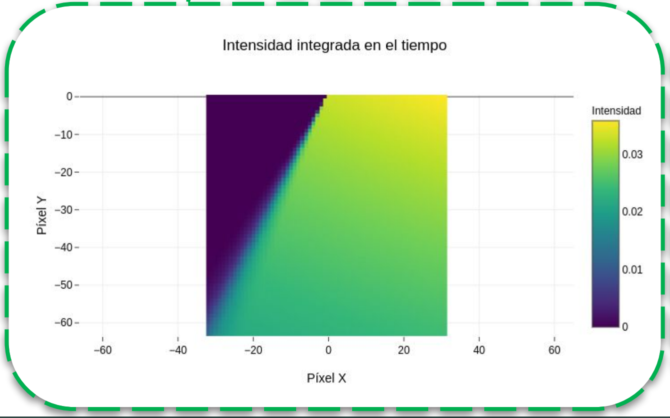
Option to remove the walls

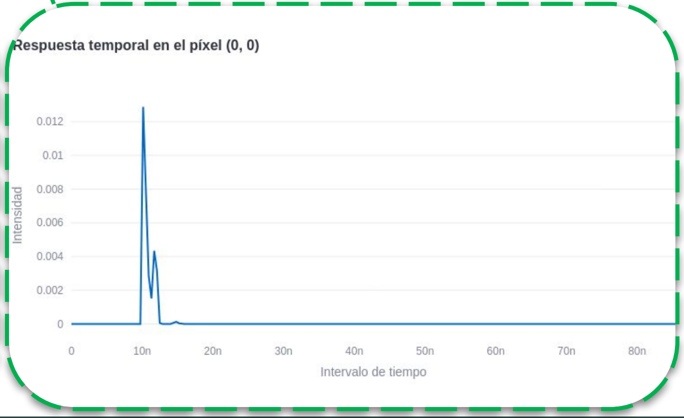












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