IS 2 - 4 Depth Image Enhancement Using Local Tangent Plane Approximations

HOKUYO Unique product & Best Sensing — aoki media sensing lab.

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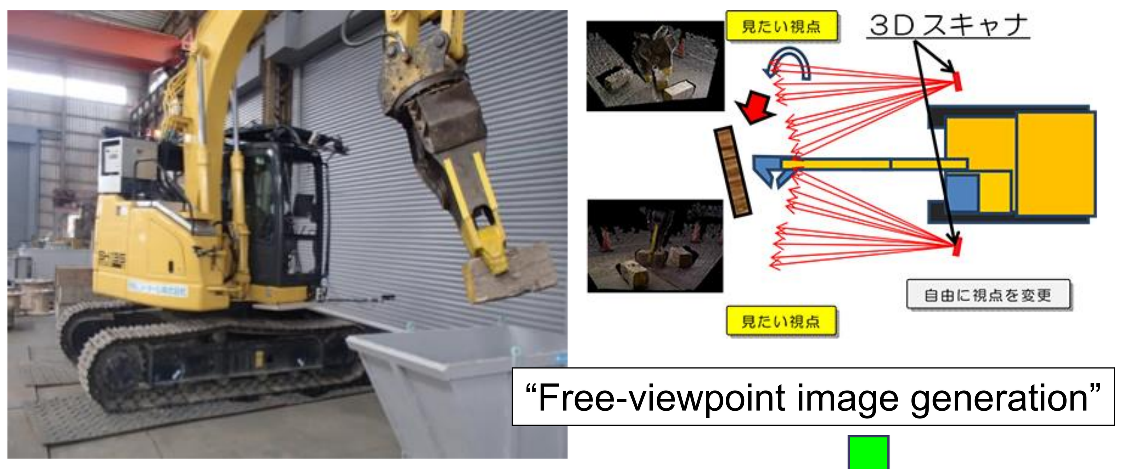
Introduction

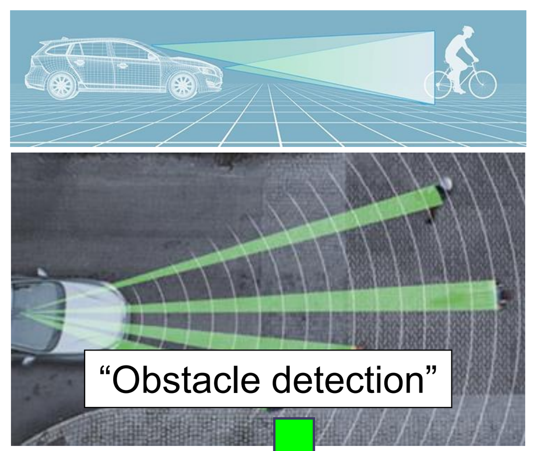
3D Measurement for Industrial Applications

*1 "Remote control of heavy machinery by using 3D scanners" [News release of Shimizu Corporation 21 Oct 2013]
*2 "Cyclist detection" [Volvo Car Japan.]

Remote Control of Heavy Machinery *1



Collision Avoidance System *2

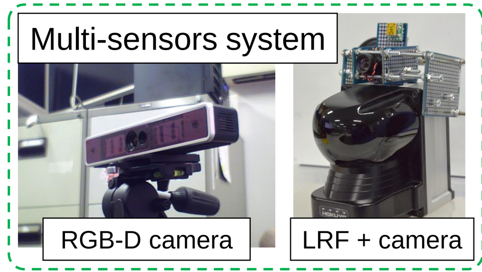


Improvement for full automation of machines

Accurate and dense shape measurement | **Accurate and long-distance shape measurement**

But current sensors do not have suitable capability individually.

