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

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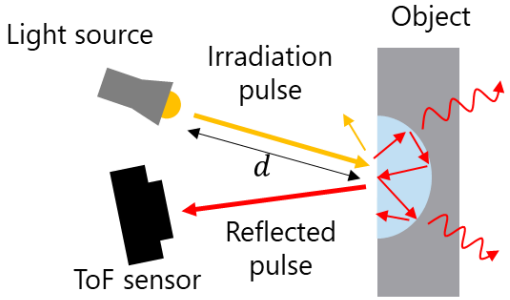
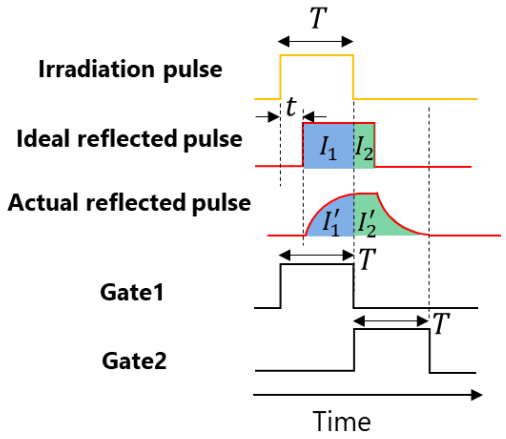
Background

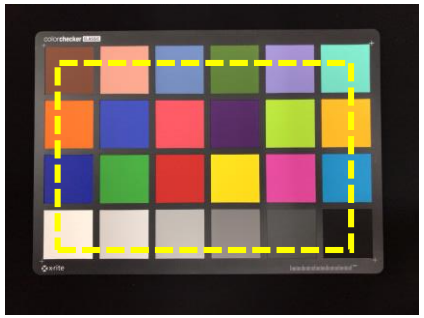
- Time-of-Flight (ToF) Camera
  - A kind of 3D camera that estimates depth based on round-trip time of light
  - Low cost, high speed, and compact form due to simple measurement system
- Drawback: Depth Distortion
  - A kind of depth error depending on material of object
  - Mainly caused by optical phenomenon (reflection, scattering, transmission, etc.)