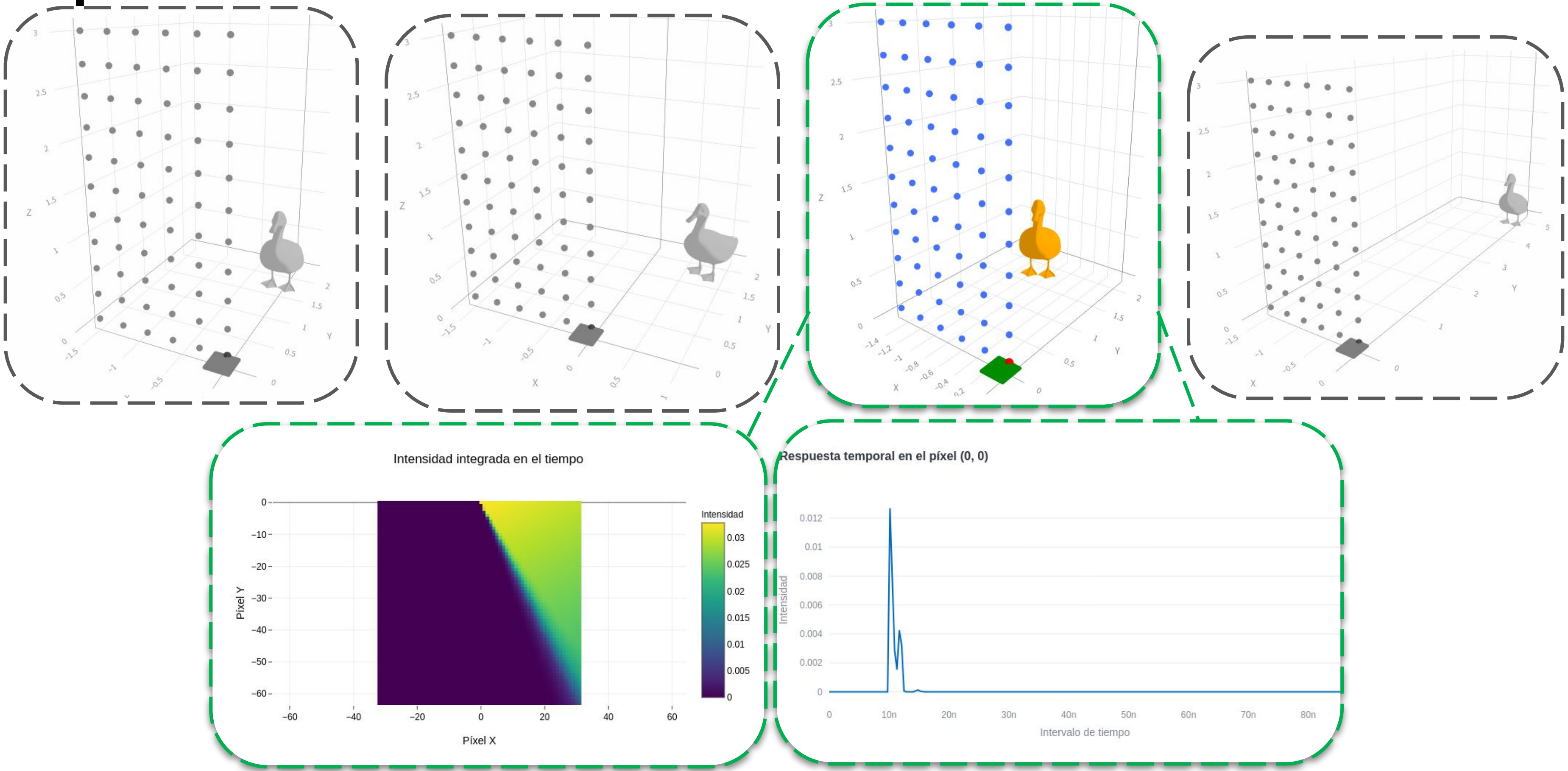
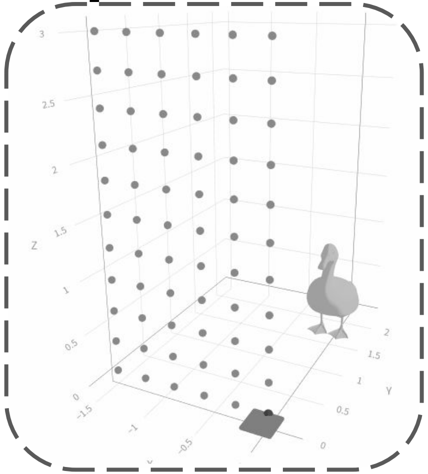
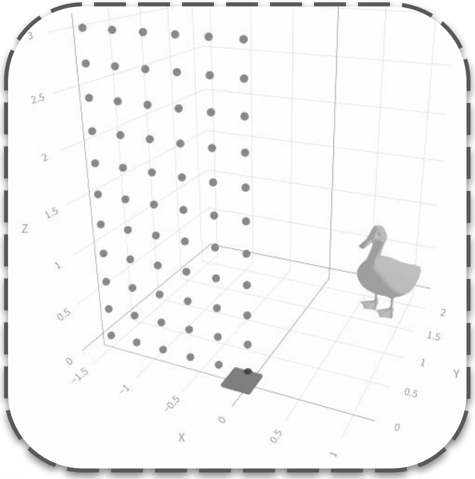
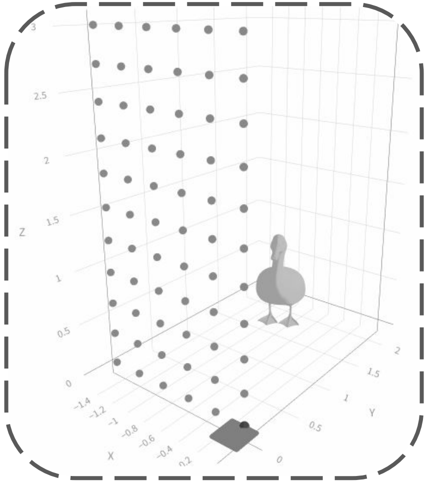
Option to remove the walls