Multi-sensors system



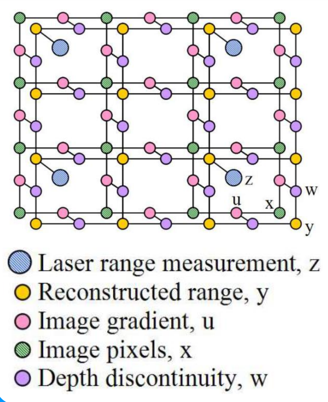
Weak points of individual current sensors
- ***Stereo visions -> Robustness to environmental lights**
- ***Laser range finder -> Density of the measurement**

Data-fusion techniques on multi-sensors system are required.

We focus on the enhancement of data measured by an RGB-D camera as the first step of this research.

Related Work

Global Optimization Based Method



1. **Measured depth data is used as optimization data prior.**
2. **Various pixel based information is used as optimization smoothness prior.** (image gradient, segmentation, edge saliency, non-local mean, and co-sparseness etc.)
3. **Depth enhancement is achieved by an optimization of over the image grid.**

"An application of Markov random fields to range sensing" [NIPS 2006 Diebel et al.]
"High quality depth map upsampling for 3d-tof cameras" [ICCV 2011 Park et al.]
"A Joint intensity and depth co-sparse analysis model for depth map superresolution" [ICCV 2013 Kiechle et al.]
"Depth map inpainting under a second-order smoothness prior" [Image Analysis vol. 7944 Herrera et al.] etc.

Local Filter Based Method

$$d(x) = \frac{\sum_{y \in N(x)} w(x,y) d_{low}(y)}{\sum_{y \in N(x)} w(x,y)}$$

w : weight function

ex. $w(x,y) = \exp\left(-\frac{|x-y|}{\sigma_p}\right)\exp\left(-\frac{|I(x)-I(y)|}{\sigma_c}\right)$

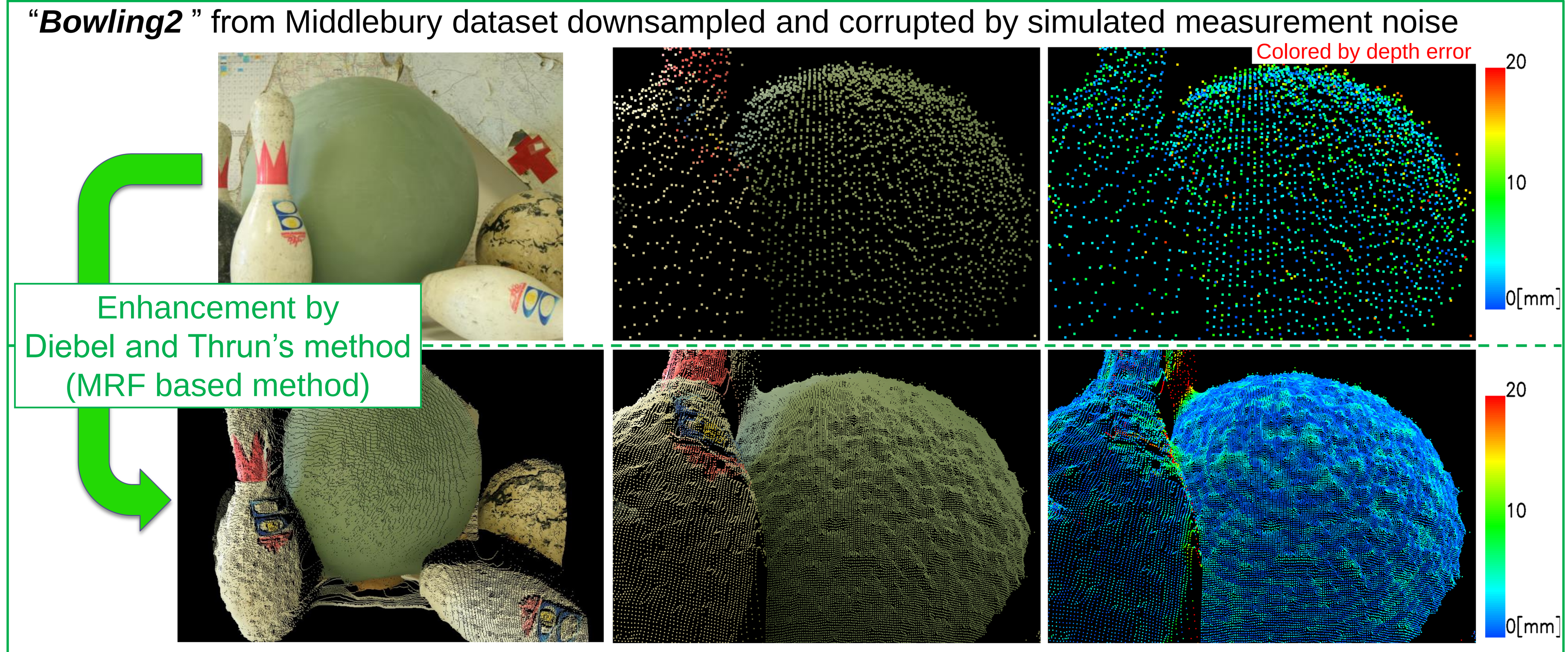
1. **Local measured depth data is summarized by using similarity weights.**
2. **Similarity weights are defined on the global image plane coordinates.** (pixel-distance, color-difference, depth gradient, and color geodesic distance, etc.)
3. **Depth enhancement is achieved by local calculations on the image grid.**