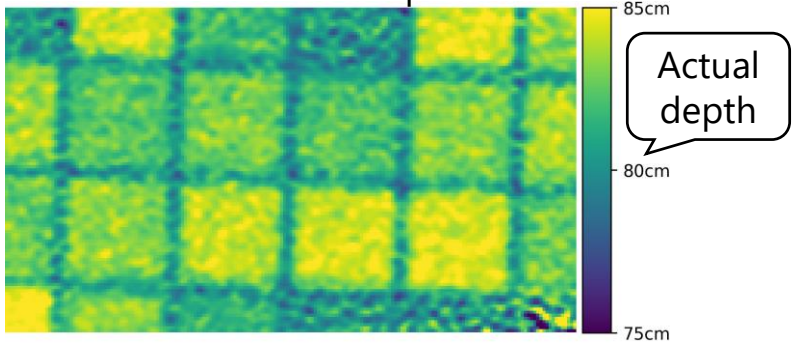


Round-trip time $t = \frac{I_2}{I_1 + I_2} T$ ➡ Depth $d = \frac{tc}{2}$

RGB image

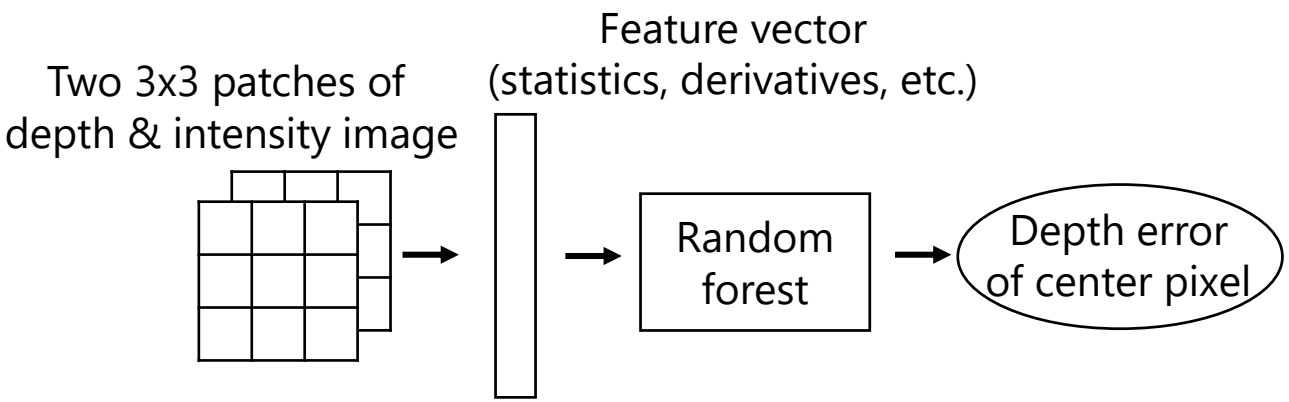


Measured depth



Difficult to model depth distortion process,
so machine learning approach is commonly used for depth correction

Conventional Depth Correction Method(1): [Fuersattel+,2017]