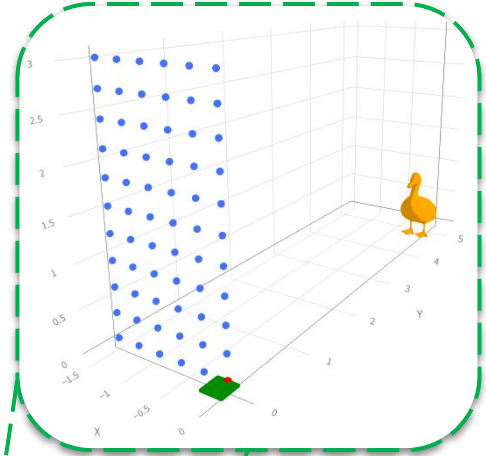


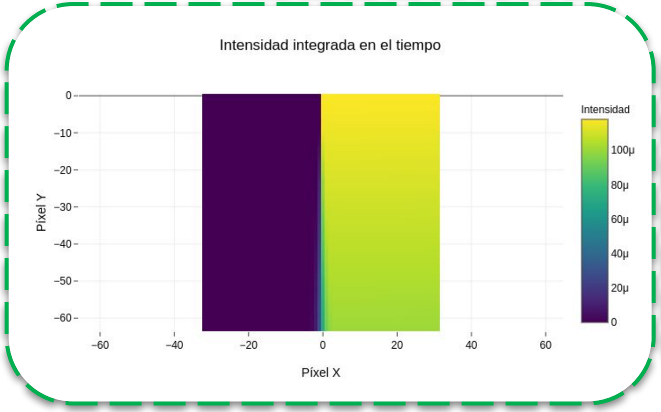
Option to remove the walls

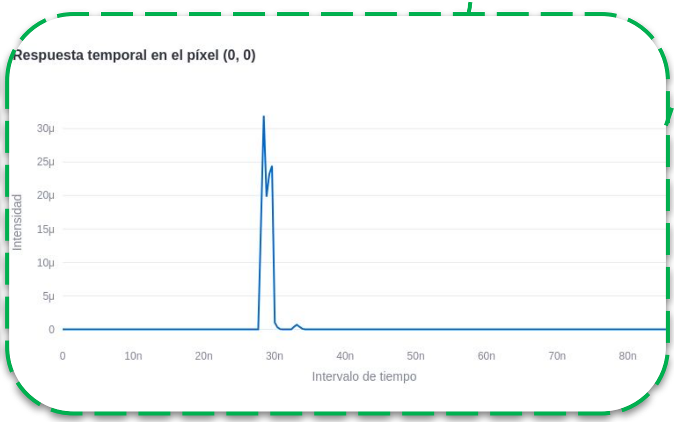




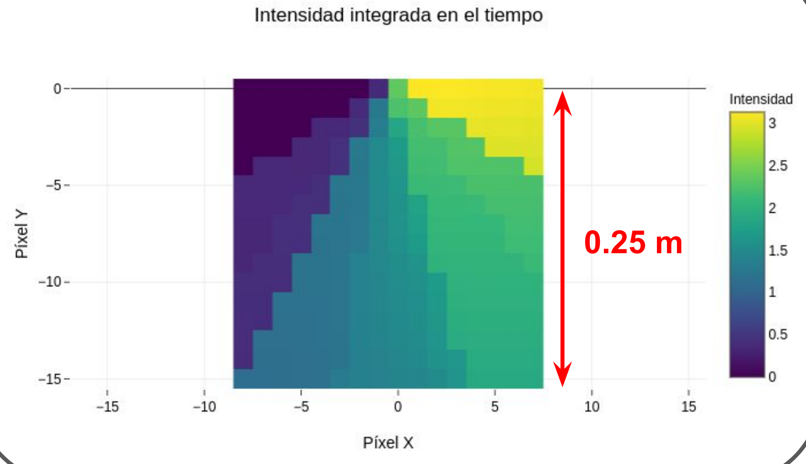


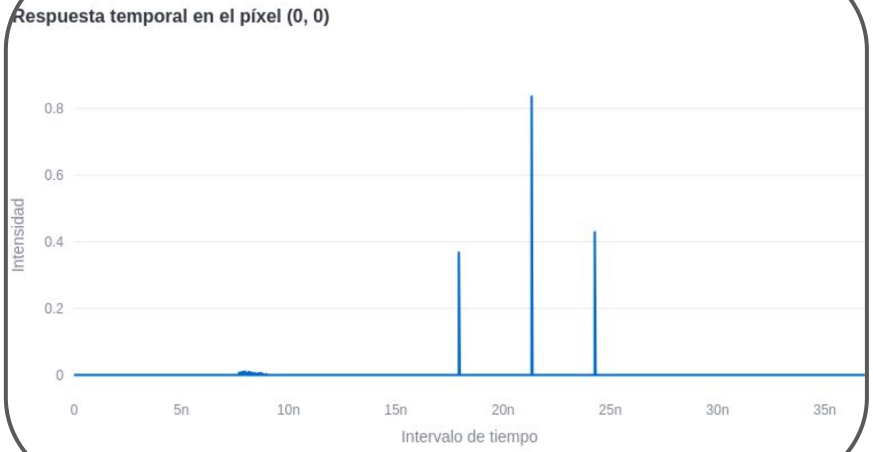


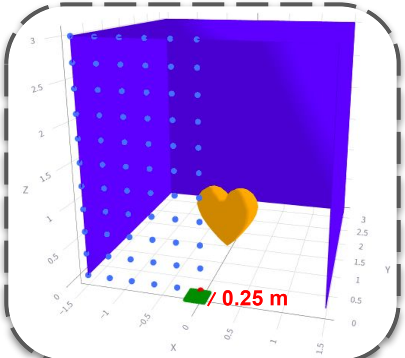




Analysis of the Camera and Laser Parameters

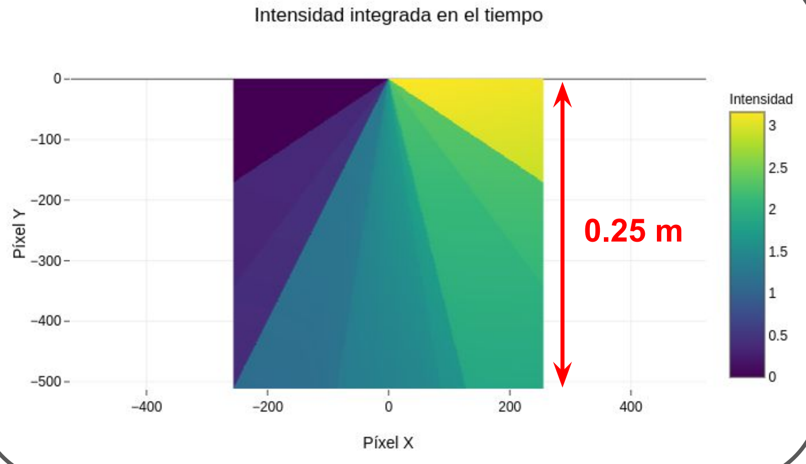


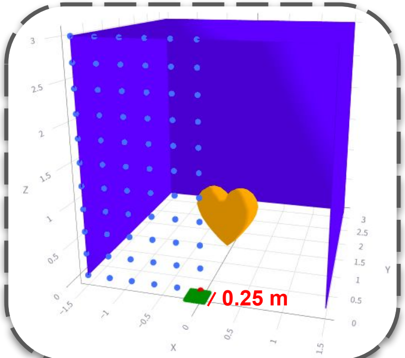




Camera FOV: 0.25 m
Camera Pixel Dimension: 16 x 16 pixels
Bin Size: 1.0e-12 s
Laser intensity: 1000 mW