"Joint bilateral upsampling" [ACM transactions on Graphics 2007 Kopf et al.]
"Spatial-depth super resolution for range images" [CVPR 2007 Yang et al.]
"Pixel weighted average strategy for depth sensor data fusion" [ICIP 2010 Garcia et al.]
"Upsampling range data in dynamic environments" [CVPR 2010 Dolson et al.]
"Joint geodesic upsampling of depth images" [CVPR 2013 Liu et al.] etc.

Previous methods use the **pixel-coordinates**, that is not suitable to recover the smooth geometries of measured surfaces

Preliminary evaluation of a previous pixel-coordinate-based method

"*Bowling2*" from Middlebury dataset downsampled and corrupted by simulated measurement noise

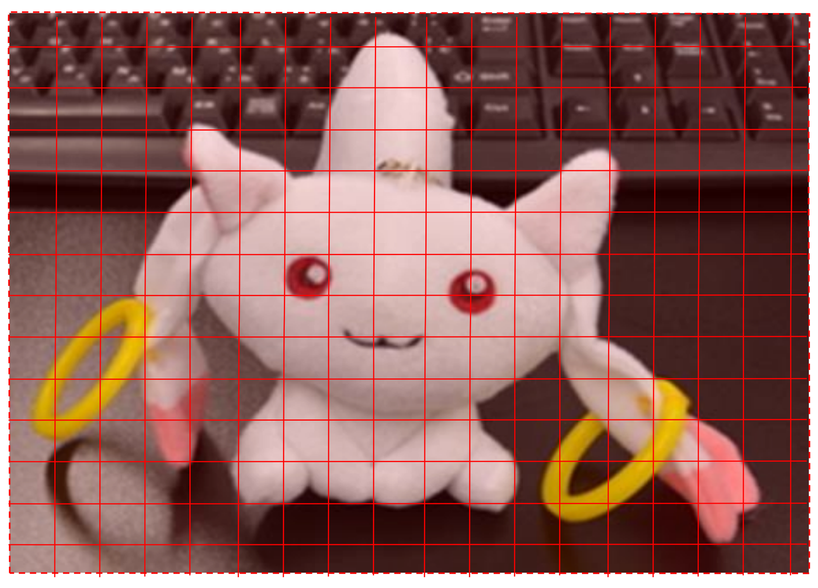


Granular noises are remained even on simple smooth surfaces.

