Mozart: A Mobile ToF System for Sensing in the Dark through Phase Manipulation

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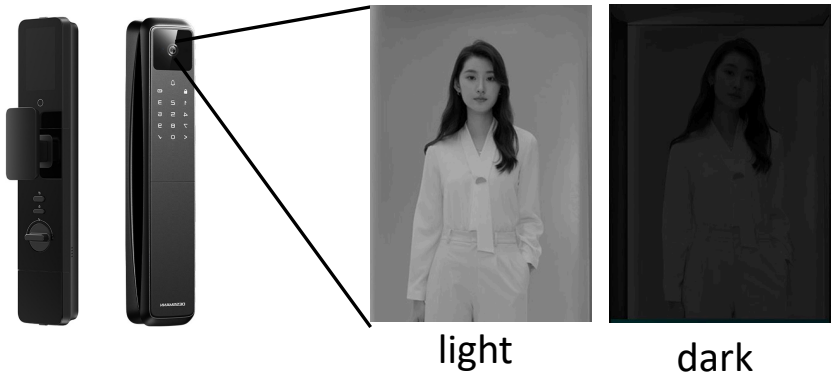
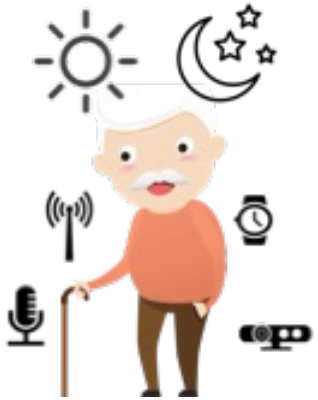
Sensing in the Dark: Applications



Smart door lock

Patrol robot

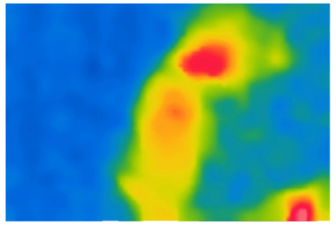


7/24 health monitoring

Security and surveillance

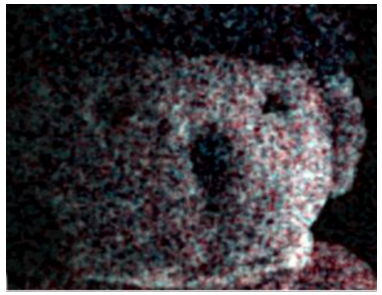
Sensing in the Dark: Current Solutions

Passive Sensing



Thermal camera

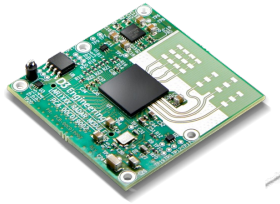
❌ low resolution

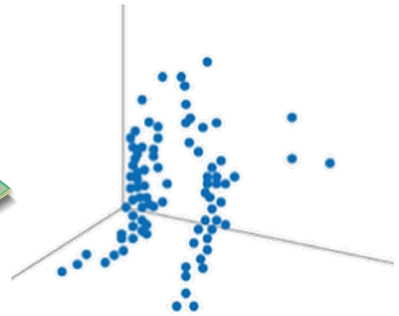


Enhanced RGB camera

❌ high noise

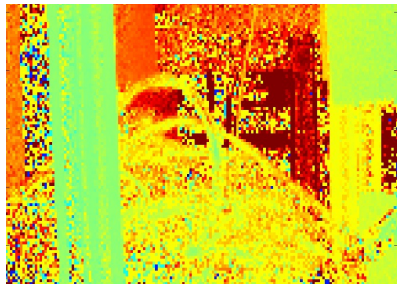
Active Sensing





mmWave radar

❌ sparse point cloud



ToF depth camera

❌ low quality

Mozart: Sensing in the Dark with ToF Camera

ToF Cameras

Kinect

Original Functionality

Depth Image

Smartphone

Vision pro

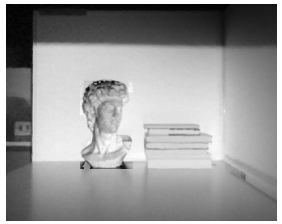
Mozart

Mozart Image

Key idea: exposing texture information from ToF cameras.

Designing Mozart: Challenges

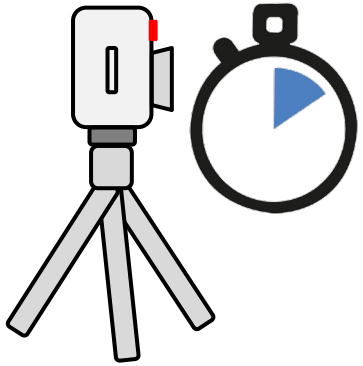
- Improve texture resolution while retaining depth measurement.