Analysis of the Camera and Laser Parameters





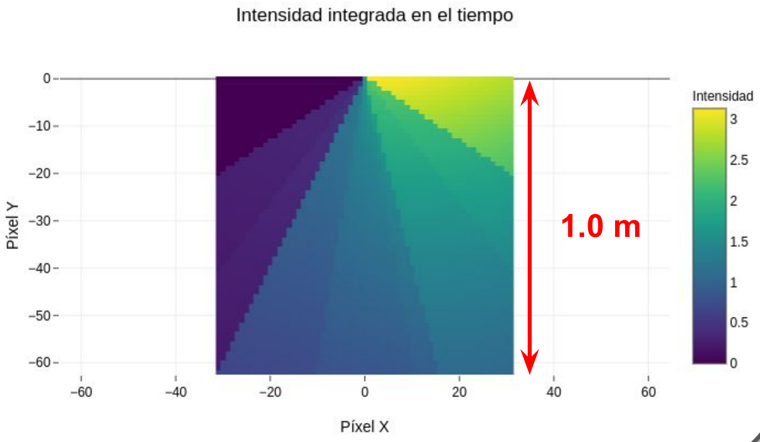
Camera FOV: 0.25 m

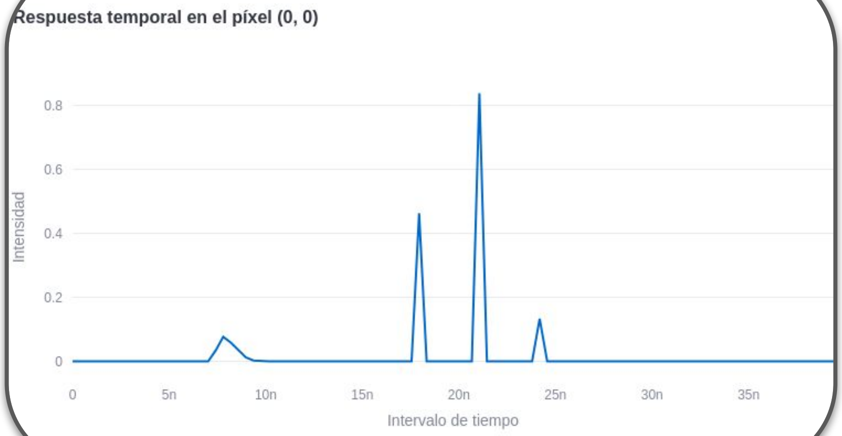
Camera Pixel Dimension: 512 x 512 pixels