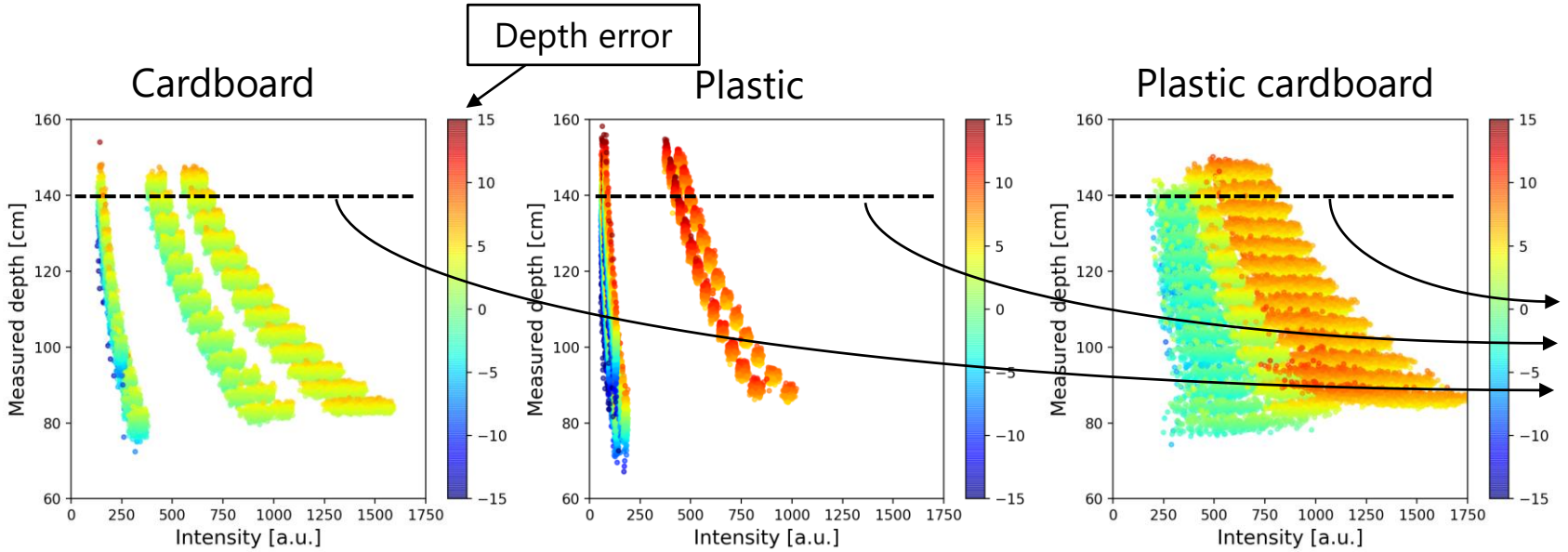


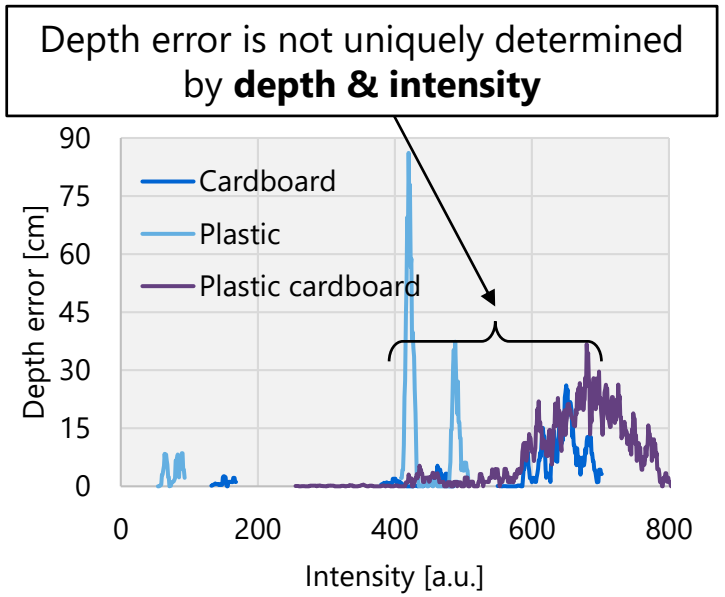
Method

- Calculate feature vector from **depth & intensity**
- Train random forest regressor to estimate depth error

Limitation

- **Doesn't** consider material property explicitly





This method may not work well for diverse materials

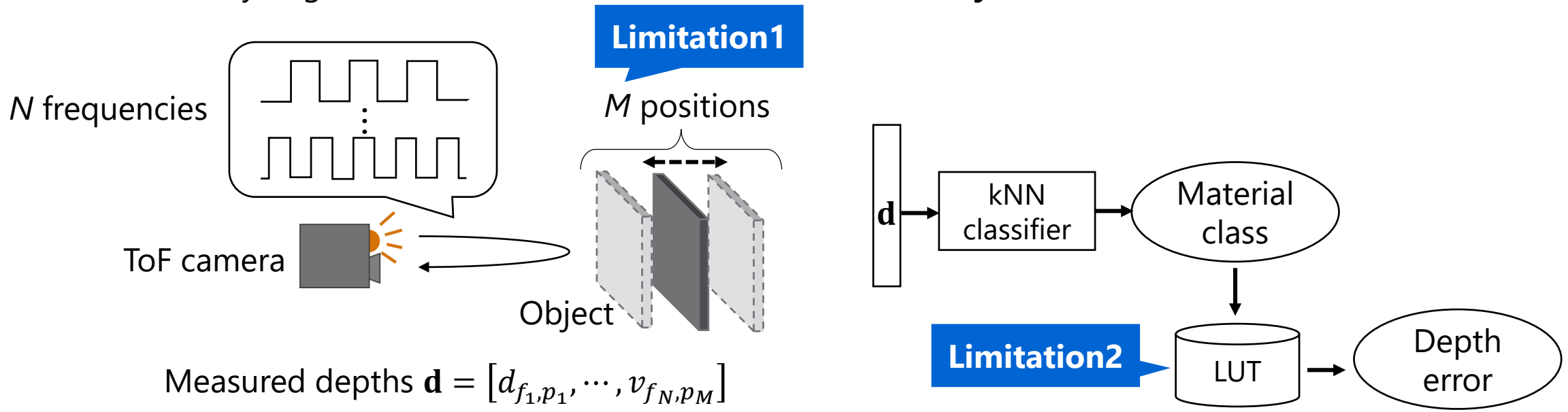
Conventional Depth Correction Method(2): [Tanaka+,2017]

Method

- Measure multiple depths (**not 1-shot**) containing material property using **multiple frequencies & positions**
- Estimate material, then get depth error from LUT using material as query

Limitation

- Require sweeping (**camera and object are fixed** in many industrial applications)
- Performace may degrade for unknown materials (LUT includes **only known materials**)