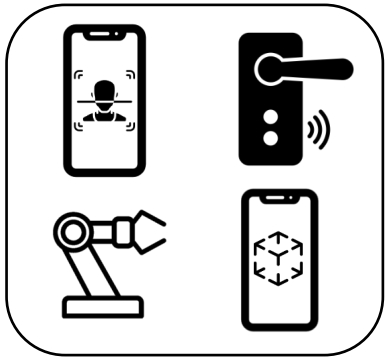


Mozart image

Depth image

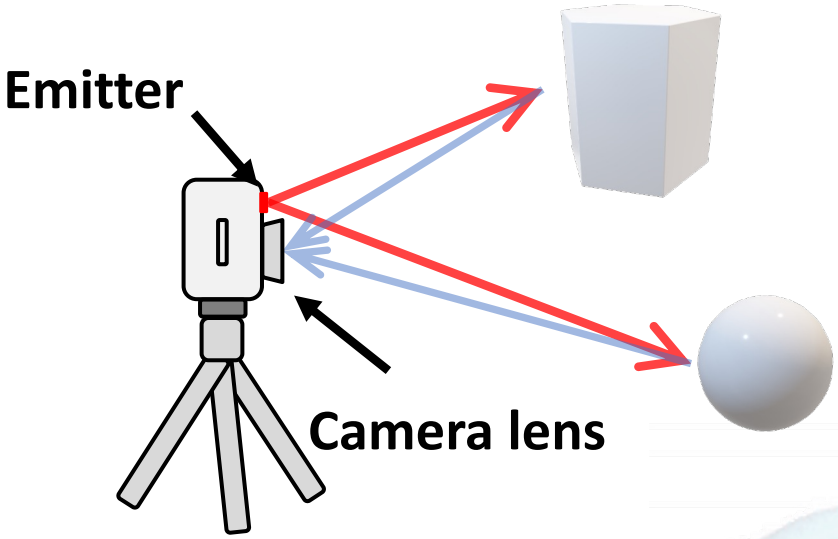
- Generate high quality images in real time.