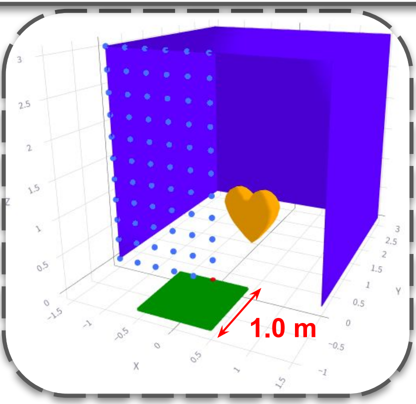
Bin Size: 1.0e-8 s

Laser intensity: 1000 mW

Analysis of the Camera and Laser Parameters







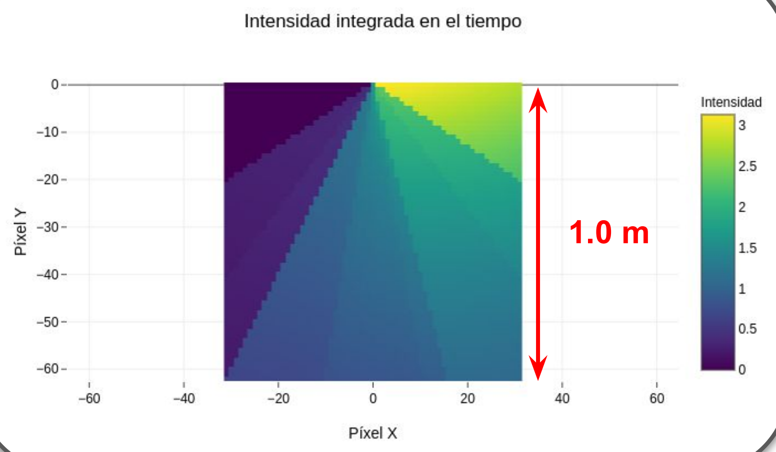
Camera FOV: 1.0 m

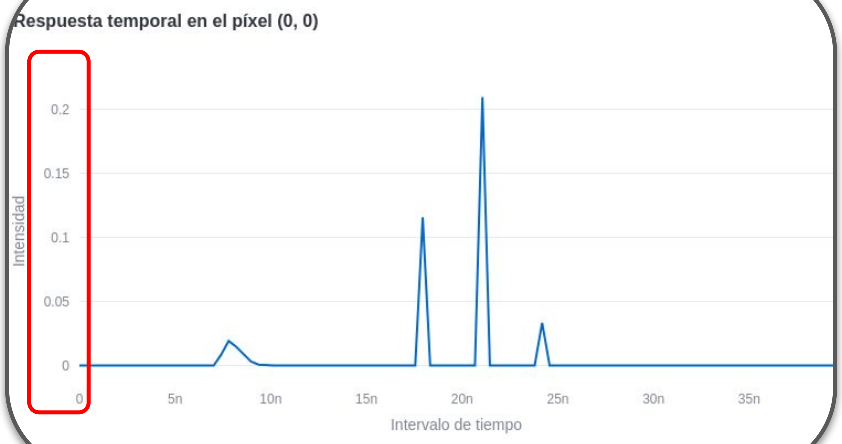
Camera Pixel Dimension: 64 x 64 pixels

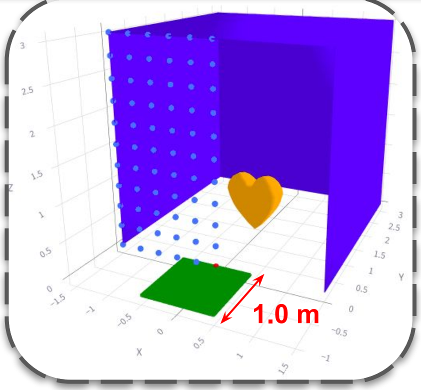
Bin Size: 3.9e-10 s

Laser intensity: 1000 mW

Analysis of the Camera and Laser Parameters

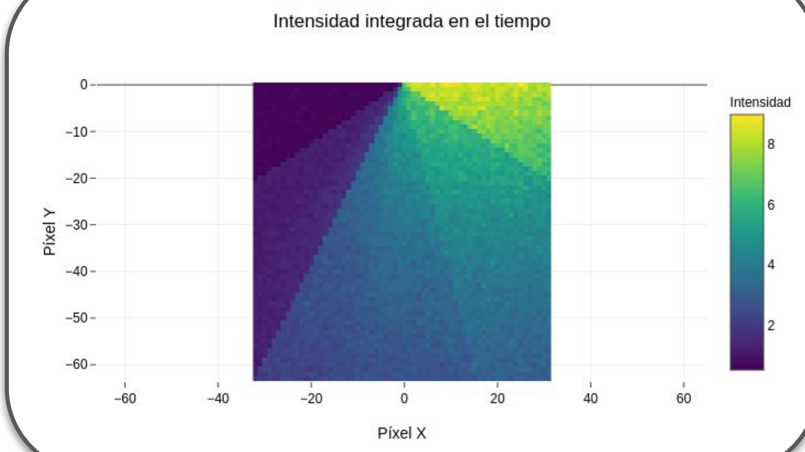


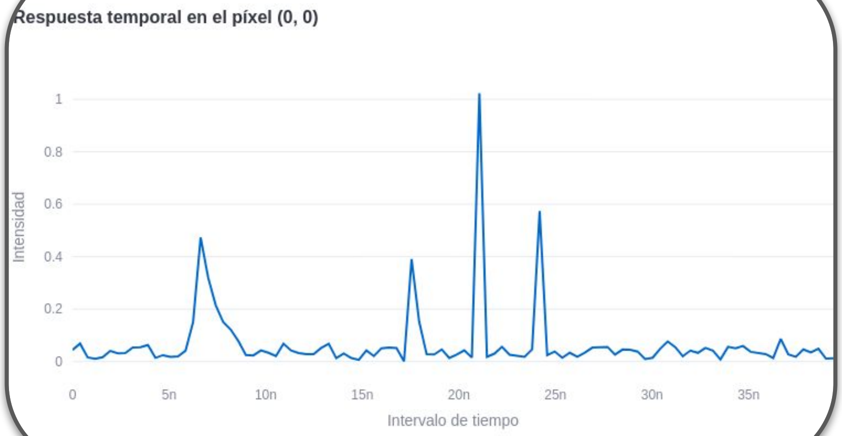


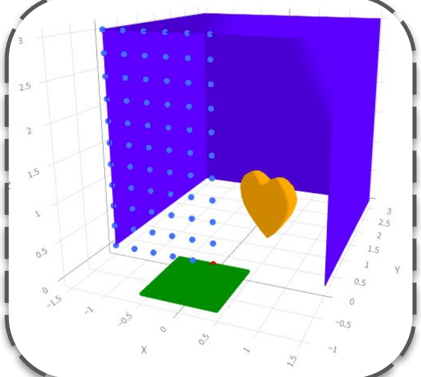


Camera FOV: 1.0 m
Camera Pixel Dimension: 64 x 64 pixels
Bin Size: 3.9e-10 s
Laser intensity: 250 mW

