Inside your life !

본질 집중
깊은 사고

새로운 시도
집요한 실행

정직과 신의

대외비 2급

TOF Validation

CTO
Software개발1팀

LG이노텍

Validation Items

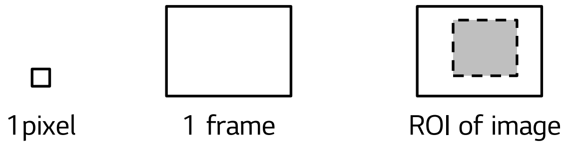
대외비 2급

* 유사항목은 같은 행에 작성되어 있음

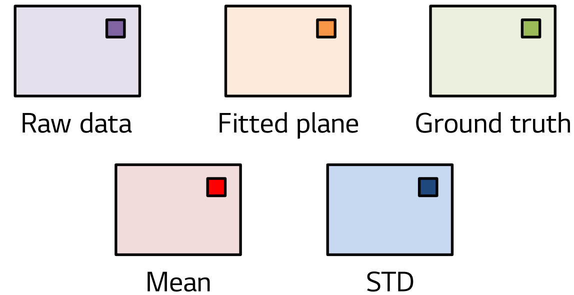
Infineon 기준 validation 항목		SONY 기준 validation 항목	
Meaning	Validation Item	Validation Item	Meaning
std(amplitude)	amplitude_std		
mean(amplitude)	amplitude_mean		
max(amplitude)	amplitude_max		
min(amplitude)	amplitude_min		
mean(depth– fitted_plane)	depth_precision_spatial		
mean(depth – GT)	single_shot_depth_error		
std(depth)	depth_precision_temporal	Depth Noise	mean(depth_std) # in ROI 10x10
std(depth) # in ROI 5x5	center noise		
mean(depth – GT)	depth_accuracy	Depth Error	mean(depth– GT) # in ROI 10x10
mean(depth – GT)/GT	depth_accuracy_percent		
the number of calibrated pixels (non-masked)	number_of _calibrated_pixels_in_roi		
number_of_calibrated_pixels_in_roi / number_of_pixels_in_roi	valid_pixels_percentages		
the top 10% of (depth – fitted_plane)	Q90norm		
max(depth – fitted plane)	plane_error_max		
mean(depth – fitted_plane)	plane_error_mean		
std(depth – fitted_plane)	plane_error_std		
angle of plane fit about y-axis	plane_tilt_angle		
angle of plane fit about x-axis	plane_pan_angle		
		DENU	std(depth – GT) # in ROI 50x50
		DNR	mean(depth_std/depth) # in ROI 10x10
		DNNU	std(depth_std/depth) # in ROI 50x50
		SAD	mean(|depth – GT|)
		SAD 10	mean(|depth-GT|) # in ROI 10x10
		depthAvg	mean(depth)
		depthMin	min(depth)
		depthMax	max(depth)

Notation

Figure



Color

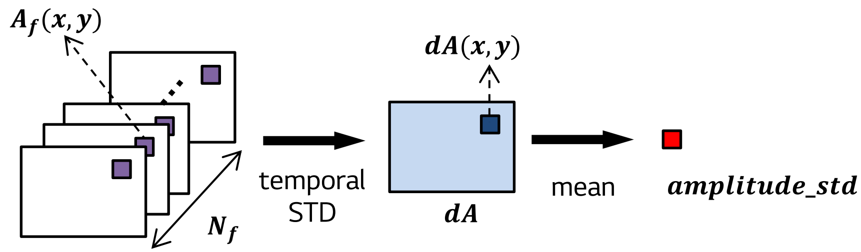


Common Parameters

- N_f: *the number of frames*
- w: *width*
- h: *height*
- w_{ROI}: *width of ROI*
- h_{ROI}: *height of ROI*
- x_{ROI}: *start x position of ROI*
- y_{ROI}: *start y position of ROI*
- (x, y): *position in frame*
- A_f: *Amplitude of* f_{th} *frame*
- D_f: *Depth of* f_{th} *frame*
- D_f^{Fit}: *Fitted plane of* f_{th} *frame*

Amplitude STD

대외비 2급



Description

- Temporal stability of the ToF system

Calculation

- $dA(x,y)$ = temporal standard deviation of the amplitudes of single pixel, $A_f(x,y)$

$$dA(x,y) = \sqrt{\frac{1}{N_f}\sum_{f=1}^{N_f}\left(A_f(x,y) - \overline{AT}(x,y)\right)^2}$$

- $amplitude\_std$ = mean of dA_f

$$amplitude\_std = \frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h} dA(x,y)$$