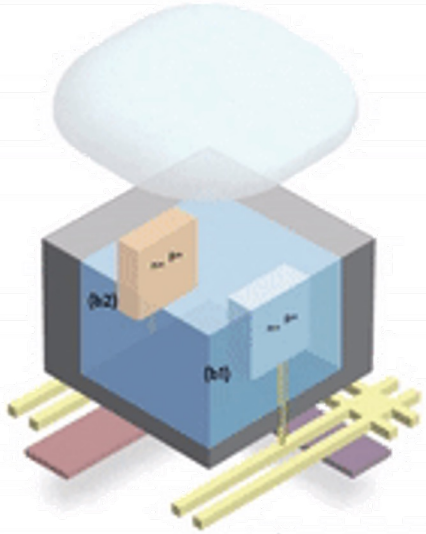


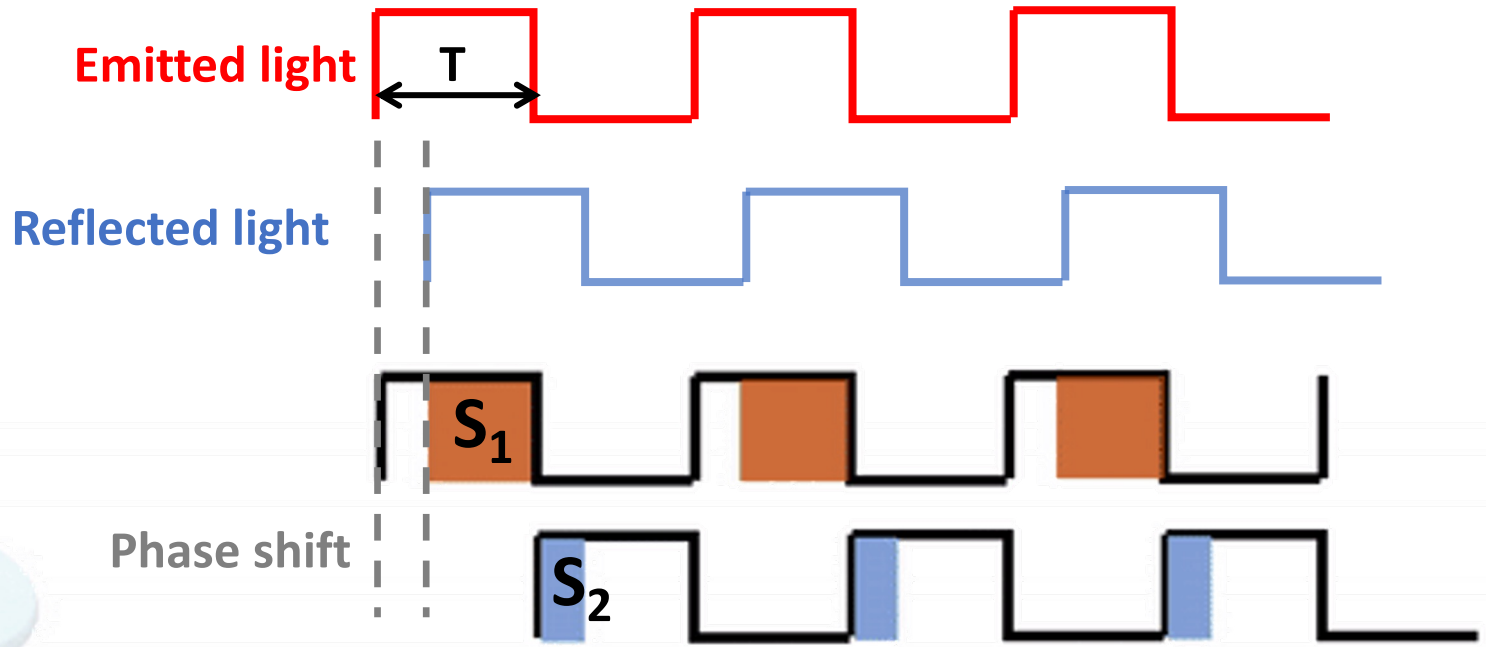


Real-time applications in the dark

Understanding ToF Depth Sensing

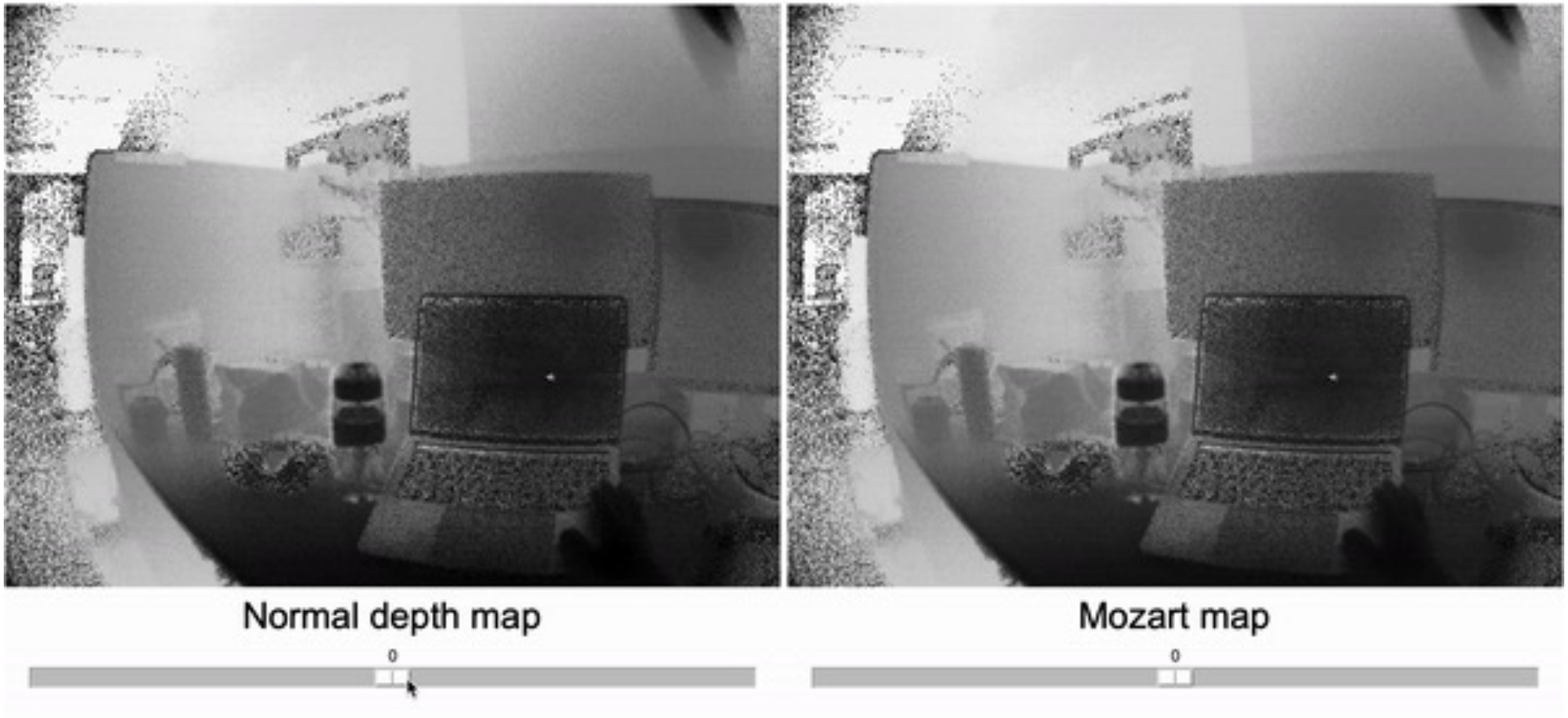






$$\text{distance} = \frac{S_2}{S_1 + S_2} \cdot \frac{cT}{2}$$

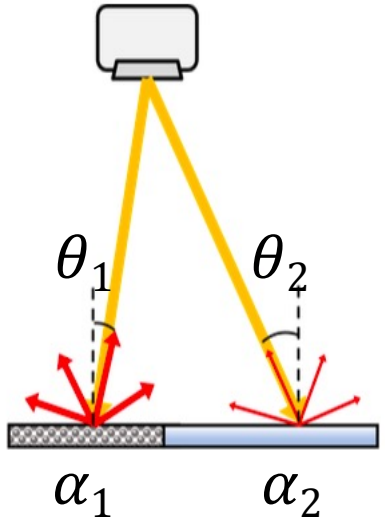
Expose Textures via Phase Manipulation



ΔS_1 ΔS_2

Mozart: Physics Model for Exposing Textures

Lambertian reflection model



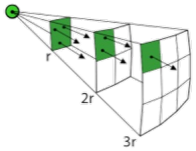
α: reflectivity
θ: angle of incidence

Texture-related

Albedo: $\beta = \alpha \cos\theta$

The phase components S_1 and S_2 can be represented by albedo β and distance d.