Analysis of the Noise Levels



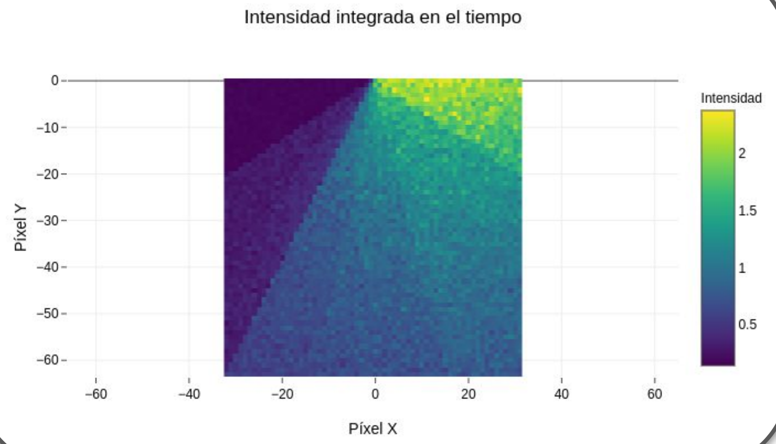


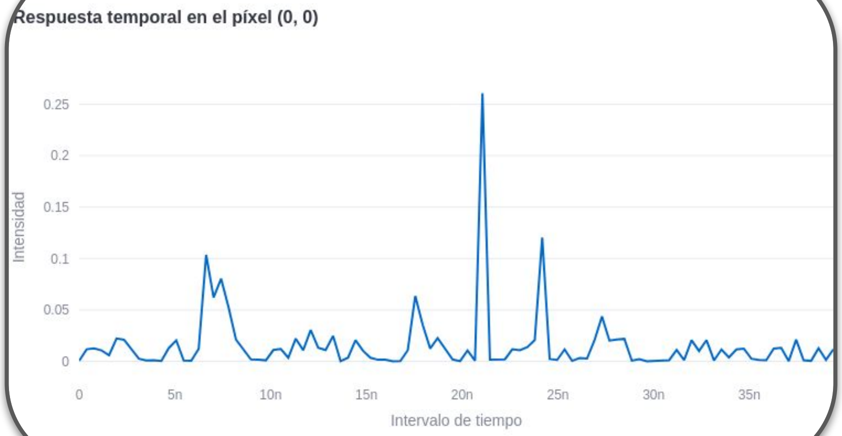


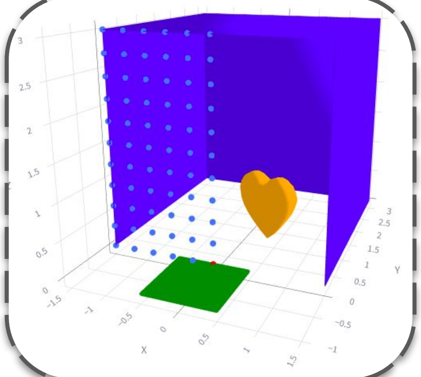
Camera FOV: 1.0 m
Camera Pixel Dimension: 64 x 64 pixels
Bin Size: 3.9e-10 s
Laser intensity: 1000 mW