Contributions

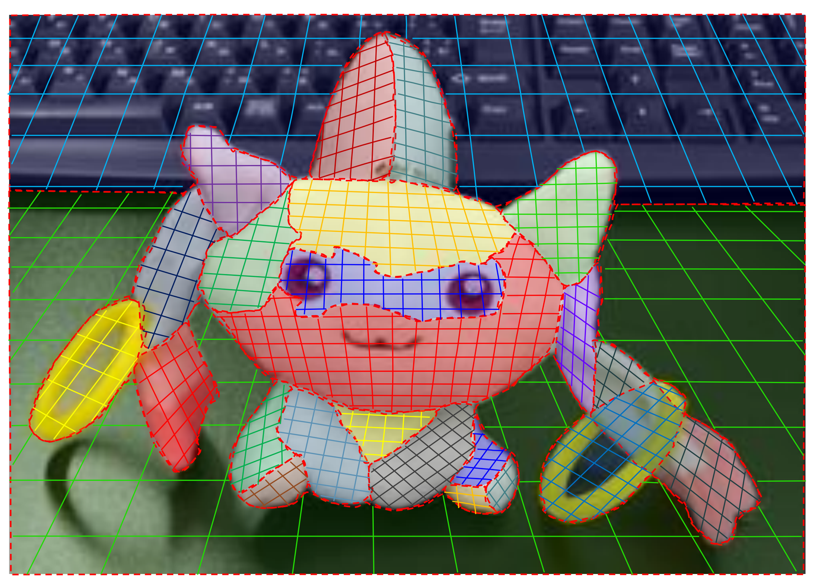
To improve enhancement accuracy, we introduce **local tangent planes as local coordinates to handle the geometries.**

Global coordinates



- pixel-coordinates of the image
- depend only on the measuring device (independent of the measuring surfaces)

Local coordinates



- charts defined on each local tangent
- depend on the local geometries of measuring surfaces

[**Challenging point**]
- Estimation of **the local tangent planes of the uncorrupted surfaces** from **a noisy low-resolution depth image**

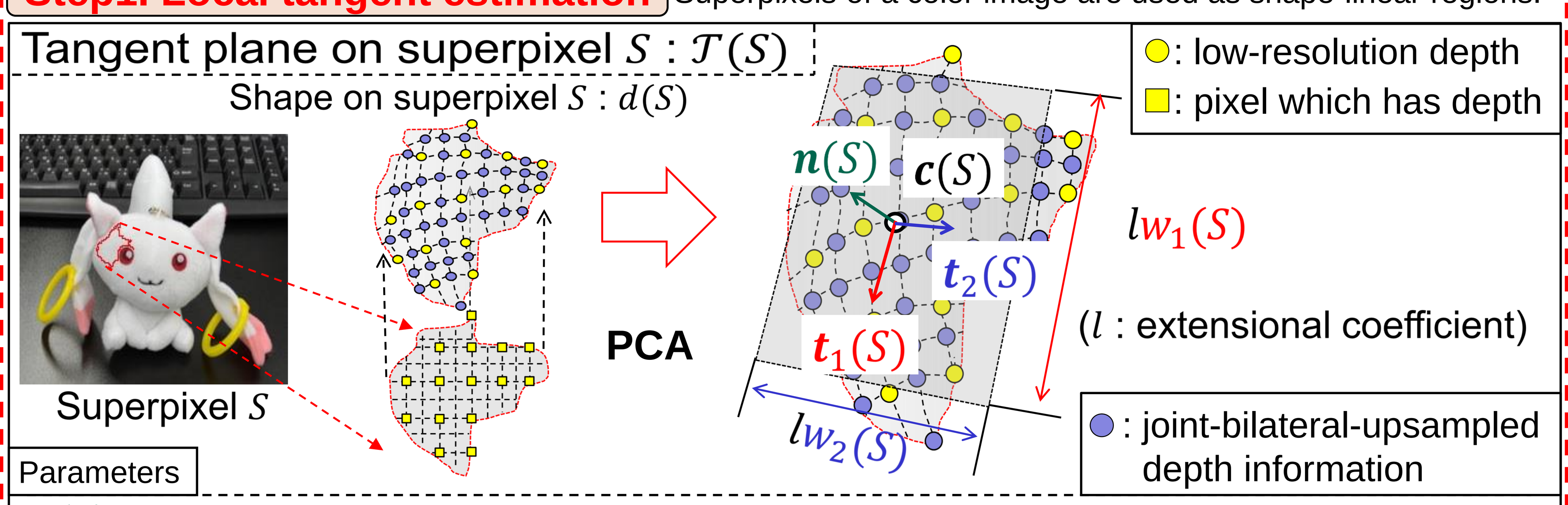
Proposed Method

Input data : A pair of images captured by a consumer RGB-D camera
Output data : A high-resolution and accurate depth image

Step1. Local tangent estimation Superpixels of a color image are used as shape-linear regions.