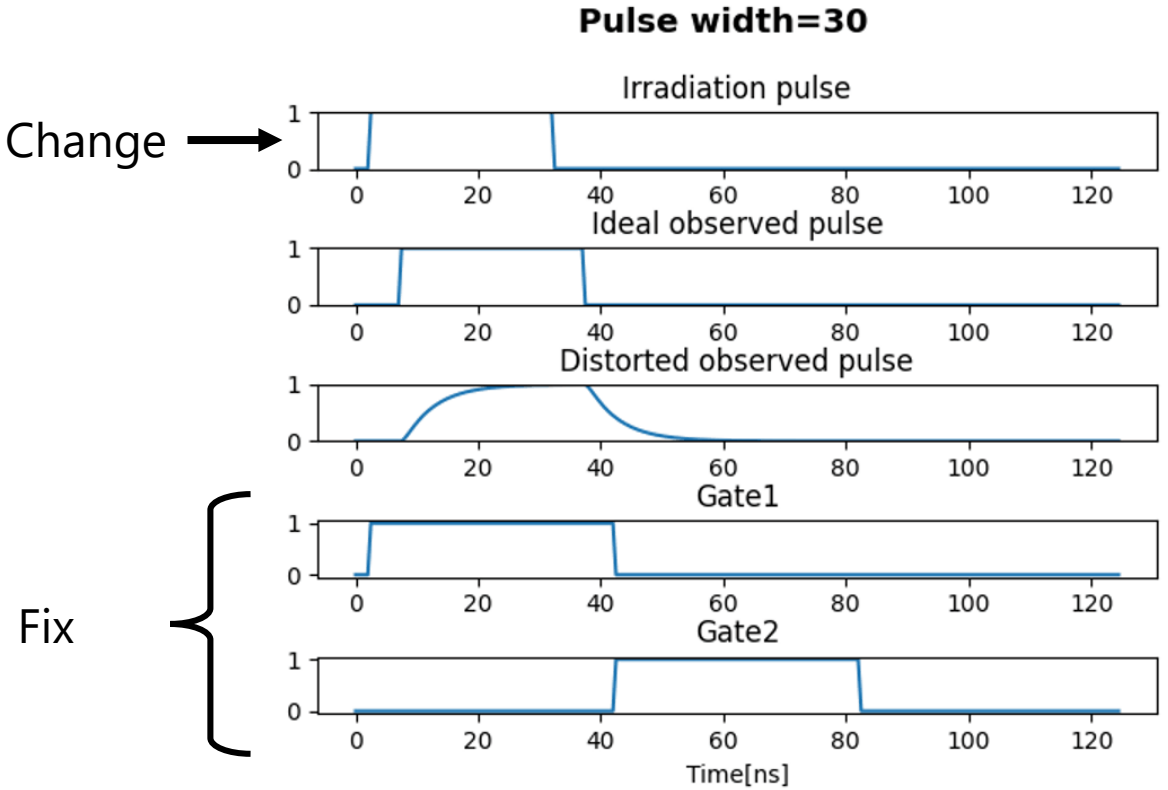
Proposed method can overcome these limitation because of:
1) no sweeping in feature extraction
2) direct estimation w/o material classification