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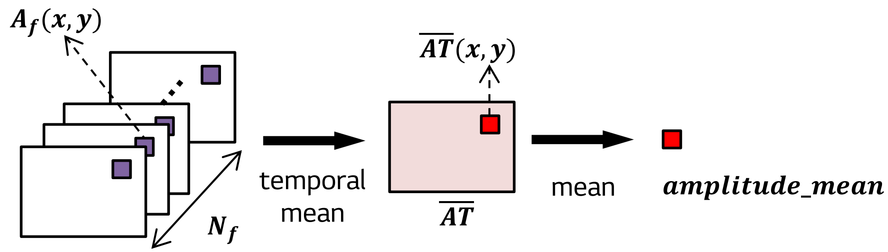
Amplitude Mean/Min/Max

대외비 2급



Description

- Modulated signal strength of ToF system
- amplitude_max: the best performing pixel
- amplitude_min: the worst performing pixel

Calculation

- $\overline{AT}(x,y)$ = temporal average of the amplitudes of single pixel, $A_f(x,y)$

$$\overline{\boldsymbol{AT}}(\boldsymbol{x},\boldsymbol{y}) = \frac{\mathbf{1}}{\boldsymbol{N_f}}\sum_{f=1}^{N_f} \boldsymbol{A_f}(\boldsymbol{x},\boldsymbol{y})$$

- $amplitude\_mean$ = mean of $\overline{AT}$

$$\boldsymbol{amplitude\_mean} = \frac{\mathbf{1}}{\boldsymbol{wh}}\sum_{x=1}^{w}\sum_{y=1}^{h} \overline{\boldsymbol{AT}}(\boldsymbol{x},\boldsymbol{y})$$

- $amplitude\_min$ = min of $\overline{AT}$

$$\boldsymbol{amplitude\_min} = \boldsymbol{min}\{\overline{\boldsymbol{AT}}\}$$

- $amplitude\_max$ = max of $\overline{AT}$

$$\boldsymbol{amplitude\_max} = \boldsymbol{max}\{\overline{\boldsymbol{AT}}\}$$

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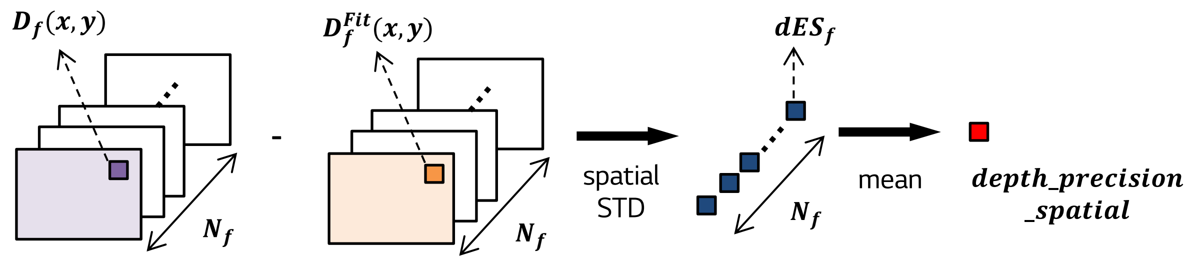
Depth Precision Spatial

대외비 2급

Description

- Spatial noise of the depth error



Calculation

- $\overline{ES\_fit}_f$ = spatial average of the depth error for frame

$$\overline{ES\_fit}_f = \frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h}(D_f(x,y) - D_f^{Fit}(x,y))$$

- dES = spatial standard deviation of the depth error for frame

$$dES_f = \sqrt{\frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h}((D_f(x,y) - D_f^{Fit}(x,y)) - \overline{ES\_fit}_f)^2}$$

- $depth\_precision\_spatial$ = mean of the dES

$$depth\_precision\_spatial = \frac{1}{N_f}\sum_{f=1}^{N_f} dES_f$$

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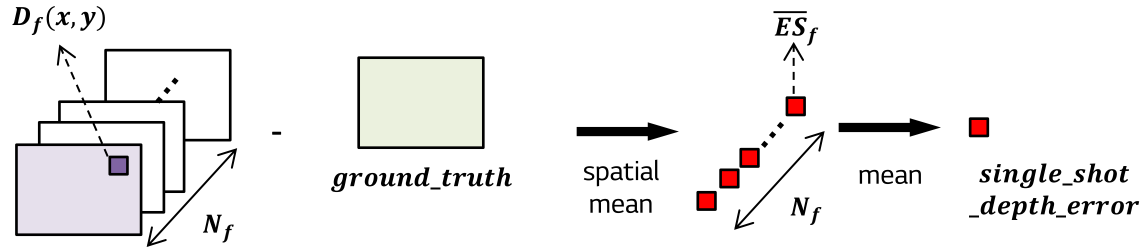
Single Shot Depth Error