Tangent plane on superpixel S : $\mathcal{T}(S)$

Shape on superpixel S : $d(S)$

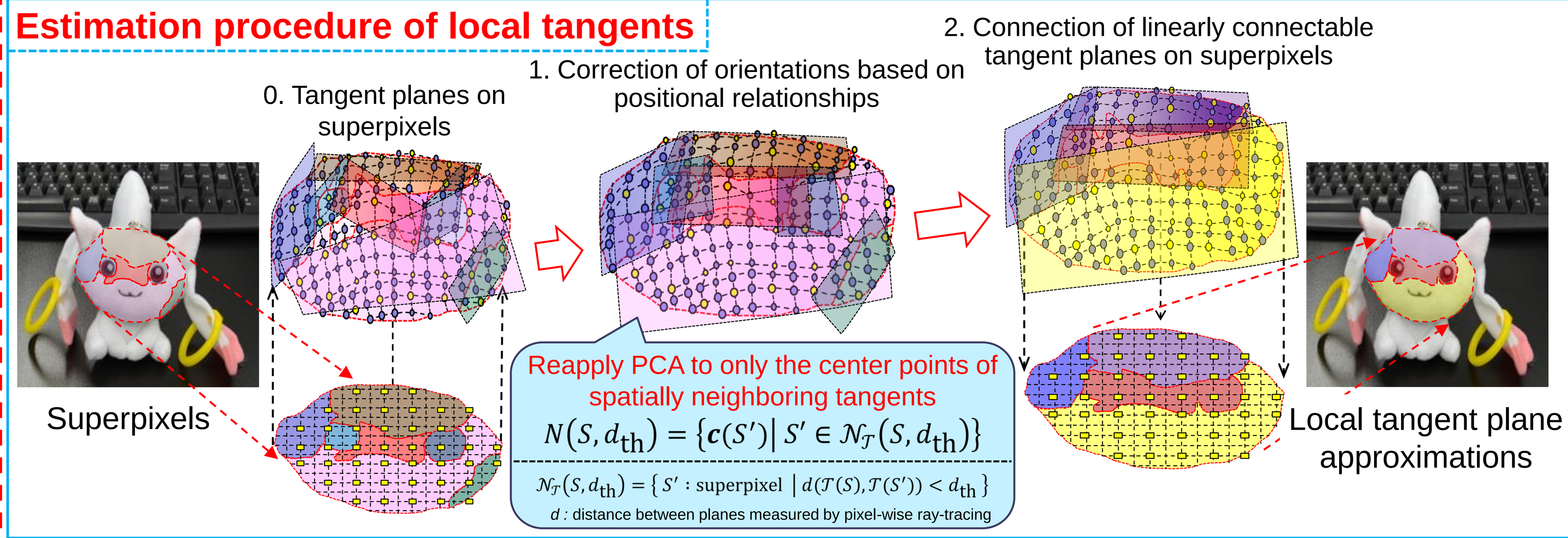


Parameters

$\boldsymbol{n}(S)$: normal vector $\boldsymbol{t}_1(S)$: tangent vector1 $w_1(S)$: square root of largest eigen value
$\boldsymbol{c}(S)$: center $\boldsymbol{t}_2(S)$: tangent vector2 $w_2(S)$: square root of second largest eigen value

Proposed in "Depth interpolation via smooth surface segmentation using tangent planes based on the superpixels of a color image" [ICCVW 2013 Matsuo and Aoki.]

