TaCOS: Task-Specific Camera Optimization with Simulation

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Project Page

Camera Design For Perception Tasks

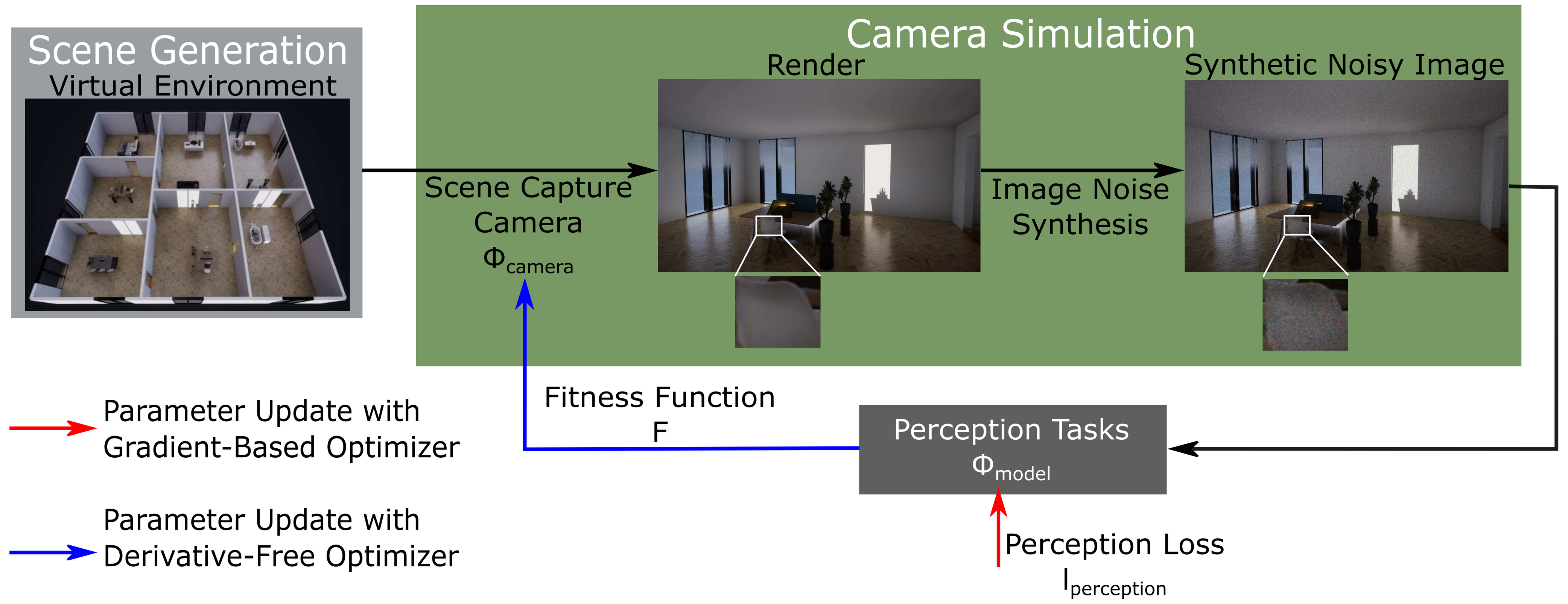
- The performance of perception tasks is influenced by cameras.
- Designing cameras with high performance is costly, requires human labour and hardware experiments.
- Most cameras and perception tasks are designed in isolation.

Previous Works

- Fully differentiable task-specific optics optimization. [1]
  - Cannot optimize camera's resolution, placement, and unconventional cameras such as light field and stereo cameras.
- Task-specific camera optimization with Reinforcement Learning. [2]
  - Long optimization time.

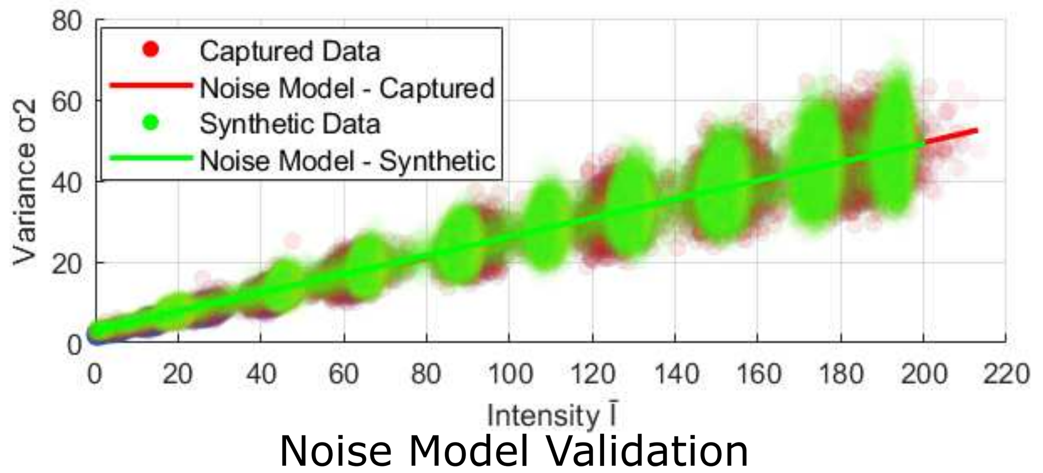
- In this work, we combine derivative-free and gradient-based optimizers to design cameras efficiently while supporting continuous, discrete, and categorical parameters.
- We additionally develop a camera simulation method including a scene capture component and a physics-based noise model, and provide a procedurally generated indoor virtual environment.