Description

- Reliability of the depth measurement
- Spatial depth error



Calculation

- $\overline{ES}_f$ = spatial average of the depth error for frame

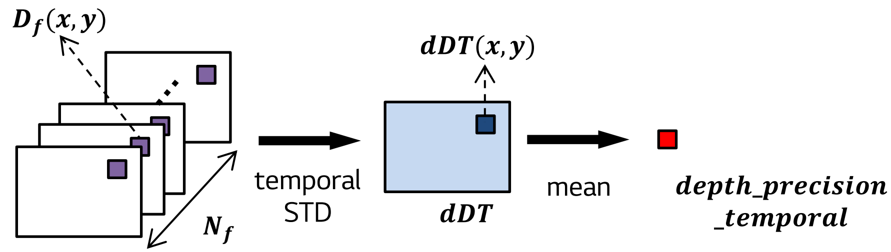
$$\overline{\boldsymbol{ES}}_{\boldsymbol{f}} = \frac{\mathbf{1}}{\boldsymbol{wh}} \sum_{x=1}^{w} \sum_{y=1}^{h} (\boldsymbol{D}_{\boldsymbol{f}}(\boldsymbol{x},\boldsymbol{y}) - -\boldsymbol{ground\_truth})$$

- $single\_shot\_depth\_error$ = mean of the $\overline{ES}_f$

$$\boldsymbol{single\_shot\_depth\_error} = \frac{\mathbf{1}}{\boldsymbol{N}_{\boldsymbol{f}}} \sum_{f=1}^{N_f} \overline{\boldsymbol{ES}}_{\boldsymbol{f}}$$

Depth Precision Temporal

대외비 2급



Description

- Temporal noise of the depth values

Calculation

- $\overline{DT}(x,y)$ = temporal average of the calculated depth of single pixel, $D_f(x,y)$

$$\overline{DT}(x,y) = \frac{1}{N_f}\sum_{f=1}^{N_f} D_f(x,y)$$

- $dDT(x,y)$ = temporal standard deviation of the calculated depth of single pixel, $D_f(x,y)$

$$dDT(x,y) = \sqrt{\frac{1}{N_f}\sum_{f=1}^{N_f}\left(D_f(x,y) - \overline{DT}(x,y)\right)^2}$$

- $depth\_precision\_temporal$ = mean of the dDT

$$depth\_precision\_temporal = \frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h} dDT(x,y)$$

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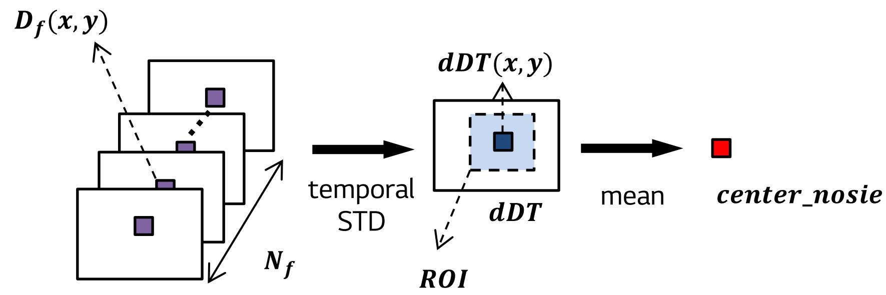
Center Noise

대외비 2급

Description

- Temporal noise of the depth values in ROI
- ROI: center 5x5



Calculation

- $\overline{DT}(x,y)$ = temporal average of the calculated depth of single pixel, $D_f(x,y)$

$$\overline{\boldsymbol{DT}}(\boldsymbol{x},\boldsymbol{y}) = \frac{1}{N_f}\sum_{f=1}^{N_f} D_f(x,y)$$

- $dDT(x,y)$ = temporal standard deviation of the calculated depth of single pixel, $D_f(x,y)$

$$dDT(x,y) = \sqrt{\frac{1}{N_f}\sum_{f=1}^{N_f}\left(D_f(x,y) - \overline{DT}(x,y)\right)^2}$$

- $center\_noise$ = mean of the dDT in ROI

$$center\_noise = \frac{1}{w_{ROI}h_{ROI}}\sum_{x=x_{ROI}}^{w_{ROI}}\sum_{y=y_{ROI}}^{h_{ROI}} dDT(x,y)$$

