Deep Learning based Compensation of Motion and Multi Path Interference in Time-of-Flight Cameras

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Introduction to ToF Technology

- What are ToF (Time of Flight) cameras?
- Working principle of ToF camera

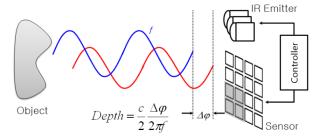


Figure: Working principle of ToF camera [Hansard et al., 2012]

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Classification of ToF camera artifacts

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Classification of ToF camera artifacts

Systematic artifacts

- ► Shot noise
- ▶ Depth wiggling
- ► Integration error
- ► Temperature error

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Classification of ToF camera artifacts

Systematic artifacts

- Shot noise
- Depth wiggling
- Integration error
- Temperature error

Non-systematic artifacts

- Multipath interference (MPI)
- Motion artifacts
- Flying pixels

Introduction









What is Multipath interference in ToF cameras?

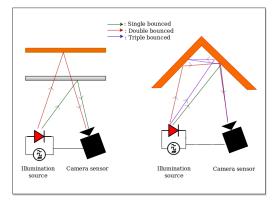


Figure: An illustration of Multipath interference (MPI) artifacts in ToF camera

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What are motion artifacts in ToF cameras?

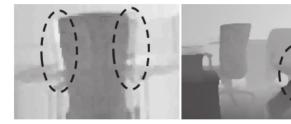


Figure: An illustration of ToF depth motion artifact [Lee et al., 2012]. Blurred regions of the swivel chair is shown in the dashed ellipses.

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Performance evaluation of the approach proposed by [Guo et al., 2018] applied to PMD (Photonic mixer device) camera.

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Performance evaluation of the approach proposed by [Guo et al., 2018] applied to PMD (Photonic mixer device) camera.

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Performance evaluation of the approach proposed by [Guo et al., 2018] applied to PMD (Photonic mixer device) camera.

- PMD Dataset
 - Sensor model
 - Noise model

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Performance evaluation of the approach proposed by [Guo et al., 2018] applied to PMD (Photonic mixer device) camera.

- PMD Dataset
 - Sensor model
 - Noise model
- Number of phases to determine the depth of a scene.

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Dataset Generation:

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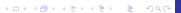
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Dataset Generation:

▶ Simulated measurements using FLAT [Guo et al., 2018] dataset

PMD dataset generation







Dataset Generation:

- ➤ Simulated measurements using FLAT [Guo et al., 2018] dataset
 - ► What is FLAT?

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Dataset Generation:

- ▶ Simulated measurements using FLAT [Guo et al., 2018] dataset
 - ► What is FLAT?
 - Flexible, Large, Augmentable, ToF dataset

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Dataset Generation:

- ▶ Simulated measurements using FLAT [Guo et al., 2018] dataset
 - ▶ What is FLAT?
 - Flexible, Large, Augmentable, ToF dataset
 - Why FLAT dataset?

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Dataset Generation:

- Simulated measurements using FLAT [Guo et al., 2018] dataset
 - ▶ What is FLAT?
 - Flexible, Large, Augmentable, ToF dataset
 - Why FLAT dataset?
 - Scenes are rendered by Transient rendering

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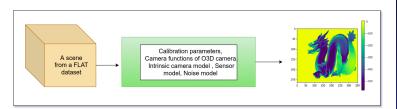


Figure: A block diagram that depicts the sequence of operations in generating the PMD measurements.

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► Why?

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- ► Why?
 - To generate sensor model for two phase operational mode.

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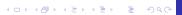
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- ► Why?
 - ► To generate sensor model for two phase operational mode.
- ► How?