Methodology

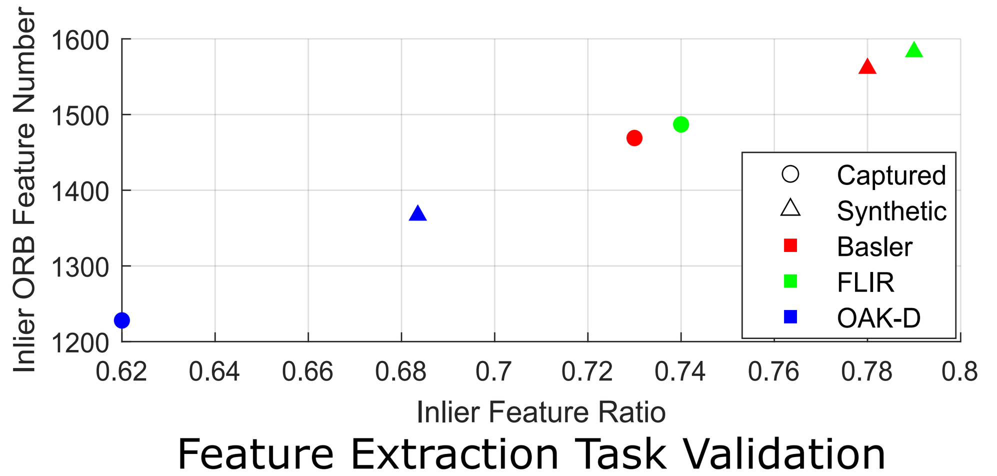


Camera Simulation

- We use the Unreal Engine camera to capture scene renders of simulation environments.
- We incorporate the affine noise model [3] to introduce noise.
- Validation shows our simulation has simular intensity variances and numbers of extracted ORB features with captured images.



Noise Model Validation



Feature Extraction Task Validation

Optimization

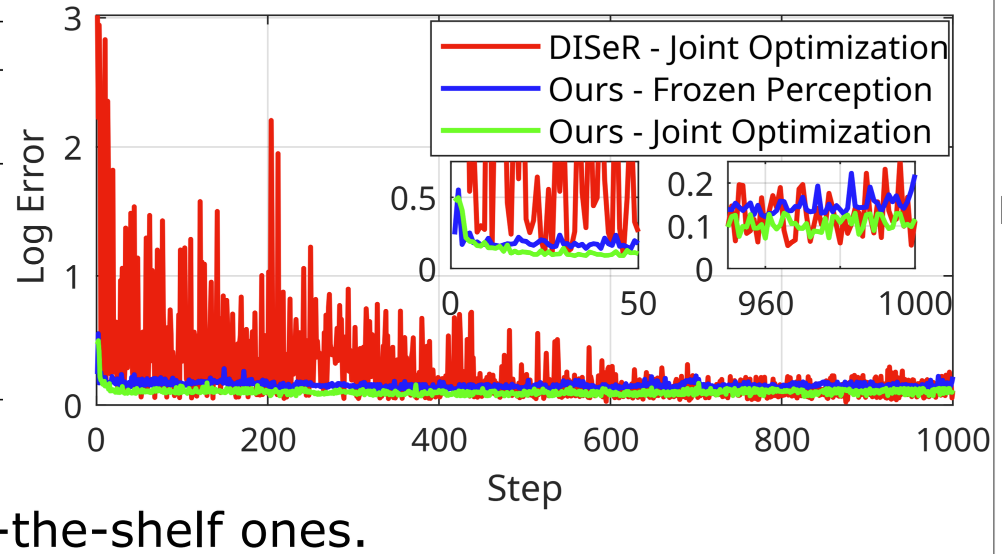
- Camera parameters are optimized with the genetic algorithm, perception tasks are jointly optimized with gradient-based optimizers.
- Discrete camera parameters with interdependency are optimized with the "quantized continuous" method proposed in [1].