Proposed Method: Feature Extraction

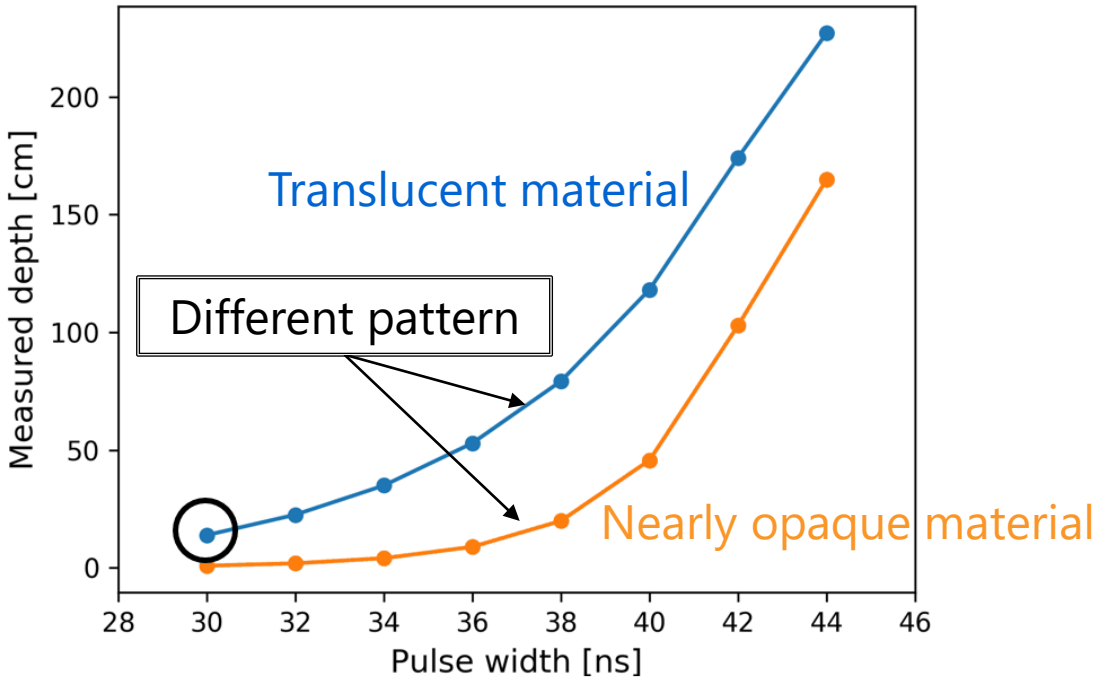
Utilize property that depth changes with pulse width of irradiation light and material

