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Depth Correction for Time-of-Flight Camera Using Depth Distortion Dependency on Pulse Width of Irradiated Light

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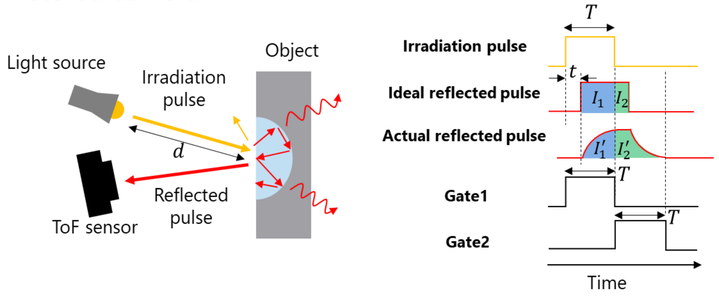
1. Time-of-Flight (ToF) camera

- A kind of 3D camera that estimates depth based on round-trip time of light
- Low cost, high speed, and compact form due to simple measurement system
- It's possible to acquire depth of no texture regions, unlike stereo camera



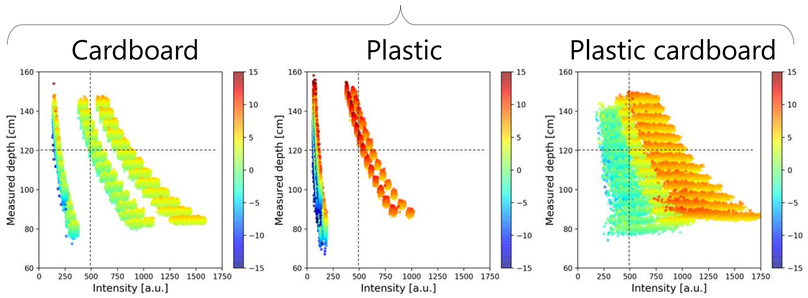
Round-trip time $t = \frac{I_2}{I_1 + I_2} T$ ➡ Measured depth $d = \frac{tc}{2}$

2. Drawback of ToF camera: Depth Distortion

- A kind of depth error depending on material of object
- Mainly caused by optical phenomenon (reflection, scattering, transmission, etc.)
- Difficult to model depth distortion process, so machine learning approach is commonly used for depth correction
- However, **depth error is not uniquely determined** from measured depth & intensity for diverse materials

Conventional method[1] using measured depth & intensity **may not work well**

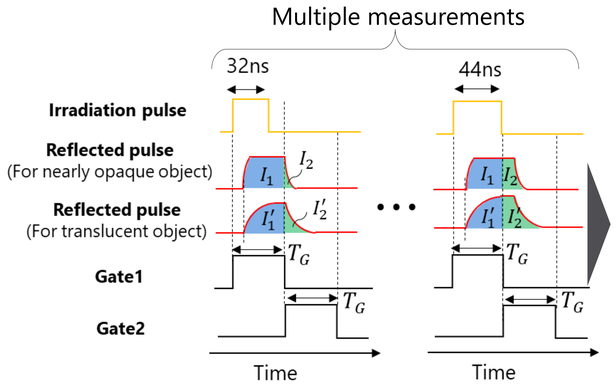
Depth error map(x-axis: intensity, y-axis: measured depth)



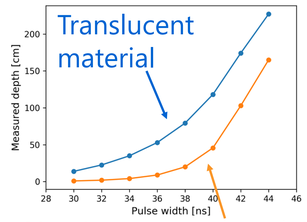
3-1. Our Method: Feature Extraction

- Measure multiple depths using **multiple pulse width** by fixing Gate1,2 (unusual setting)
- **No sweeping** unlike similar method [2,3]
- We confirmed proposed **feature vector depends on material** by simulation and formula