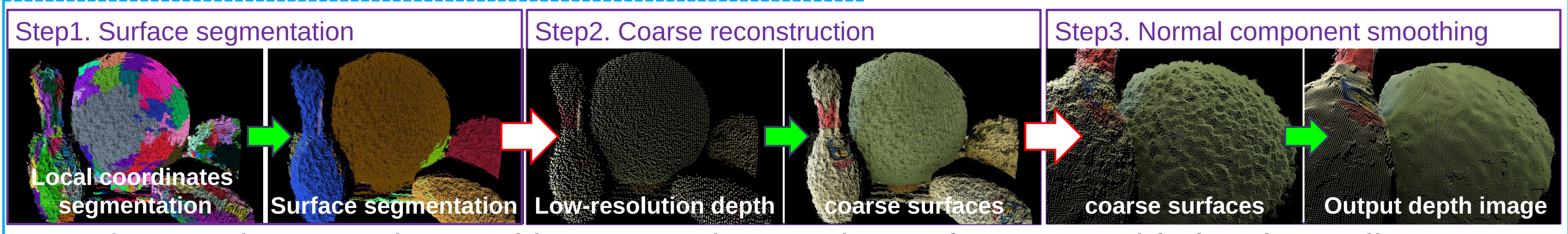
Estimation procedure of local tangents



This superpixel based method estimates **data-driven linear approximations** and recalculation of the orientations using center points provides **noise-robustness**.

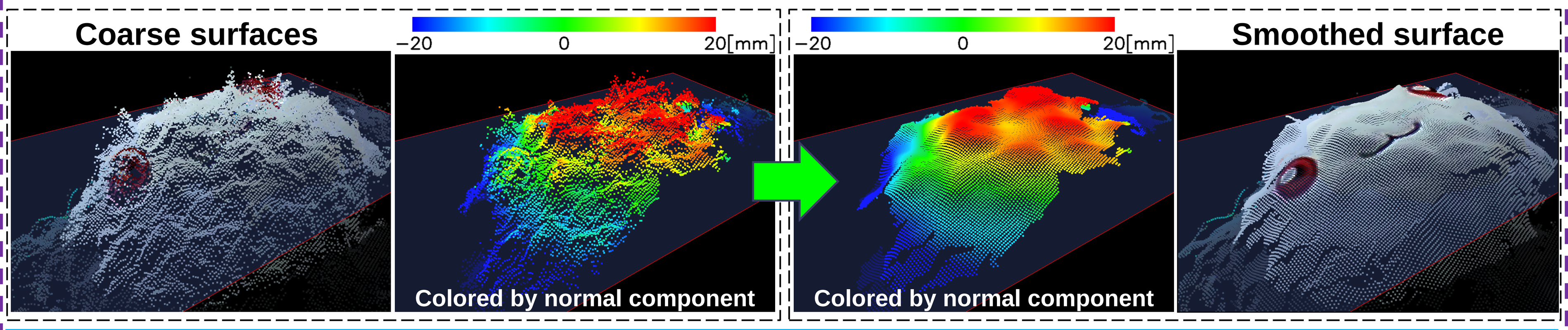
Step2. Surface reconstruction

Estimation procedure of surface reconstruction



1. Surface regions are detected by connecting continuously connectable local coordinates
2. Each surface is reconstructed by region-restricted JBU filter.
3. Normal direction components of surfaces are smoothed on each local coordinates