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

Measurement procedure



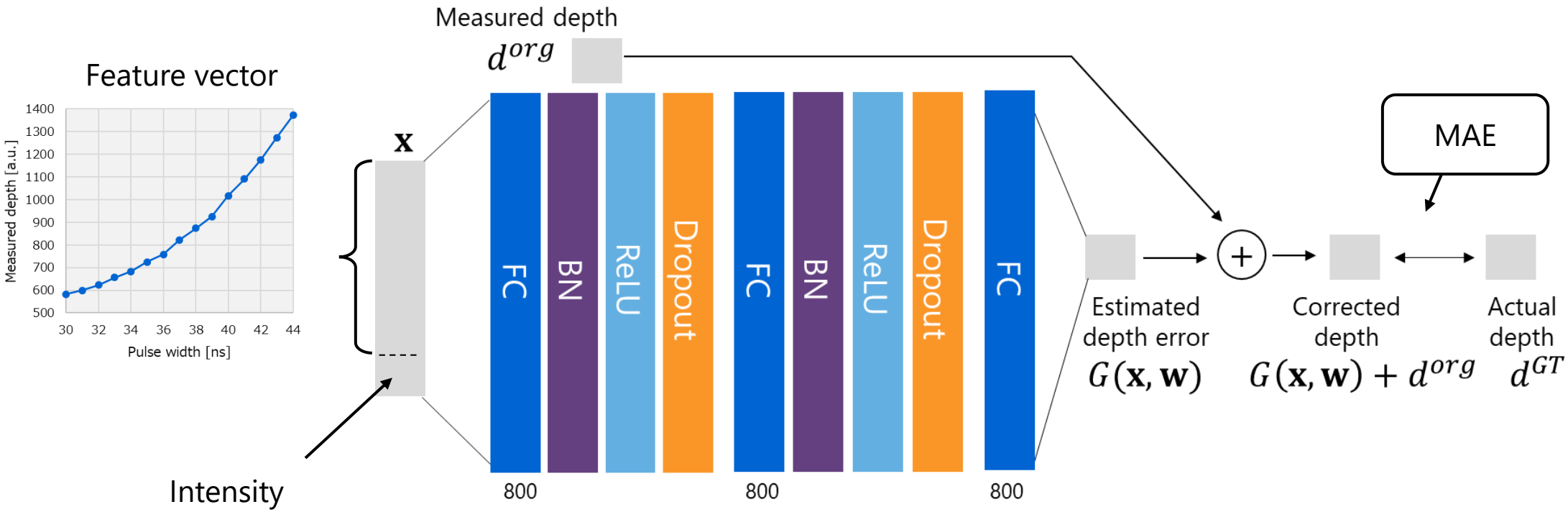
Results of multiple measurements



Proposed Method: Depth Correction

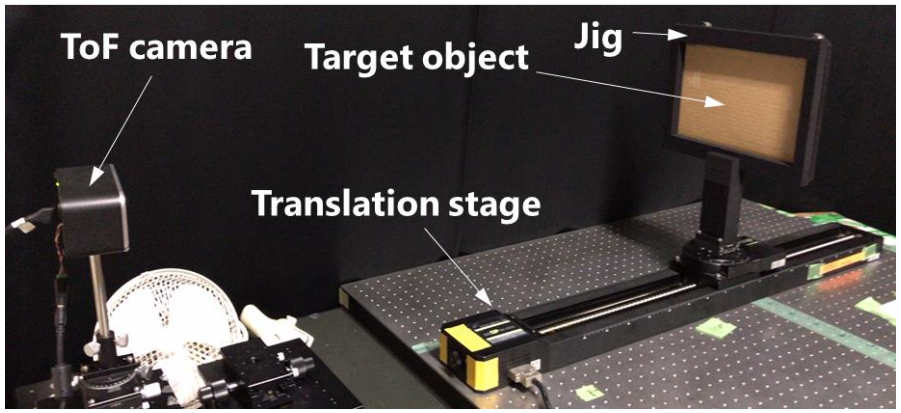
Estimate depth error based on feature vector using neural network

✓ Direct manner may deal with **unknown material*** by utilizing similarity of intermediate features
*Not exactly same but similar materials in training data

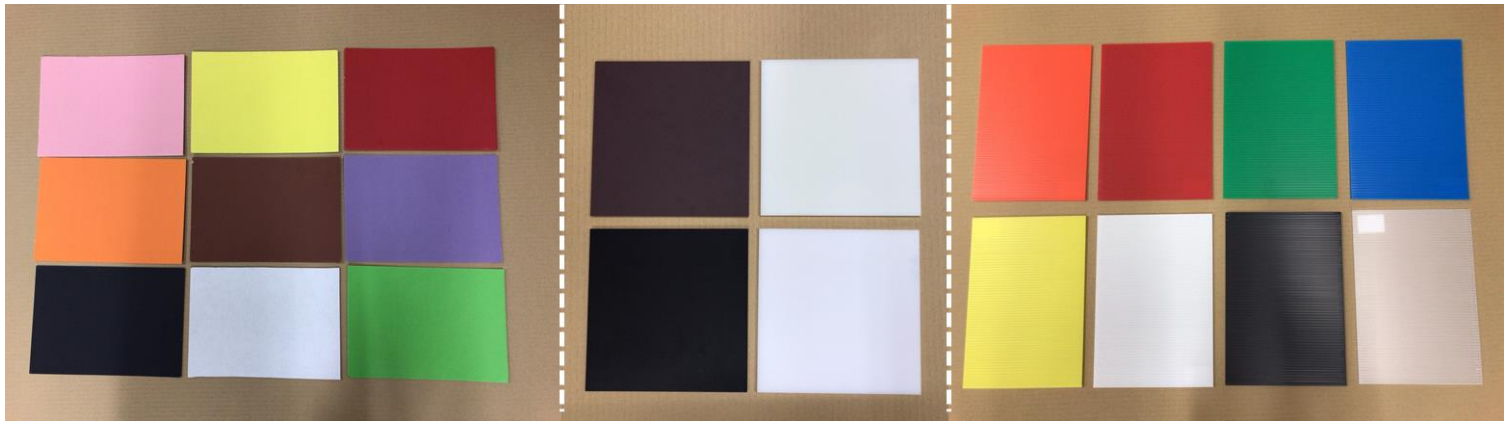


Experimental Setup

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



Cardboard | Plastic | Plastic cardboard



Evaluation for Known Materials

- Same material for training and testing
- Randomly selected 80% of pixels for training, remaining 20% for testing
- Calculate MAE of each object, then evaluate mean(MAE_{mean}) and max(MAE_{max}) for each material

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
[Fuersattel+,2017]	0.55 / 1.60	1.59 / 1.96	**0.54** / **0.98**	0.73 / 1.96
[Fuersattel+,2017]*	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**