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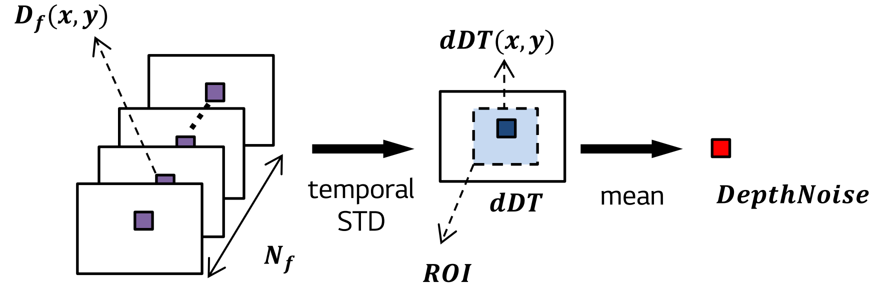
Depth Noise

대외비 2급



Description

- Temporal noise of the depth values
- ROI: center 10x10

Calculation

- $\overline{DT}(x,y)$ = temporal average of the calculated depth of single pixel, $D_f(x,y)$

$$\overline{\boldsymbol{DT}}(\boldsymbol{x},\boldsymbol{y}) = \frac{\mathbf{1}}{\boldsymbol{N_f}}\sum_{f=1}^{N_f} \boldsymbol{D_f}(\boldsymbol{x},\boldsymbol{y})$$

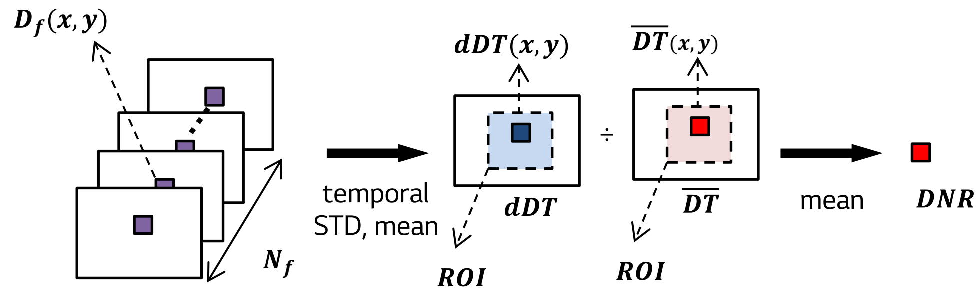
- $dDT(x,y)$ = temporal standard deviation of the calculated depth of single pixel, $D_f(x,y)$

$$\boldsymbol{dDT}(\boldsymbol{x},\boldsymbol{y}) = \sqrt{\frac{\mathbf{1}}{\boldsymbol{N_f}}\sum_{f=1}^{N_f}\left(\boldsymbol{D_f}(\boldsymbol{x},\boldsymbol{y}) - \overline{\boldsymbol{DT}}(\boldsymbol{x},\boldsymbol{y})\right)^2}$$

- $DepthNoise$ = mean of the dDT

$$\boldsymbol{DepthNoise} = \frac{\mathbf{1}}{\boldsymbol{w_{ROI}h_{ROI}}}\sum_{x=x_{ROI}}^{w_{ROI}}\sum_{y=y_{ROI}}^{h_{ROI}} \boldsymbol{dDT}(\boldsymbol{x},\boldsymbol{y})$$

DNR



Description

- DNR = Depth Noise Ratio
- ROI : center 10x10

Calculation

- $rDT(x,y)$ = relative of temporal mean and standard deviation of single pixel

$$rDT(x,y) = \frac{dDT(x,y)}{\overline{DT}(x,y)}$$

$$DNR = \frac{1}{w_{ROI}h_{ROI}} \sum_{x=x_{ROI}}^{w_{ROI}} \sum_{y=y_{ROI}}^{h_{ROI}} rDT(x,y) * 100$$

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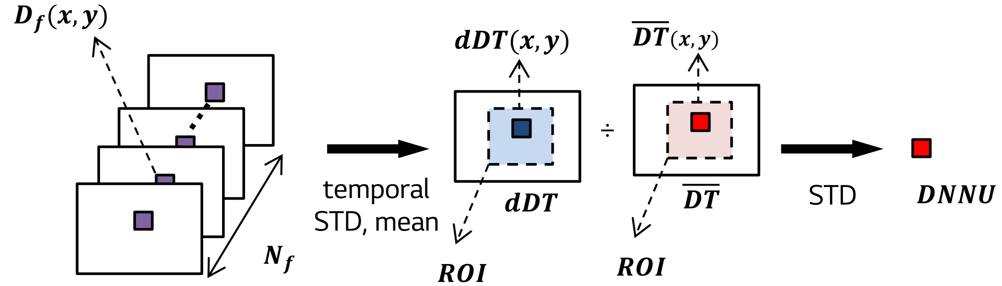
DNNU