SNR: 20.0 db
SBR: 1.0 db
Scale factor: 100

Analysis of the Noise Levels



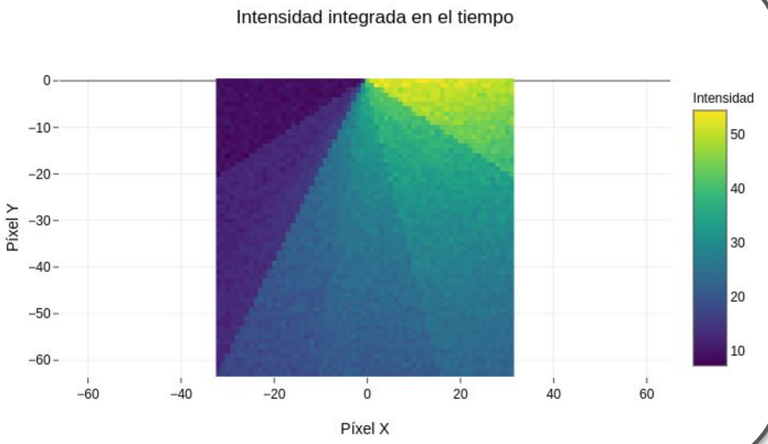


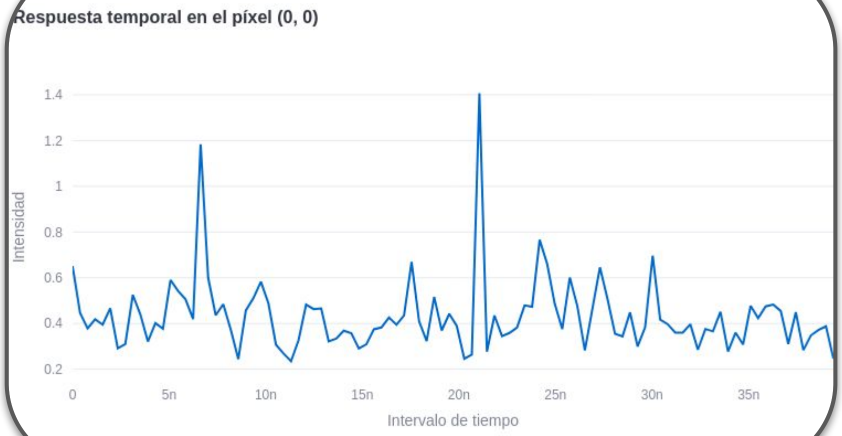


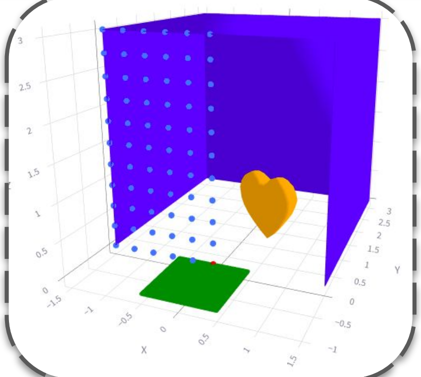
Camera FOV: 1.0 m
Camera Pixel Dimension: 64 x 64 pixels
Bin Size: 3.9e-10 s
Laser intensity: 250 mW

SNR: 20.0 db
SBR: 1.0 db
Scale factor: 100

Analysis of the Noise Levels



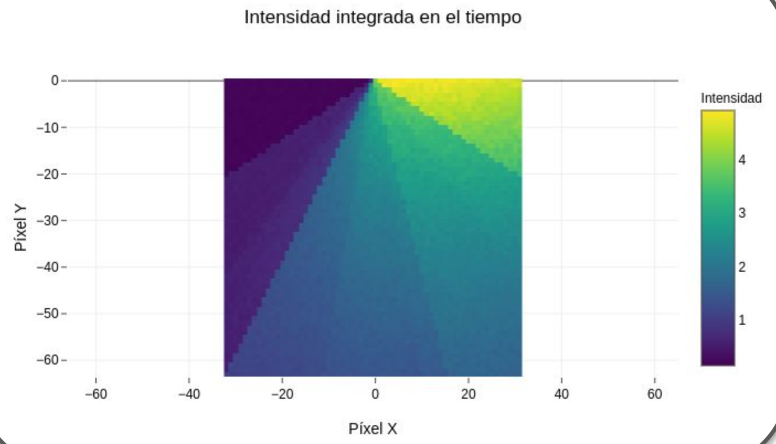


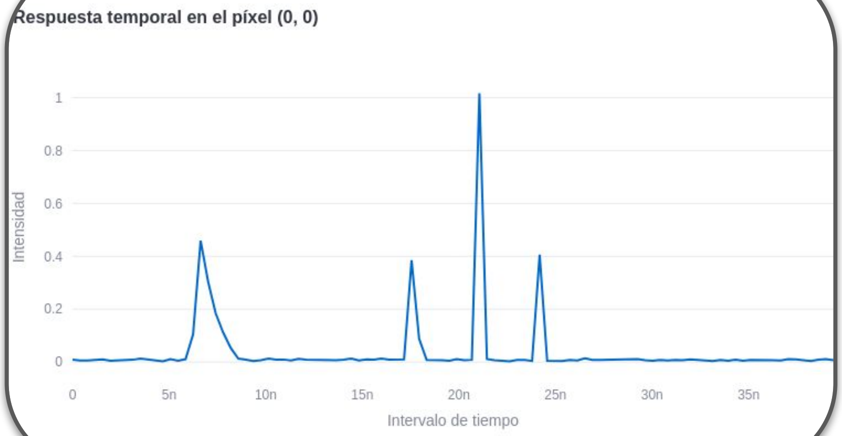


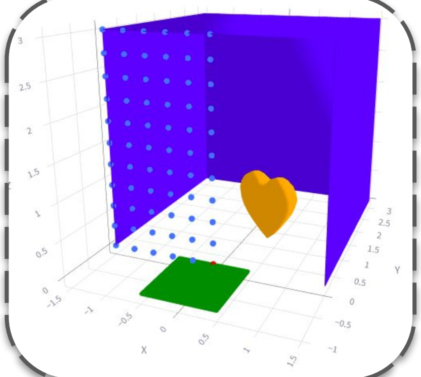
Camera FOV: 1.0 m
Camera Pixel Dimension: 64 x 64 pixels
Bin Size: 3.9e-10 s
Laser intensity: 1000 mW