Experiment: Stereo Camera Design For Autonomous Vehicle

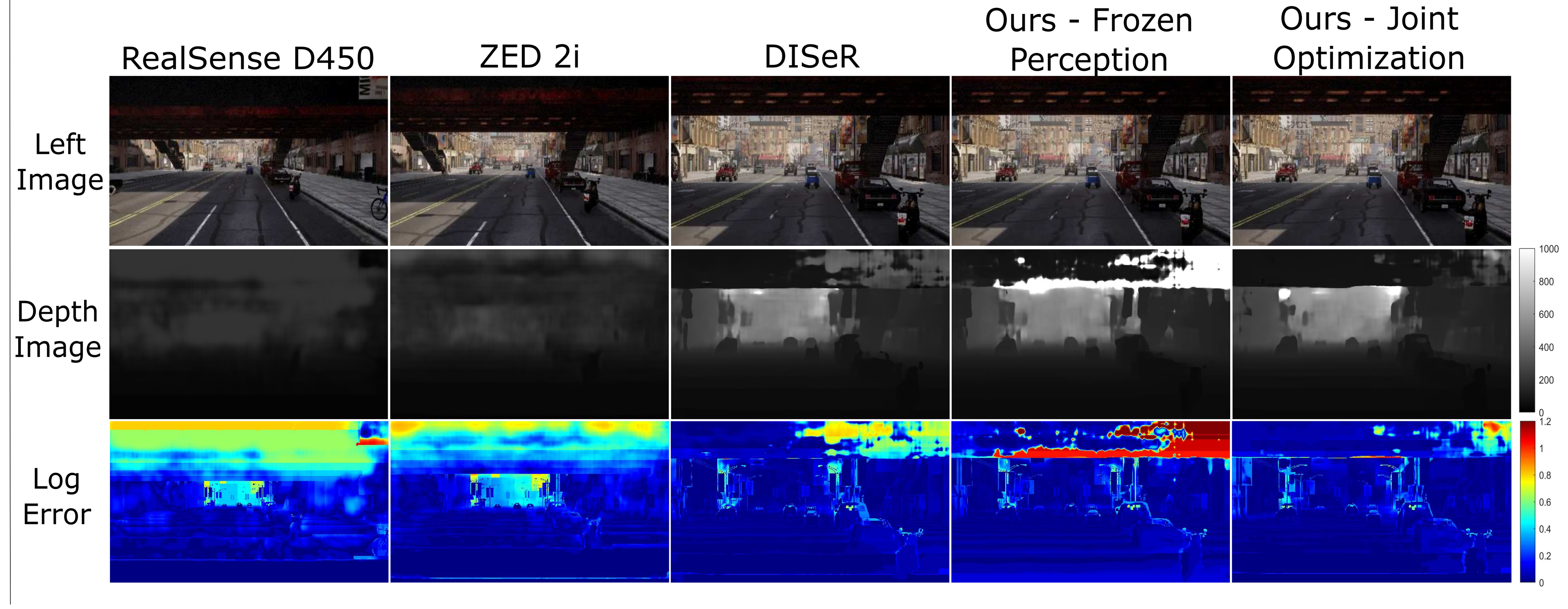
- We optimize the field of view and the baseline distance for a stereo camera pair using the CARLA simulator [4].
- We optimize the stereo camera for depth estimation.

Camera	Camera Parameters		Performance	
	Baseline b (m)	Horizontal FOV fov (°)	Log Error ↓	RMSE ↓
RealSense	0.095 ●	87 ●	0.39 ●	178.94 ●
ZED	0.12 ●	72 ●	0.29 ●	134.74 ●
DISeR	1.84 ●	50 ●	0.16 ●	**75.05** ●
Ours - Frozen	1.41 ●	50 ●	0.19 ●	111 ●
Ours - Joint	1.6 ●	50 ●	**0.14** ●	79.81 ●

● - Optimized ● - Fixed



- TaCOS designs camera that outperforms off-the-shelf ones.
- TaCOS achieves similar performance with the SOTA method DISeR but with fewer optimization steps and less time.
- Jointly optimizing task and camera hardware outperforms isolated optimization.