Description

- DNNU = Depth Noise Ratio Non-Uniformity
- ROI: center 50x50

Calculation

- $DNNU(x,y)$ = noise of DNR in ROI

$$DNR = \frac{1}{w_{ROI}h_{ROI}} \sum_{x_{ROI}=1}^{w_{ROI}} \sum_{y_{ROI}=1}^{h_{ROI}} rDT(x,y)$$

$$DNNU = \sqrt{\frac{1}{w_{ROI}h_{ROI}} \sum_{x=x_{ROI}}^{w_{ROI}} \sum_{y=y_{ROI}}^{h_{ROI}} (rDT\,(x,y) - DNR)^2}$$

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Depth Accuracy

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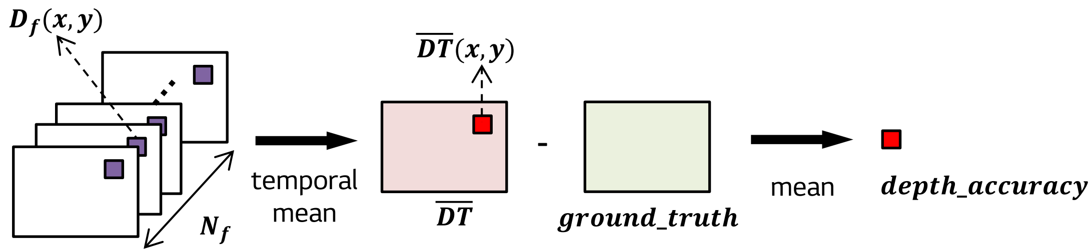


Description

- Reliability of the depth measurement

Calculation

- $\overline{DT}(x,y)$ = temporal average of the calculated depth of single pixel, $D_f(x,y)$

$$\overline{DT}(x,y) = \frac{1}{N_f}\sum_{f=1}^{N_f} D_f(x,y)$$

- $depth\_accuracy$ = mean of difference between temporal average and ground truth

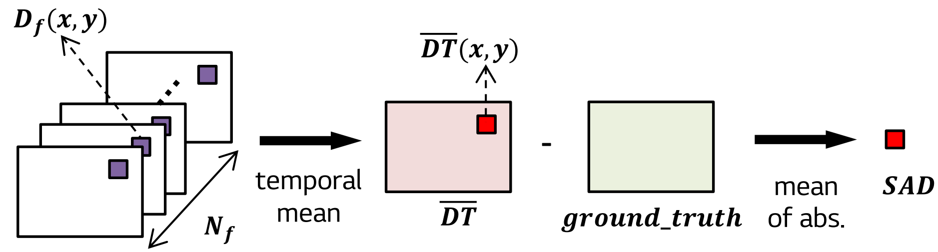
$$depth\_accuracy = \frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h}(\overline{DT}(x,y) - ground\_truth)$$

- $depth\_accuracy\_percent$ = the relative depth error

$$depth\_accuracy\_percent = \frac{depth\_accuracy}{ground\_truth}$$

SAD/ SAD10

대외비 2급



Description

- Reliability of the depth measurement
- Sum of absolute difference error

Calculation

- $\overline{DT}(x,y)$ = temporal average of the calculated depth of single pixel, $D_f(x,y)$

$$\overline{DT}(x,y) = \frac{1}{N_f}\sum_{f=1}^{N_f} D_f(x,y)$$

- SAD = mean of absolute difference between temporal average and ground truth

$$SAD = \frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h}\left|\overline{DT}(x,y) - ground\_truth\right|$$

- $SAD10$ = mean of absolute difference between temporal average and ground truth in ROI 10x10

$$SAD10 = \frac{1}{w_{ROI}h_{ROI}}\sum_{x=x_{ROI}}^{w_{ROI}}\sum_{y=y_{ROI}}^{h_{ROI}}\left|\overline{DT}(x,y) - ground\_truth\right|$$

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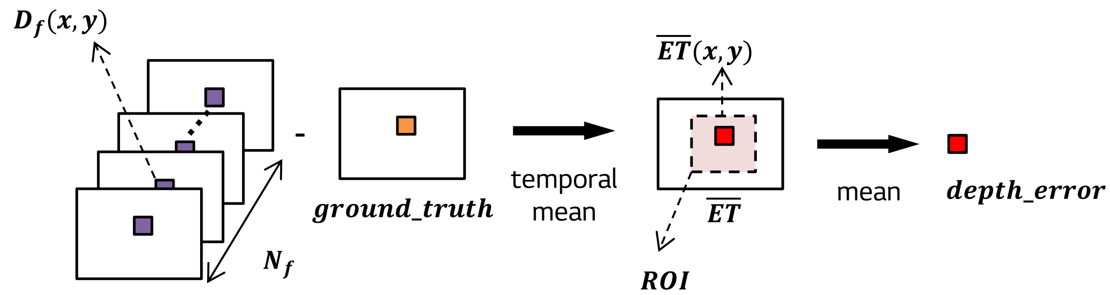
Depth Error