SNR: 5.0 db
SBR: 0.1 db
Scale factor: 50

Analysis of the Noise Levels



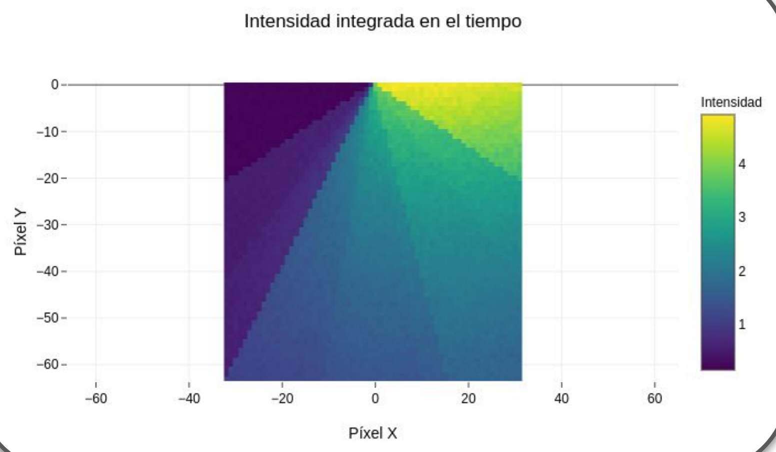


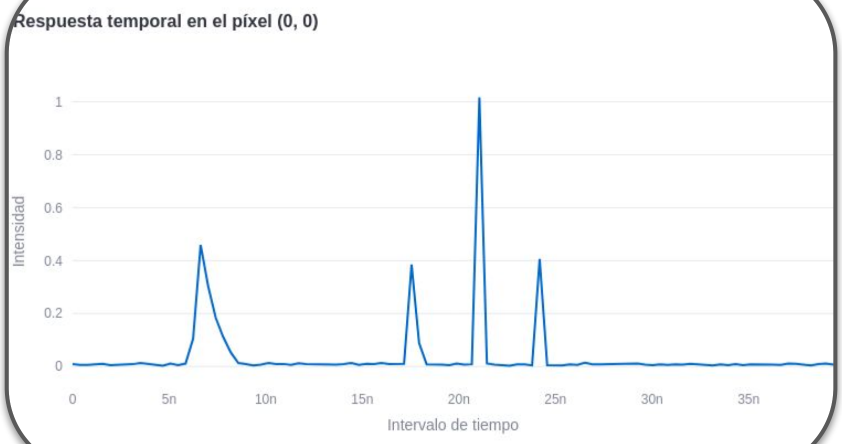


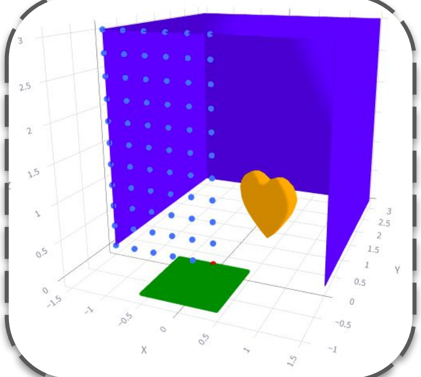
Camera FOV: 1.0 m
Camera Pixel Dimension: 64 x 64 pixels
Bin Size: 3.9e-10 s
Laser intensity: 1000 mW

SNR: 30.0 db
SBR: 5.0 db
Scale factor: 1000

Analysis of the Noise Levels







3. Simular el proceso de conteo de fotones generados por una fuente de iluminación pulsada, por medio de una cámara parametrizada en términos del número de píxeles y resolución temporal.

Validation

Validation

Point object
Delete walls

$$bin = argmax(i_t)$$
$$t = bin \times \Delta_t$$
$$d_o = \frac{t}{2} \times c$$
$$d_e = \|\mathbf{x} - \mathbf{l}\|$$

$$Error = |d_e - d_o|$$

Δ_t $[s]$	**Coordenadas del objeto**	t $[s]$	d_e $[m]$	d_o $[m]$	Error [m]
1×10^{-8}	[1.5, 0.0, 3.0]	2,000	3,3541	2,9979	0.3562
1×10^{-10}	[1.5, 0.0, 3.0]	$2{,}2300 \times 10^2$	3,3541	3,3426	0.0115
1×10^{-12}	[1.5, 0.0, 3.0]	$2{,}2362 \times 10^4$	3,3541	3,3519	**0.0022**
1×10^{-8}	[1.5, 1.5, 3.0]	2,000	3,6742	2,9979	0.6763
1×10^{-10}	[1.5, 1.5, 3.0]	$2{,}4500 \times 10^2$	3,6742	3,6724	0.0018
1×10^{-12}	[1.5, 1.5, 3.0]	$2{,}4506 \times 10^4$	3,6742	3,6738	**0.0004**
1×10^{-8}	[1.5, 3.0, 3.0]	3,000	4,5000	4,4968	0.0032
1×10^{-10}	[1.5, 3.0, 3.0]	$3{,}000 \times 10^2$	4,5000	4,4968	0.0032
1×10^{-12}	[1.5, 3.0, 3.0]	$3{,}002 \times 10^4$	4,5000	4,4998	**0.0002**
1×10^{-8}	[1.5, 1.5, 0.0]	1,000	2,1213	1,4989	0.6224
1×10^{-10}	[1.5, 1.5, 0.0]	$1{,}410 \times 10^2$	2,1213	2,1135	0.0078
1×10^{-12}	[1.5, 1.5, 0.0]	$1{,}412 \times 10^4$	2,1213	2,1165	**0.0048**

Conclusions

Conclusions

The use of triangular meshes allows an adequate and effective simulation process to generate transient images of multiple objects.

The number of parameters in the simulator gives a flexibility to the tool that allows the generation of transient images in a wide variety of scenarios adapted to specific needs.

The use of a GUI, facilitates the interaction with the different parameters of the simulator, the configuration of the scenario and the analysis of the results obtained.

Thank you for your attention