Monotonicity



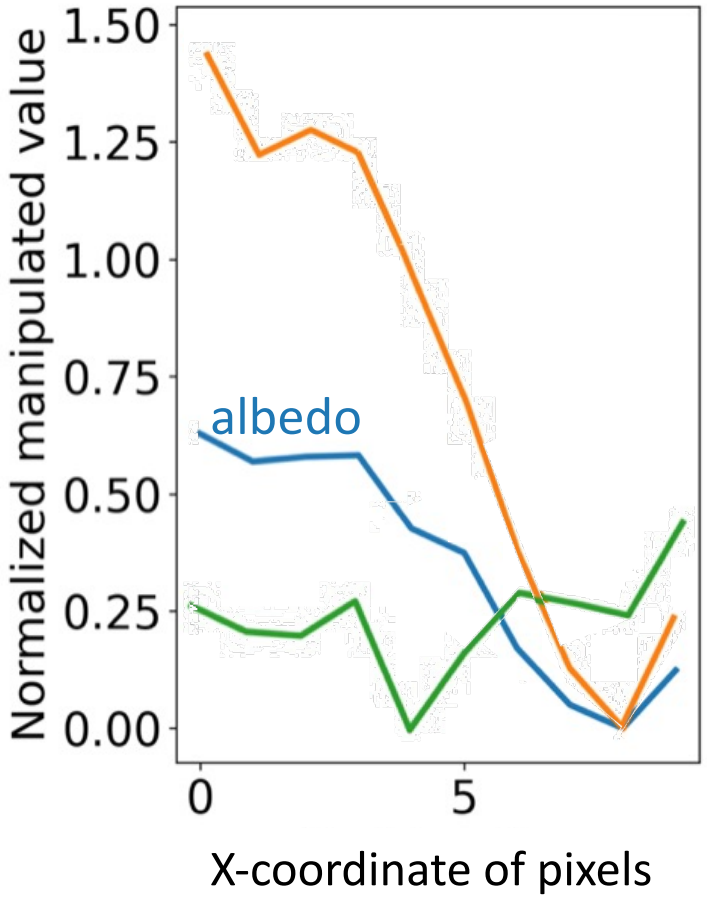
Impact of Distance

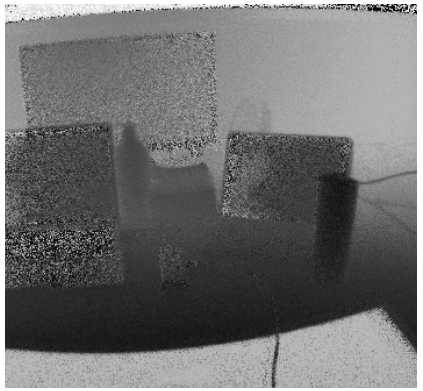
Lambertian Reflection Model

Total Reflection

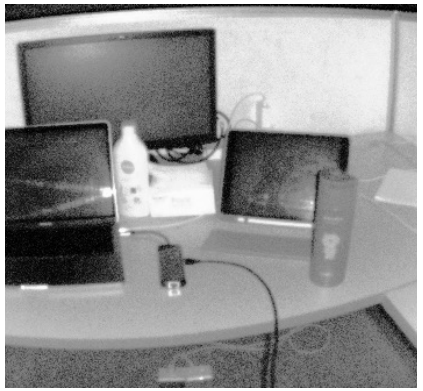
Observation 1: Monotonicity to Albedo

Monotonicity



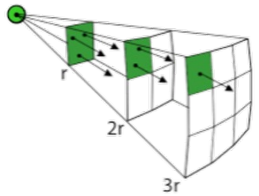


Non-monotonic to albedo



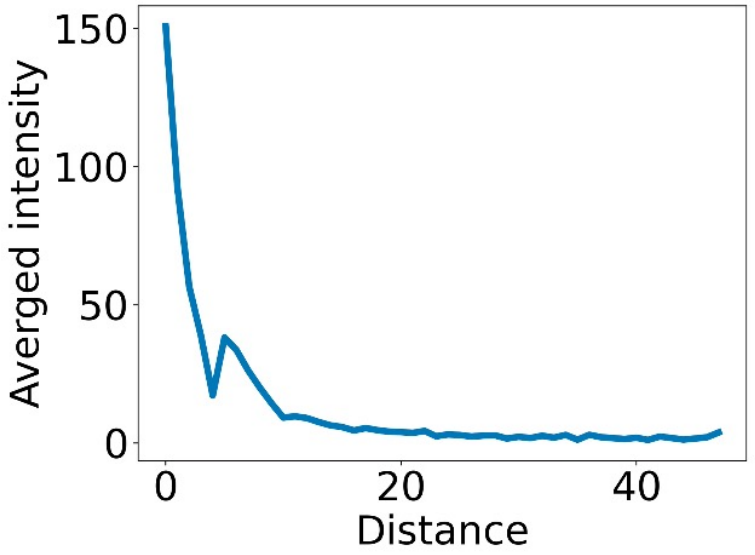
Monotonic to albedo

Observation 2: Impact of Distance



Impact of Distance

A typical image after phase manipulation

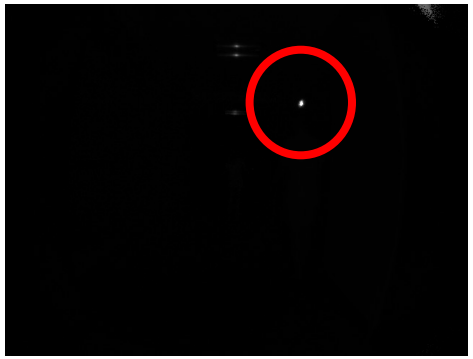


The phase components are reversely proportional to the square of distance.