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Sensor model







- ► Why?
 - To generate sensor model for two phase operational mode.
- ► How?
 - By solving a least square minimization problem

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- ► Why?
 - To generate sensor model for two phase operational mode.
- ► How?
 - By solving a least square minimization problem

$$\sum_{i} e^2 =$$

$$\left(f_{cal}(A^{P},B^{P})-\frac{1}{2}[(A^{P}-B^{P})-(A^{P+180^{\circ}}-B^{P+180^{\circ}})]\right)^{2}$$

and
$$f_{cal}(A^P, B^P)$$
 is defined as, $f_{cal}(A^P, B^P) = m_1.A^P - n_1.B^P + t_1$

where A, B are sensor readout values. $P = [0^{\circ}, 90^{\circ}]$.



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Noise model

- Estimate the noise associated with A-B measurements.
- Performed acquisition of raw measurements.
- Noise model Normal distribution with standard deviation depending linearly on amount of light integrated.

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Noise model

Estimate the noise associated with A-B measurements.

- Performed acquisition of raw measurements.
- Noise model Normal distribution with standard deviation depending linearly on amount of light integrated.

The standard deviation of A, B can be represented as,

$$\sigma_A = n_1 \cdot \mu_A + t_1$$
$$\sigma_B = n_2 \cdot \mu_B + t_2$$

where μ_A , μ_B indicate mean of A, B respectively.

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Noise model

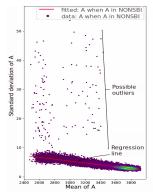


Figure: Plot of standard deviation of A vs. mean of A

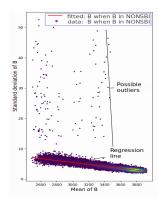


Figure: Plot of standard deviation of B vs. mean of B

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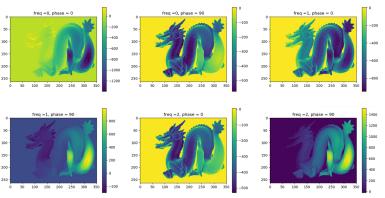
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Conclusion on









 $Figure: Sample full PMD \ raw \ measurements \ of \ a \ static \ scene. \ Frequency \ and \ phase \ values \ are \ displayed \ on \ each \ subplot. \ These \ six \ raw \ measurements \ are \ used \ to \ measure \ the \ depth \ of \ a \ scene.$





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Deep learning models

- Experiments
 - Multi reflection experiment
 - Motion experiment
- Both experiments are structured as follow
 - System architecture
 - Setup
 - Dataset statistics
 - Loss function
 - Baseline
 - Loss curves
 - Results

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Deep learning models







Multi reflection experiment

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Multi reflection experiment









System architecture

 Multi reflection model based on Kernel predictive network (KPN) [Bako et al., 2017]

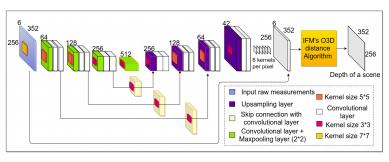


Figure: Architecture of the Multi reflection model (MRM).





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Setup

Dataset statistics

Table: Details of the dataset used in the multi reflection experiment

Scene type	Train	Test	Total
Foreground scenes	648	0	648
Background scenes	202	117	319
Total	850	117	967

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Setup

Dataset statistics

Table: Details of the dataset used in the multi reflection experiment

Scene type	Train	Test	Total
Foreground scenes	648	0	648
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Total	850	117	967

Loss function

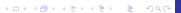
$$loss_{scene} = \sqrt{\frac{\sum (y_{out} - y')^2}{N_{validPixels}}}$$

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Setup

Dataset statistics

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Loss function

$$loss_{scene} = \sqrt{\frac{\sum (y_{out} - y')^2}{N_{validPixels}}}$$

Baseline Ifm's distance algorithm



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Loss curves:

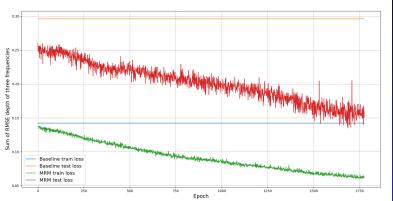


Figure: Loss curves of the the multi reflection experiment. The unit of the vertical axis is meters





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Multi reflection experiment

Results:

Table: Results of the multi reflection experiment. All statistics are calculated on test data set.