대외비 2급



Description

- Reliability of the depth measurement
- ROI: center 10x10

Calculation

- $\overline{ET}(x,y)$ = temporal average of depth error of single pixel

$$\overline{ET}(x,y) = \frac{1}{N_f}\sum_{f=1}^{N_f}(D_f(x,y) - ground\_truth)$$

- $DepthError$ = mean of $\overline{ET}$ in ROI

$$DepthError = \frac{1}{w_{ROI}h_{ROI}}\sum_{x=x_{ROI}}^{w_{ROI}}\sum_{y=y_{ROI}}^{h_{ROI}}\overline{ET}(x,y)$$

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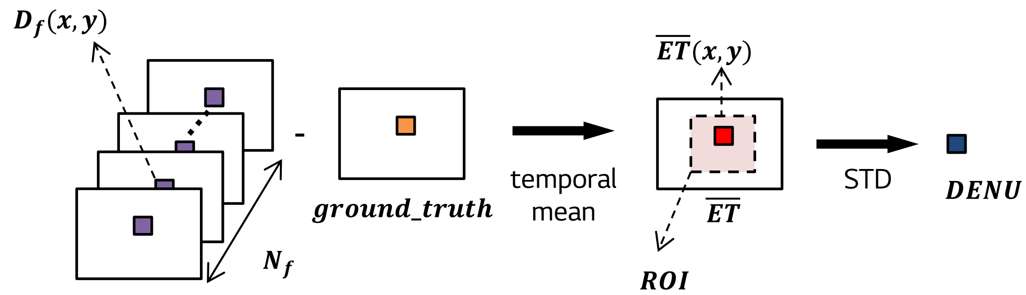
DENU

대외비 2급



Description

- DENU = Depth Error Non-Uniformity
- Temporal noise of the depth error
- ROI: center 50x50

Calculation

- $DENU$ = standard deviation $\overline{ET}$ in ROI

$$DepthError = \frac{1}{w_{ROI}h_{ROI}} \sum_{x=x_{ROI}}^{w_{ROI}} \sum_{y=y_{ROI}}^{h_{ROI}} \overline{ET}(x,y)$$

$$DENU = \sqrt{\frac{1}{w_{ROI}h_{ROI}} \sum_{x=x_{ROI}}^{w_{ROI}} \sum_{y=y_{ROI}}^{h_{ROI}} (\overline{ET}(x,y) - DepthError)^2}$$

Number_of_calibrated_pixels_in_roi

대외비 2급

Description

- the number of pixels that can be used for the measurement
- masking pixels with insufficient lighting and defect pixels

Calculation

$$\boldsymbol{number\_of\_calibrated\_pixels} = \frac{\boldsymbol{1}}{\boldsymbol{w_{ROI}h_{ROI}}} \sum_{\boldsymbol{x=x_{ROI}}}^{\boldsymbol{w_{ROI}}} \sum_{\boldsymbol{y=y_{ROI}}}^{\boldsymbol{h_{ROI}}} \sim \boldsymbol{Mask}(\boldsymbol{x},\boldsymbol{y})$$

valid_pixels_percentage

대외비 2급

Description

- Ratio of valid_pixels in ROI

Calculation

$$valid\_pixels\_percentage = \frac{1}{w_{ROI} h_{ROI}} number\_of\_calibrated\_pixels$$

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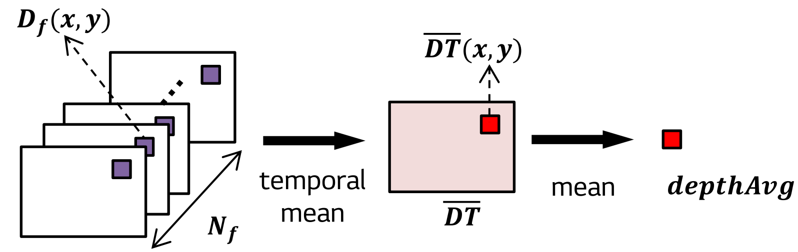
Depth Avg/Min/Max

대외비 2급



Description

- Reliability of the depth measurement

Calculation

- $\overline{DT}(x, y)$ = temporal average of the calculated depth of single pixel, $D_f(x, y)$

$$\overline{DT}(x,y) = \frac{1}{N_f}\sum_{f=1}^{N_f} D_f(x,y)$$

- $depthAvg$ = mean of $\overline{DT}$

$$depthAvg = \frac{1}{wh}\sum_{x=1}^{w}\sum_{y=1}^{h}\overline{DT}(x,y)$$

- $depthMin$ = min of $\overline{DT}$

$$depthMin = min\{\overline{DT}\}$$

- $depthMax$ = max of $\overline{DT}$

$$depthMax = max\{\overline{DT}\}$$

Plane_Error_max/mean/std

대외비 2급

Description

- Fitted plane using calibrated 3D point cloud

Calculation

- Hessian Normal Plane form $[n, d]$

$$n_1 x + n_2 y + n_3 z = d$$

- X, Y, Z = calibrated 3D point cloud

$$X = [x_1, \cdots, x_{wh}] \;, Y = [y_1, \cdots, y_{wh}], Z = [z_1, \cdots, z_{wh}]$$