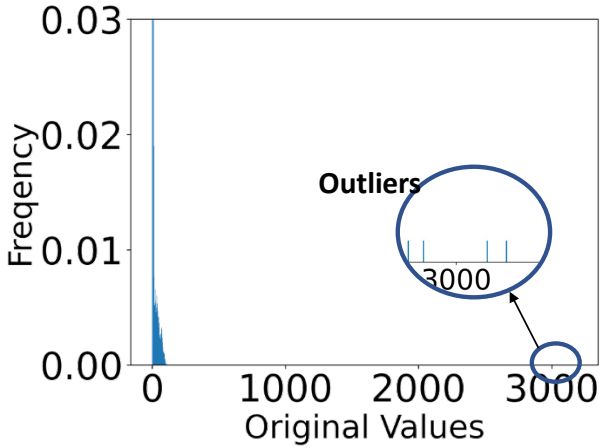
Observation 3: Addressing Total Reflection

Total Reflection

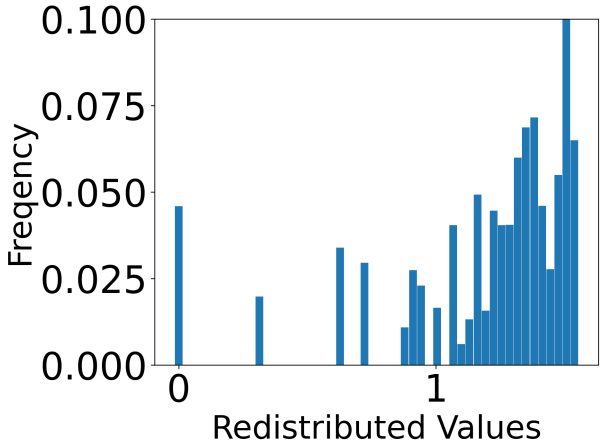
With total reflection



Caused by objects like metals and glass



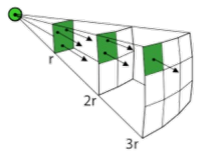
Total reflection mitigated



Mozart: Phase Manipulation Functions

Monotonicity

The phase manipulation functions must satisfy: $\frac{\partial f(S_1, S_2)}{\partial \beta} > 0$



Impact of Distance

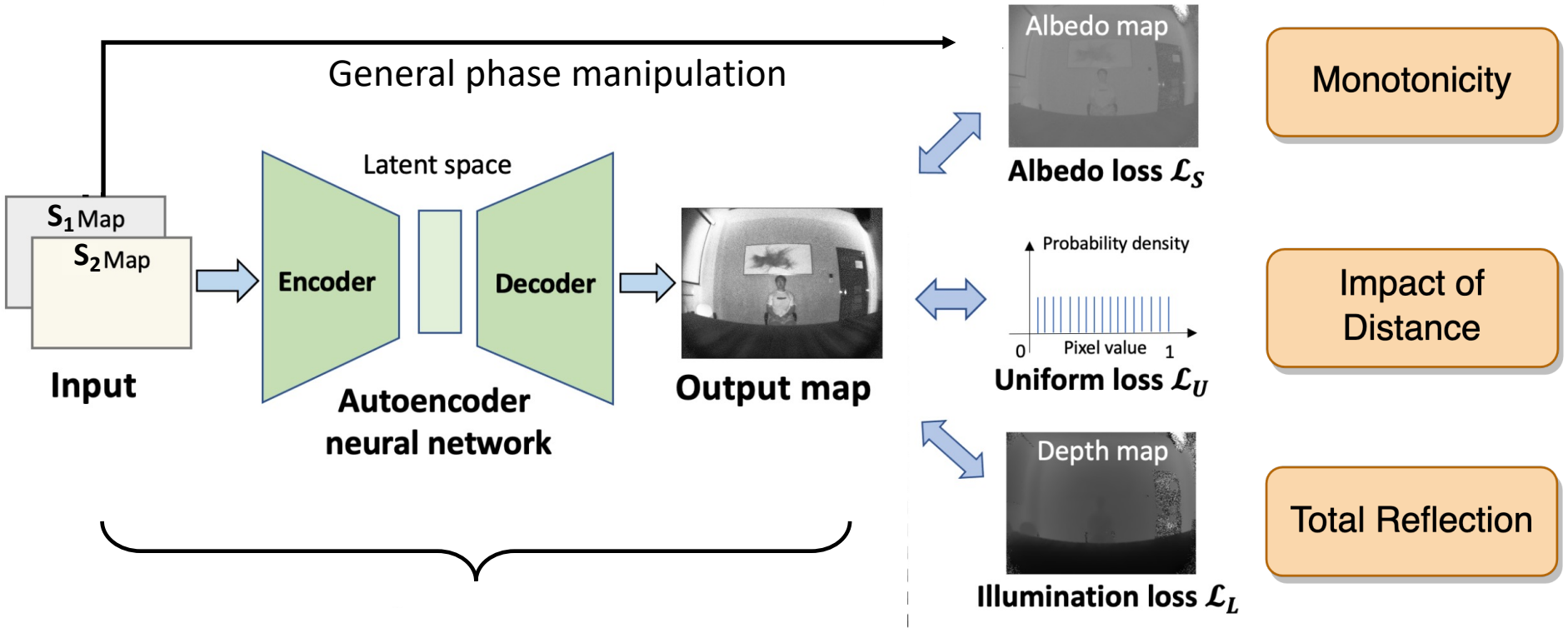
Choose a $f(S_1, S_2)$ from the variants of $g(S_1, S_2) = \frac{S_2^2}{S_1 + S_2} = \frac{E_0}{8D^2} \cdot \beta$