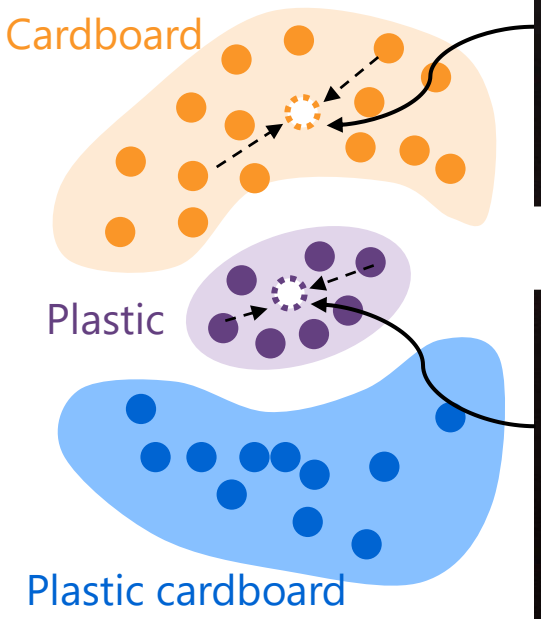
*)Using MLP instead of Random Forest

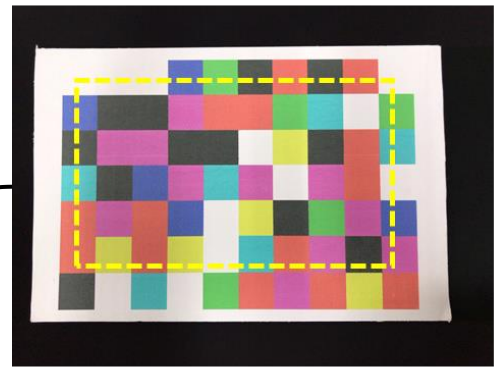
Proposed method outperform conventional method

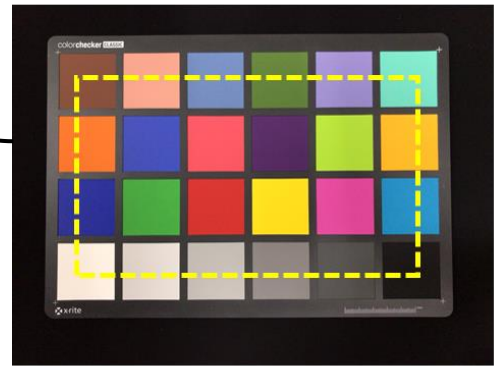
Evaluation for Unknown Materials (1)

- These two object are not exactly same materials in training data, but similar to plastic or cardboard