- Fitted plane $[n, d]$

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & 1 \\ \vdots & \vdots & \vdots \\ x_{wh} & y_{wh} & 1 \end{bmatrix}^{-1} \begin{bmatrix} z_1 \\ \vdots \\ z_{wh} \end{bmatrix}$$

$$n\_ = \left[-\frac{a_1}{a_3}, -\frac{a_2}{a_3}, \frac{1}{a_1} \right]$$

$$d = 1/norm(n\_)$$
$$n = n\_ * d$$

- Distance of points to plane (plane error)

$$PE = \left| \begin{bmatrix} x_1 & y_1 & z_1 \\ \vdots & \vdots & \vdots \\ x_{wh} & y_{wh} & z_{wh} \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} - \begin{bmatrix} d \\ \vdots \\ d \end{bmatrix} \right|$$

- Plane error max = max value of PE

$$plane\_error\_max = max\{PE\}$$

- Plane error mean = average of PE

$$plane\_error\_mean = \frac{1}{wh} \sum_{i=1}^{wh} PE(i)$$

- Plane error std= standard deviation of PE

$$plane\_error\_std = \sqrt{\frac{1}{wh} \sum_{i=1}^{wh} (PE(i) - plane\_error\_mean)^2}$$

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Q90norm

대외비 2급

Description

- the top 10 percent of plane fit error
- indicator plane error of the relative deviation

Calculation

- Q90norm = the top 10 percent of normalized plan fit error

$$\boldsymbol{PE_{norm} = \frac{PE}{d}}$$

$$\boldsymbol{PE_{sort} = sort(PE_{norm}, 'ascend')}$$

$$\boldsymbol{Q90norm = PE_{sort}(wh * 0.9)}$$

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Plane Tilt/Pan Angle

대외비 2급

Description

- Tilt: angle of plane fit about y-axis
- Pan: angle of plane fit about x-axis

Calculation

- Fitted plane $[n, d]$

$$\boldsymbol{Plane\,Tilt} = \mathbf{90^\circ} - \boldsymbol{acosd}\,(\boldsymbol{n_1})$$
$$\boldsymbol{Plane\,Pan} = \mathbf{90^\circ} - \boldsymbol{acosd}\,(\boldsymbol{n_2})$$

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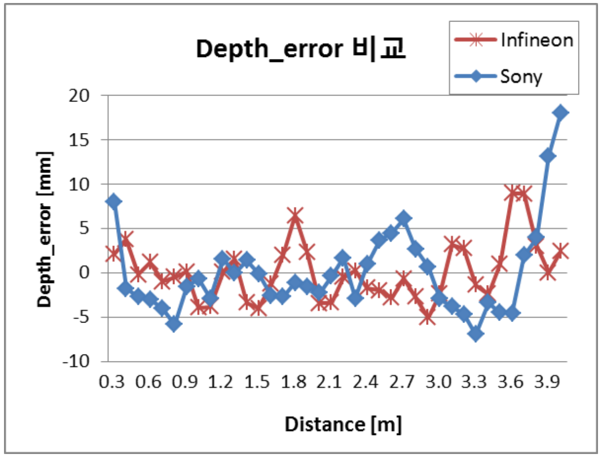
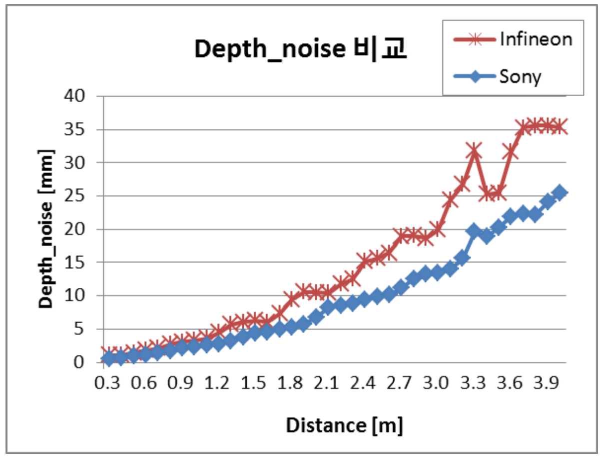
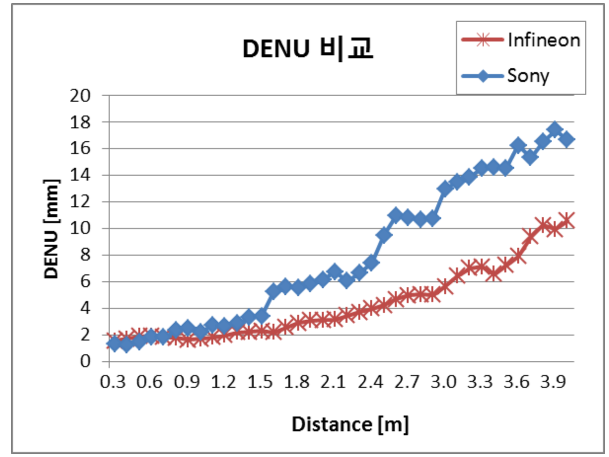
LTS Validation Result - Best