Total Reflection

Nest the redistribution function $r(S)$ outside $f(S_1, S_2)$

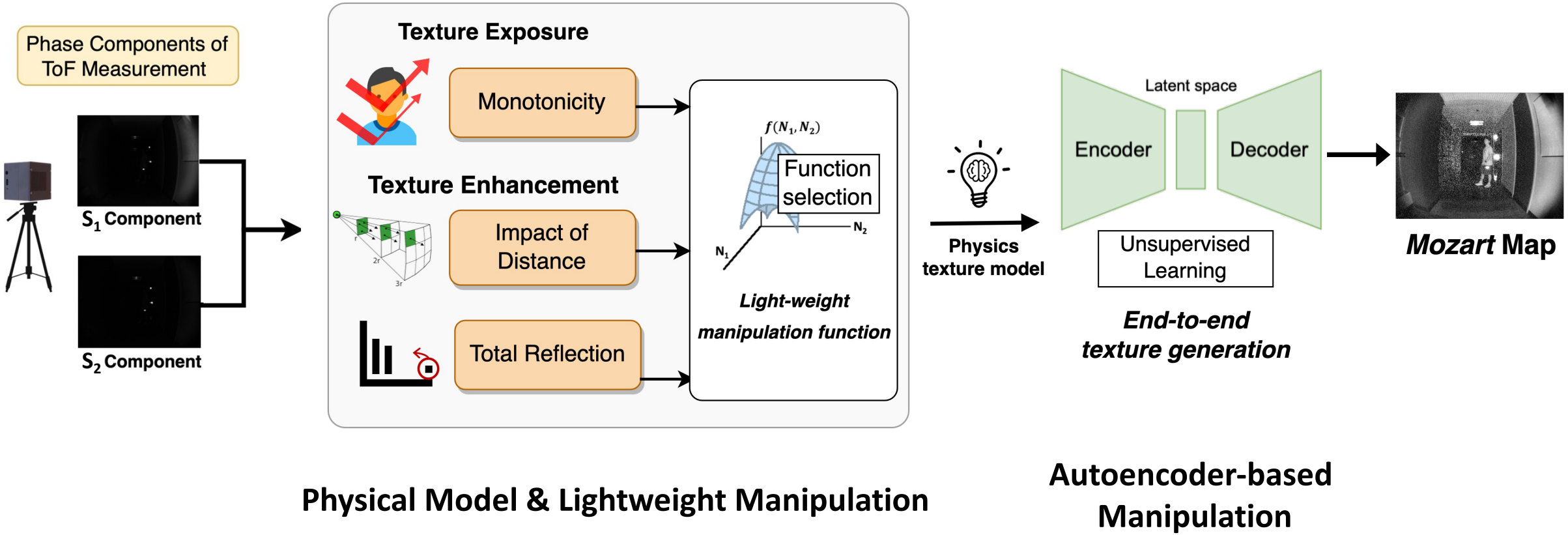
Lightweight, but requires domain expertise.

Mozart: ML-based Phase Manipulation



$$\mathcal{L} = \lambda_s \mathcal{L}_S + \lambda_l \mathcal{L}_L + \lambda_u \mathcal{L}_U$$

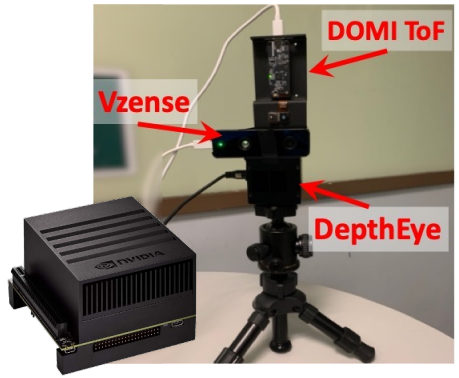
Mozart: Put it all together



System Implementation & Dataset

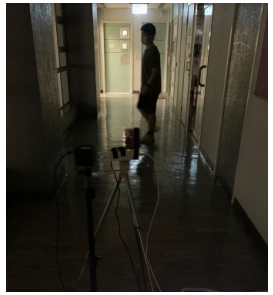
- Various platform

Samsung S20Ultra &
HUAWEI Mate30 Pro
(ARCore / AREngine)



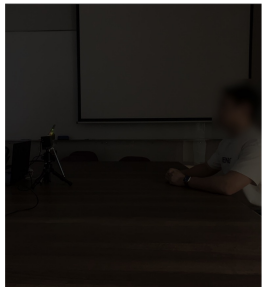
Standalone ToF cameras with
Nvidia Jetson Xavier

- Self-collected Dataset



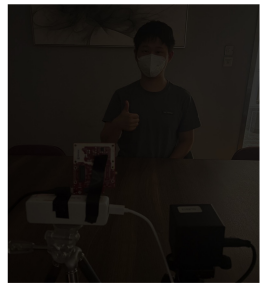
Human tracking

9 8000



Face recognition

12 15000

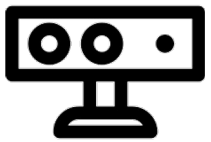


Gesture recognition

12 20

- Baselines (Five modalities)