Schematic image of evaluation scenario

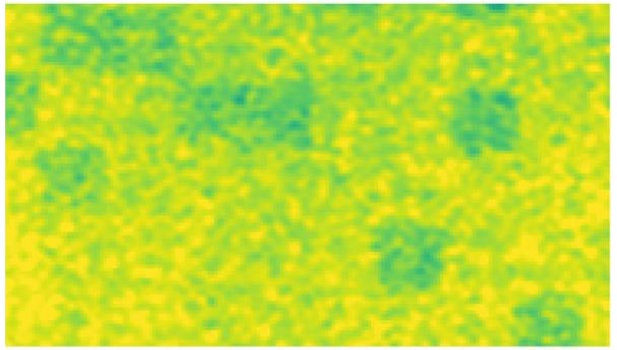




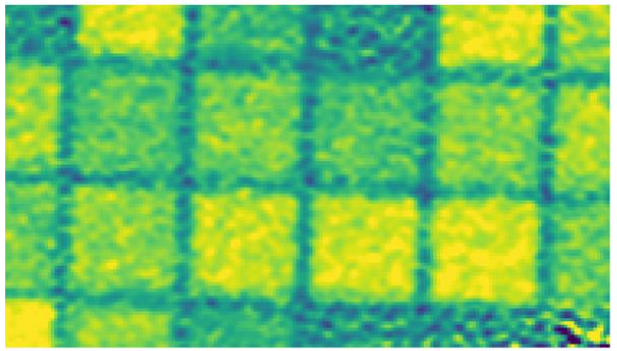


Measured depth

MAE=3.92cm

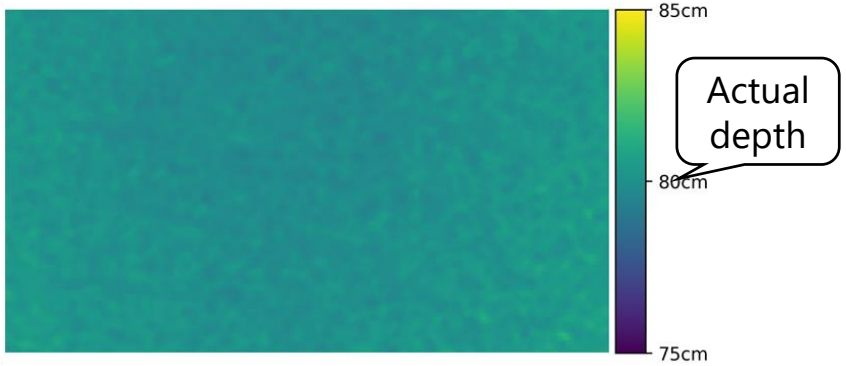


MAE=2.49cm

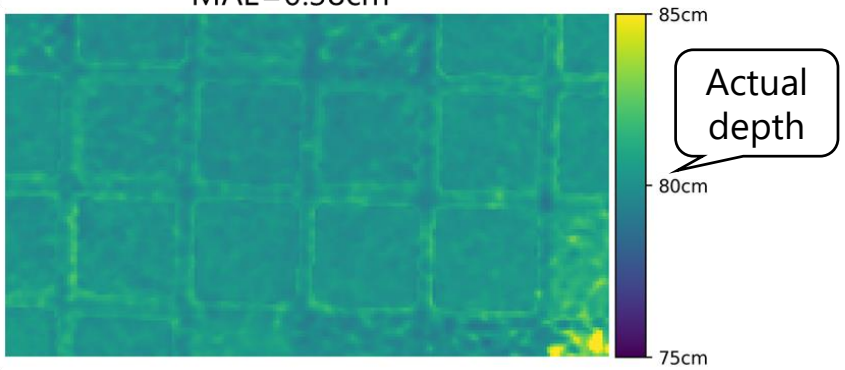


Corrected depth

MAE=0.20cm



MAE=0.38cm

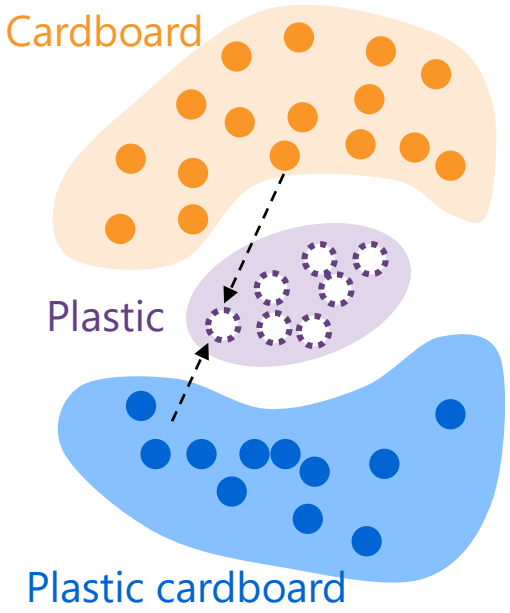


Proposed method work well for slightly different materials from trainging data

Evaluation for Unknown Materials (2)

- Evaluate unknown materials by changing combination of materials in training data

Schematic image of evaluation scenario



Material in training data			MAE_{mean} on testing 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

Better MAE desipite ***unknown material***

Proposed method work well for unknown materials by interpolating from known material information in the feature space

Summary

◆Our method

- ●Feature extraction **without sweeping**
- ●Direct depth correction **without material classification**

◆Experimental Results

- ●Our method can deal with **unknown materials**

◆Future work

- ●Expand target materials
- ●Reduce variation in MAE between materials

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Thank you