대외비 2급

- 통합 Calibration으로 사용하지 않고, 각 사의 방식으로 calibration한 결과
- Test sample
  - Infineon : PP1 10ea 중 best (8270-88B2-1AC2-4484), 80M & 60M dual
  - Sony (Cat tree) : PP2 19ea 중 best (S08), 100M & 60M dual
- 각 test 모듈 중 Best 샘플 1개씩으로 대표 비교
- Sony 가 사용하는 Minikit 으로는 amplitude를 구할 수 없는 구조라서 depth만 비교







➢ Depth error 는 비슷한 수준

➢ Depth noise 는 Sony가 더 좋음

➢ DENU(uniformity) 는 Infineon이 더 좋음

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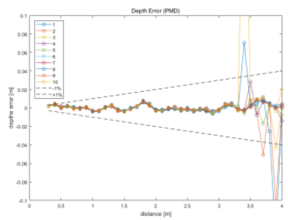
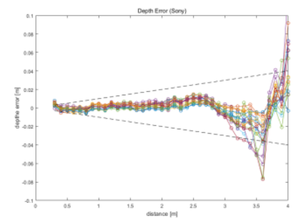
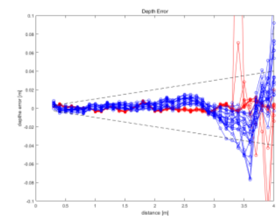
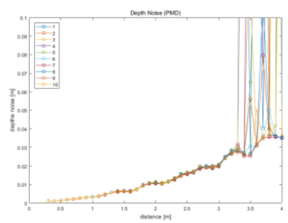
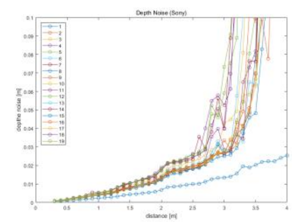
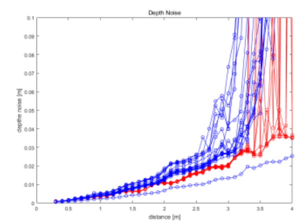
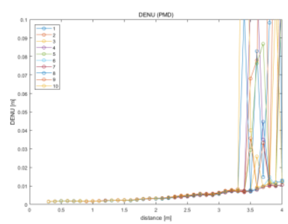
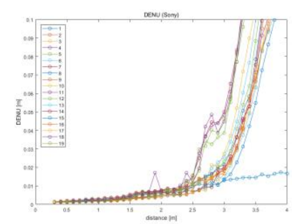
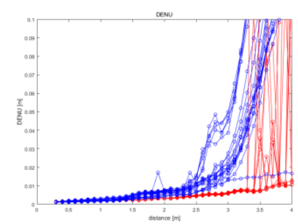
LTS Validation Result - Total

대외비 2급

- 통합 Calibration으로 사용하지 않고, 각 사의 방식으로 calibration한 결과
- Test sample
  - Infineon : PP1 10ea 전체, 80M & 60M dual
  - Sony (Cat tree) : PP2 19ea 전체, 100M & 60M dual
- Sony 가 사용하는 Minikit 으로는 amplitude를 구할 수 없는 구조라서 depth만 비교

	Infineon	Sony	Infineon vs. Sony
Depth Error [m]			
Depth Noise [m]			
DENU [m]			

Infineon
Sony

- ➢ 샘플별 편차는 모든 항목에서 Infineon이 우수함
- ➢ Depth Error : 동등 수준
  - ➢ PMD의 Spectre가 적용된다면 Infineon의 성능은 더 좋을 수 있음 (alpha 성능)
- ➢ Depth Noise (temporal uniformity) : Infineon이 우수함 (best는 Sony가 좋았음, 앞장 참고)
- ➢ DENU (spatial uniformity) : Infineon이 우수함

LG이노텍