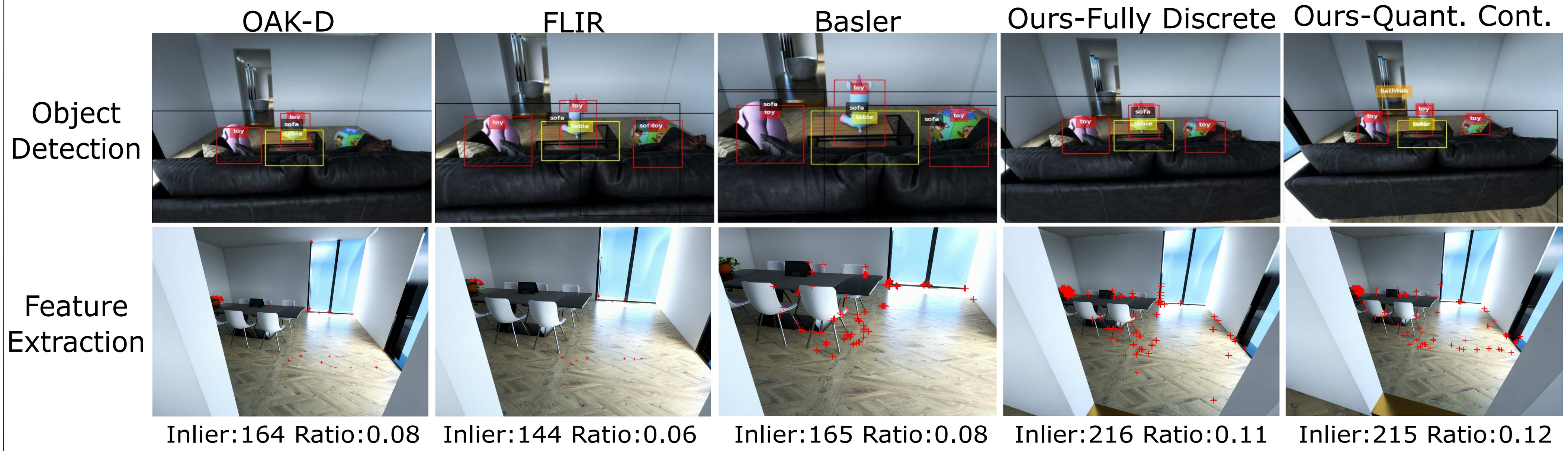


Experiment: Monocular Camera Design For MR Headset

- We optimize the focal length, image sensor, which is a categorical variable including sensor size and pixel size, and camera mounting orientation on the MR headset using our provided procedurally generated indoor environment.
- We optimize the monocular camera for object detection, obstacle avoidance, and feature extraction.

● - Optimized ● - Fixed

Camera	Camera Parameters				Performance			
	Pitch Angle θ (°)	Focal Length f (mm)	Sensor Size $w \times h$ (mm)	Pixel Size p (μm)	Obstacle Detect. Accuracy ↑	Object Detect. AP ↑	Inlier Number ↑	Inlier Ratio ↑
OAK-D	-20.04 ●	2.75 ●	6.29×4.71 ●	1.55 ●	1	0.37 ●	115	0.07
FLIR	-23.28 ●	3.6 ●	6.2×4.65 ●	1.55 ●	1	0.37 ●	77	0.05
Basler	-25.90 ●	3.6 ●	4.8×3.6 ●	3.75 ●	1	0.23 ●	131	0.08
Ours - Fully Discrete	-27.87 ●	4.01 ●	8.45×6.76 ●	6.6 ●	1	0.43 ●	191	**0.13**
	-24.69 ●	3.77 ●	8.45×6.76 ●	6.6 ●	1	0.51 ●	189	0.12
Ours - Quantized Continuous	-21.86 ●	2.99 ●	8.45×6.76 ●	6.6 ●	1	0.46 ●	**230**	**0.13**
	-26.34 ●	2.88 ●	7.31×5.58 ●	4.5 ●	1	**0.64** ●	224	**0.13**



- TaCOS designs cameras outperforms off-the-shelf ones for all tasks.
- The quantized continuous scheme outperforms traditional fully discrete scheme for optimizing categorical variable that includes interdependent variables.
- Jointly optimizing perception task and camera hardware outperforms isolated optimization.

Conclusion & Future Work

- TaCOS is an automatic camera design method that supports continous, discrete, and categorical camera parameters.
- We provide a validated camera simulation method and provide a procedurally generated indoor virtual environment.
- TaCOS can be improved by incorporating an adaptive camera control algorithm for dynamic camera parameters such as auto-exposure.

References

[1] Geoffroi Côté et al., "The differentiable lens: Compound lens search over glass surfaces and materials forobject detection", CVPR 2023.
[2] Tzofi Klinghoffer et al., "DISeR: Designing imaging systems with reinforcement learning", ICCV 2023.
[3] Alessandro Foi, "Clipped noisy images: Heteroskedas-tic modeling and practical denoising", Signal Processing 2009.
[4] Alexey Dosovitskiy et al., "CARLA: An open urban driving simulator", CoRL 2017.