IR



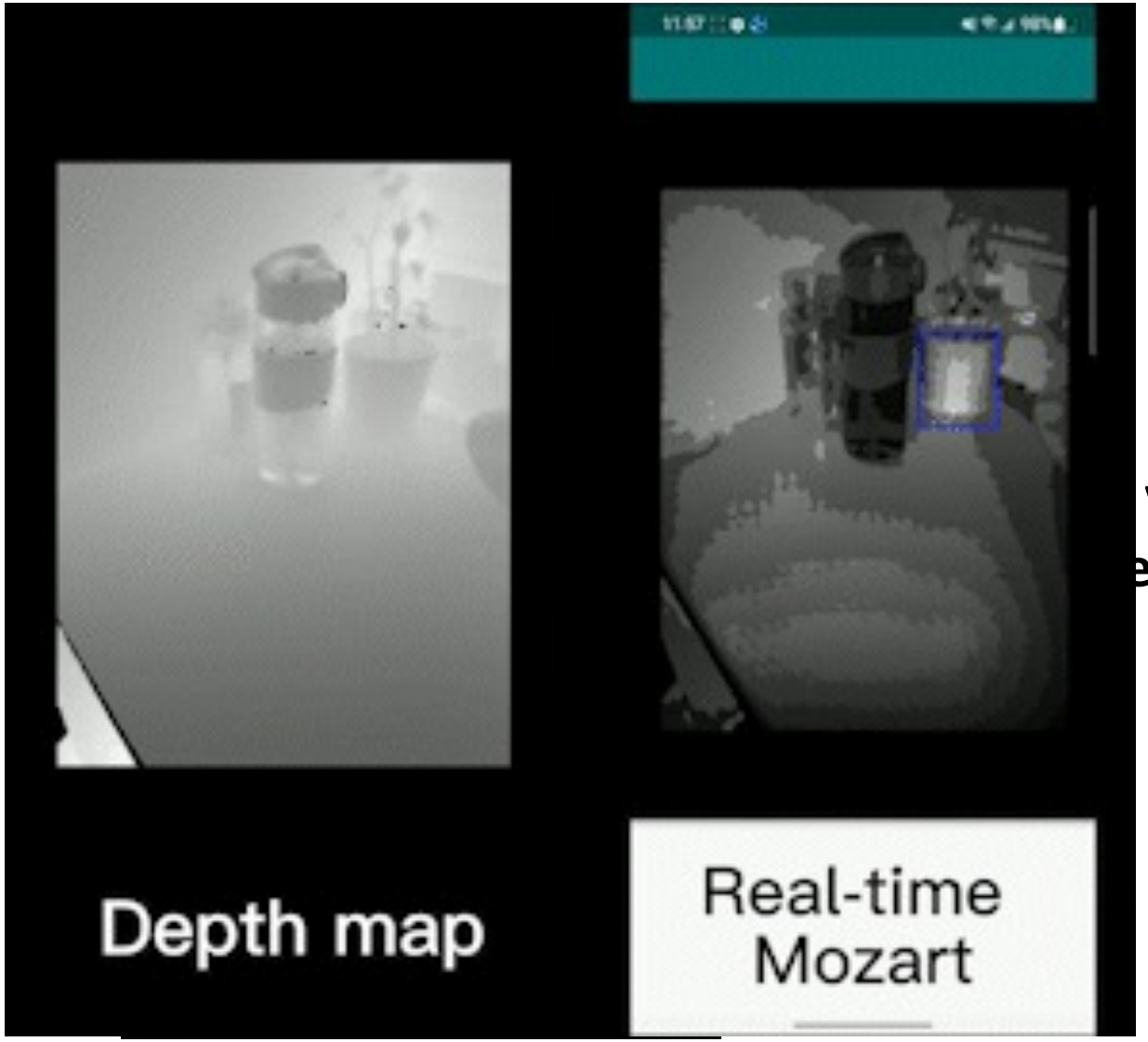
Depth

Radar

RGB

Enhanced RGB

A Real-time Demo

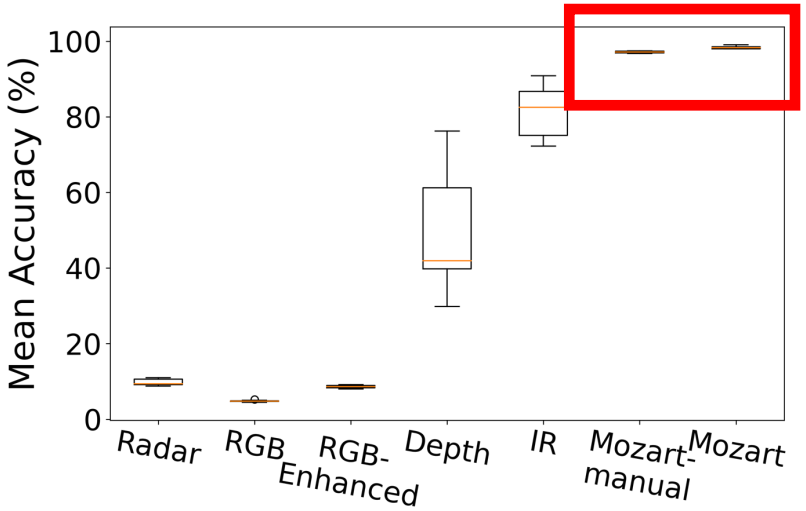


view of
e dark

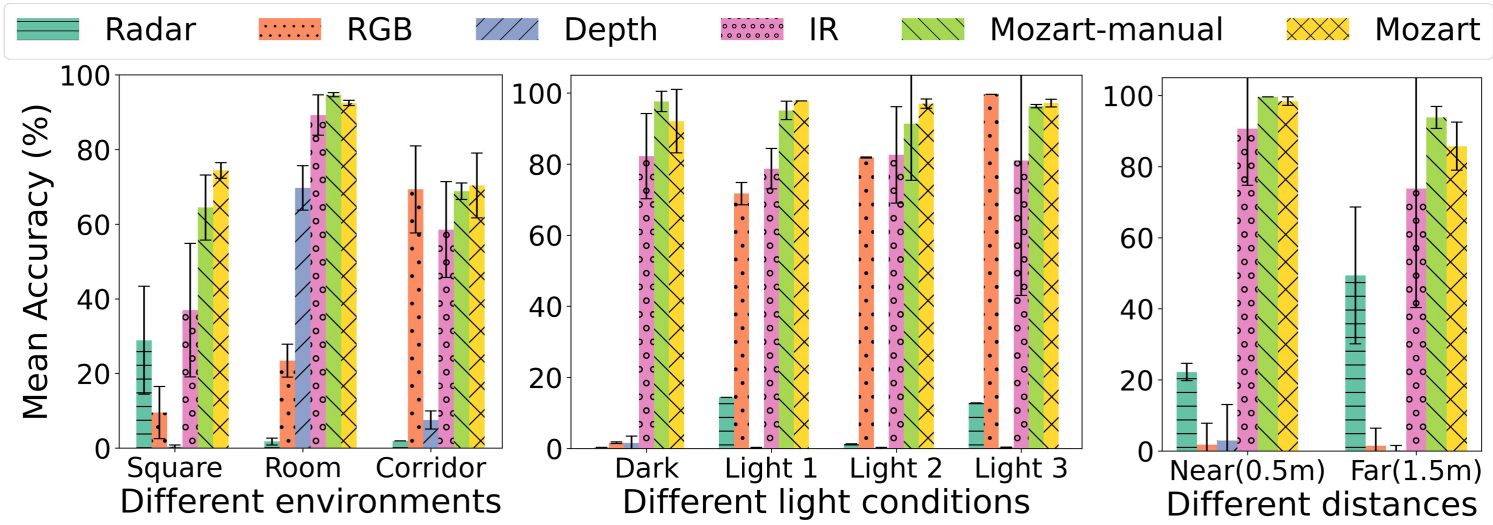
Object detection rate:

- Depth: 7%
- Mozart: 89%

Comparison with Different Modalities



Gesture recognition

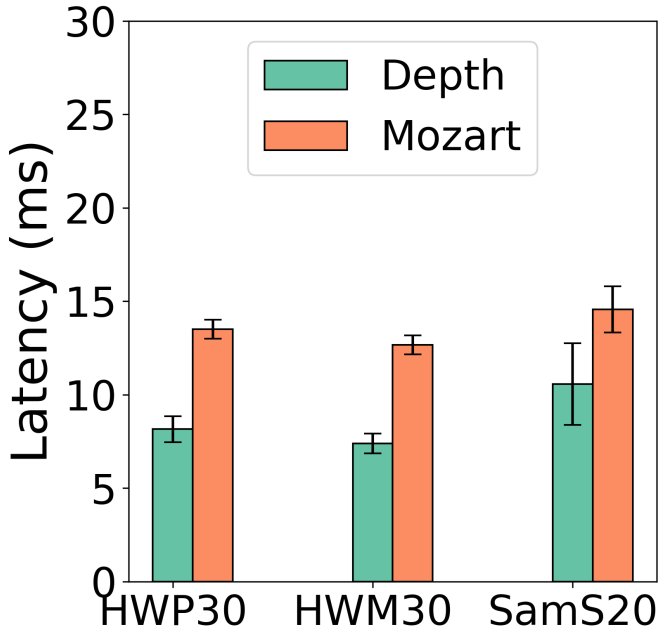


Mozart outperforms RGB, Radar, and depth images by **93.4**%, **88.46**%, and **45.76**%, respectively.

Mozart is robust to various environments, light conditions, and distances.

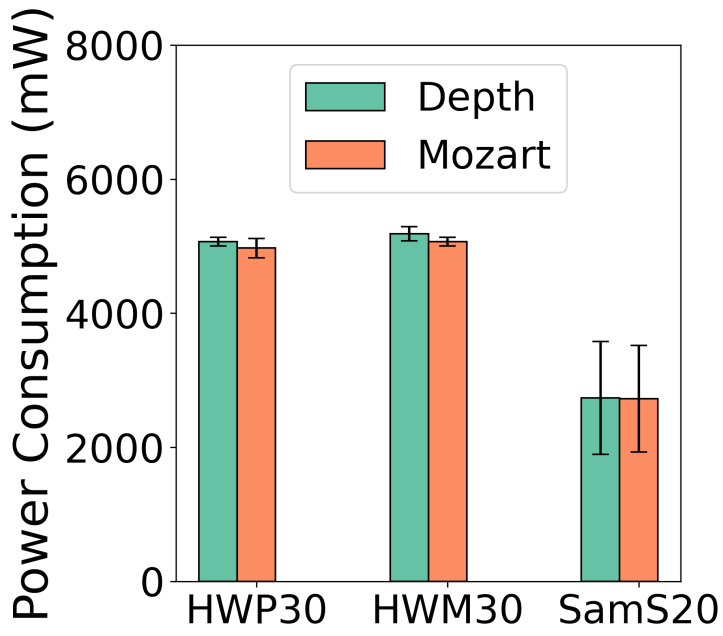
Overhead on Smartphones

➢ Latency



- Achieve more than 30 fps on smartphones

➢ Power consumption

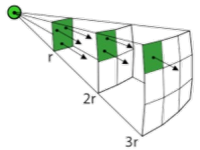


- Does not significantly increase overhead

Conclusion

- *Mozart*: a novel system for sensing in the dark using ToF cameras.
  - First-principle physical models to expose high-resolution textures from ToF cameras.

Monotonicity



Impact of Distance

Total Reflection

- Future work
  - Apply Mozart maps in multi-modality vision algorithms
  - Enable new mobile sensing and vision systems

Thanks!

- Mozart: A Mobile ToF System for Sensing in the Dark through Phase Manipulation

- Zhiyuan Xie*, Xiaomin Ouyang*, Li Pan, Wenrui Lu, Xiaoming Liu, and Guoliang Xing

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