Easily applied to real-world application



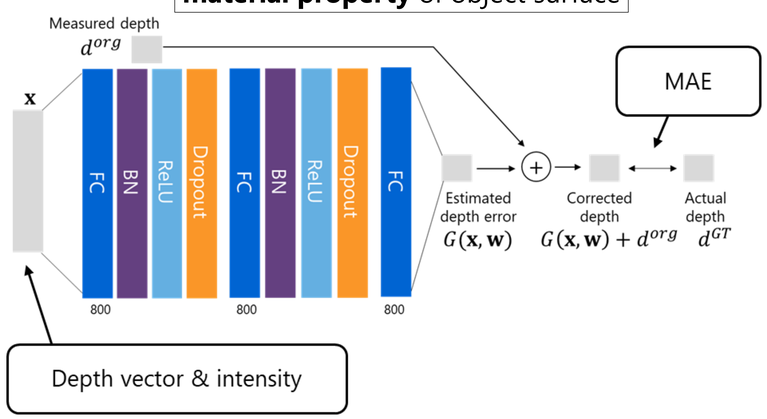
Examples of depth vector



3-2. Our Method: Depth Correction

- 3-layer MLP (hidden layer of 800 units)
- Train MLP by minimizing MAE between corrected depth and actural depth

Estimate depth error by utilizing **material property** of object surface



Direct manner may deal with **unknown material*** by utilizing similarity of intermediate features

*)Not exactly same but similar materials in training data

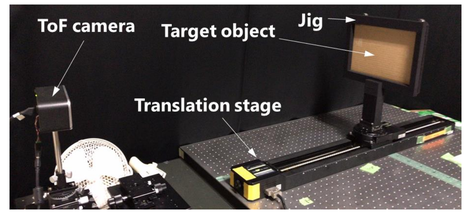
4. Experimental Setup

ToF camera

- Model: In-house prototype using Panasonic's ToF sensor (MN34902BL)
- Pulse widths: 30,32,⋯,44ns (8 pattern)
- # of frames: 300
- Calibrate measured value[a.u.] into measured depth[cm] based on depth of reference subject

Object for training data

- Material: 10 cardboards, 4 plastic boards, 8 plastic cardboards
- Distance from ToF camera : 85,90 ,⋯, 140cm (12 pattern)
- Fixed parallel to the sensor surface using photo frame-like jig

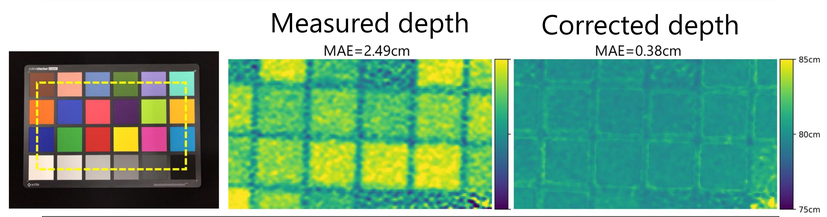


5. Results

Method	MAE$_{mean}$ / MAE$_{max}$[cm]			
	Cardboard	Plastic	Plastic cardboard	All
w/o correction	3.05 / 3.69	6.57 / 9.86	5.25 / 6.83	4.25 / 9.86
Method in [1]	0.55 / 1.60	1.59 / 1.96	**0.54** / **0.98**	0.73 / 1.96
Method in [1]*	0.71 / 1.37	0.96 / 1.63	0.61 / 1.24	0.70 / 1.63
Ours	**0.43** / **0.55**	**0.94** / **1.19**	0.72 / 1.04	**0.64** / **1.19**

*Using MLP instead of Random Forest

Ours outperforms conventional method



Ours works well for **slightly different materials** from trainging data

Material in training data			MAE$_{mean}$ on test material [cm]		
Cardboard	Plastic	Plastic Cardboard	Cardboard	Plastic	Plastic cardboard
✓			0.24	**4.01**	2.38
✓	✓		0.33	0.82	2.28
✓		✓	0.33	**2.93**	0.69

Ours works well for **unknown material**

[1] P. Fuersattel et al.(2017), "Distance error correction for time-of-flight cameras"
[2] Y. Iwaguchi et al.(2016), "Classification of Translucent Objects Using Distance Measurement Distortion of Time-of-Flight Camera as a Cue" [Translated from Japanese.]
[3] K. Tanaka et al.(2017), "Material Classification Using Frequency- and Depth-Dependent Time-of-Flight Distortion"