	Median depth error	Percentile (70 th) depth error
PMD pipeline (baseline) MRM + PMD	10.72 cm	13.92 cm
pipeline	4.68 cm	6.57 cm

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Multi reflection experiment

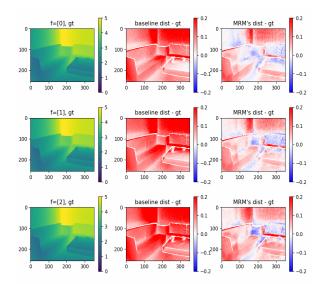


Figure: A sample scene result of the MRM experiment. The unit of colorbar is meters.

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System architectures

► Motion model base on Flownet architecture [Fischer et al., 2015]

Warping→ 256 352 Velocity warped maps measurements Skip connection with convolutional laver Convolutional laver + Maxpooling layer (2*2) Input raw measurements Warped measurements □ Convolutional laver Kernel size 5*5 Kernel size 7*7 ■ Kernel size 3*3 ■ Upsampling

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Setup

Dataset statistics

Table: Details of the dataset used in the motion experiment

Dataset	Foreground scenes	Background scenes	Augmented scenes
Train set	572	202	6400
Test set	76	117	1600
Total	648	319	8000

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Setup

Dataset statistics

Table: Details of the dataset used in the motion experiment

Dataset	Foreground scenes	Background scenes	Augmented scenes
Train set Test set Total	572	202	6400
	76	117	1600
	648	319	8000

Loss function

$$loss_{scene} = \sqrt{\frac{\sum (v_{yx} - v'_{yx})^2}{size(v_{yx})}}$$

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Setup

Dataset statistics

Table: Details of the dataset used in the motion experiment

Dataset	Foreground scenes	Background scenes	Augmented scenes
Train set Test set Total	572	202	6400
	76	117	1600
	648	319	8000

Loss function

$$loss_{scene} = \sqrt{\frac{\sum (v_{yx} - v'_{yx})^2}{size(v_{yx})}}$$

Baseline : RMSE of gt velocity maps.





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Loss curves

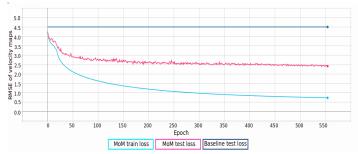


Figure: Train and test losses of motion experiment.

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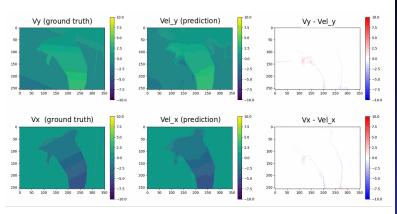


Figure: Velocity vectors difference between model's predicted and gt (from train set)



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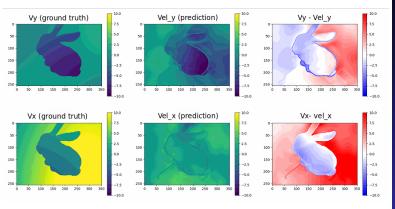


Figure: Velocity vectors difference between model's predicted and gt (from test set)



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Occlusion pixels.

on test set.

Possible reasons for high velocity vector errors on the testset:

► Trainset was not sufficient for the model to generalize

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Conclusion and future work

Conclusion:

- Used FLAT dataset for generating the PMD measurements
- Demonstrated end to end training of the MRM with two phases per frequency. Median depth error got reduced by 50%.
- The motion model did not work as expected.

Future work:

- ▶ With more data and time, motion model can be generalized on the test set.
- Motion and multi reflection models can be trained together.
- Training and testing of the models with real camera data.

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