Step2-3. Normal component smoothing



Gaussian smoothing of normal components of surfaces

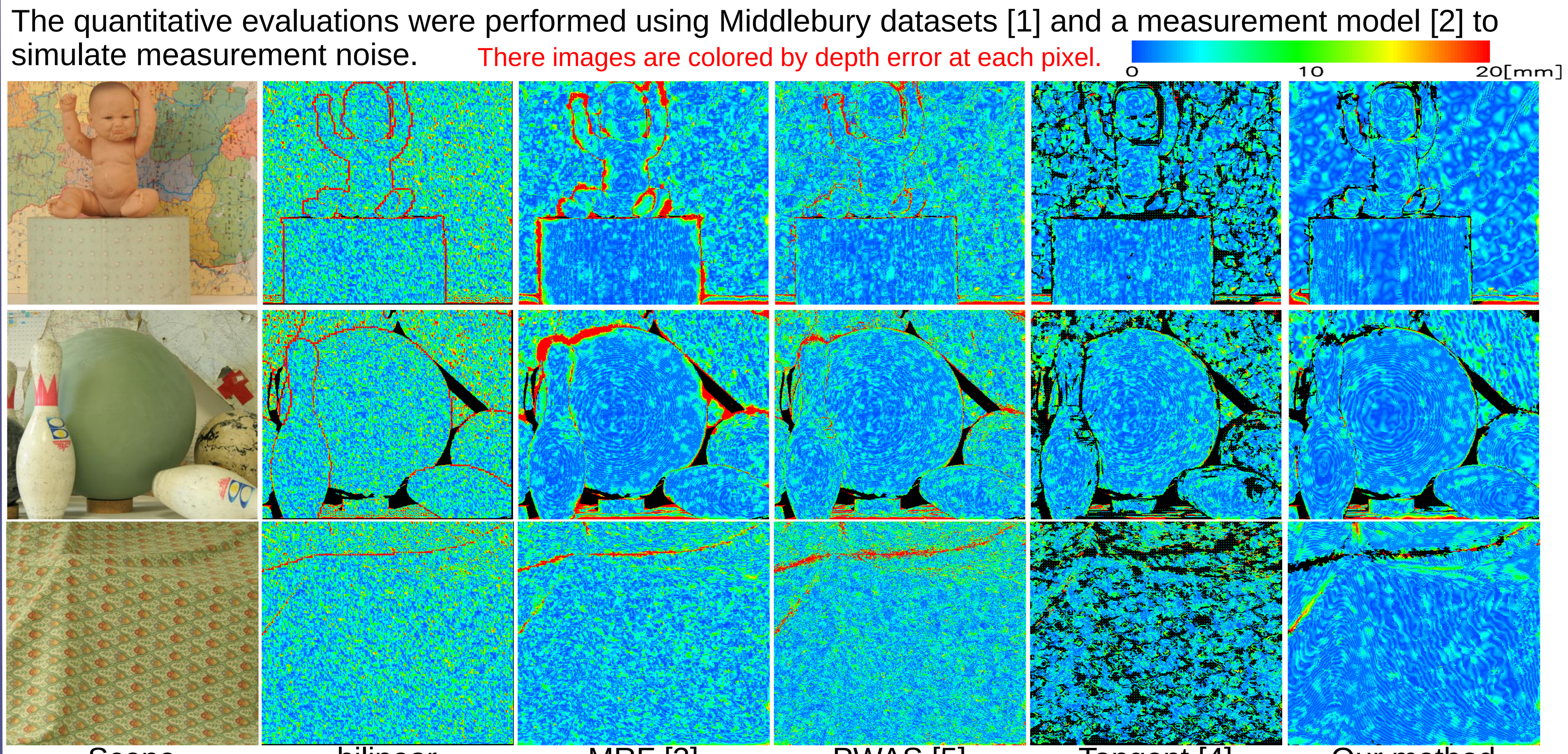
$$\tilde{\boldsymbol{x}} = \frac{1}{W}\sum_{\boldsymbol{x}' \in d(R)} w_{\mathrm{Gauss}}(|\boldsymbol{x}-\boldsymbol{x}'|_1)(\boldsymbol{x}', \boldsymbol{n}(R))\boldsymbol{n}(R) + \boldsymbol{x}_{\mathcal{T}}$$

$\boldsymbol{x}$: point R: local coordinates $\tilde{\boldsymbol{x}}$: smoothed point
$\boldsymbol{x}_{\mathcal{T}}$: tangential component of $\boldsymbol{x}$
w_{Gauss}: Gaussian weight function

These **filters on local coordinates** smooth the coarse surfaces while **preserving the local geometries** that are approximated by local tangent planes.

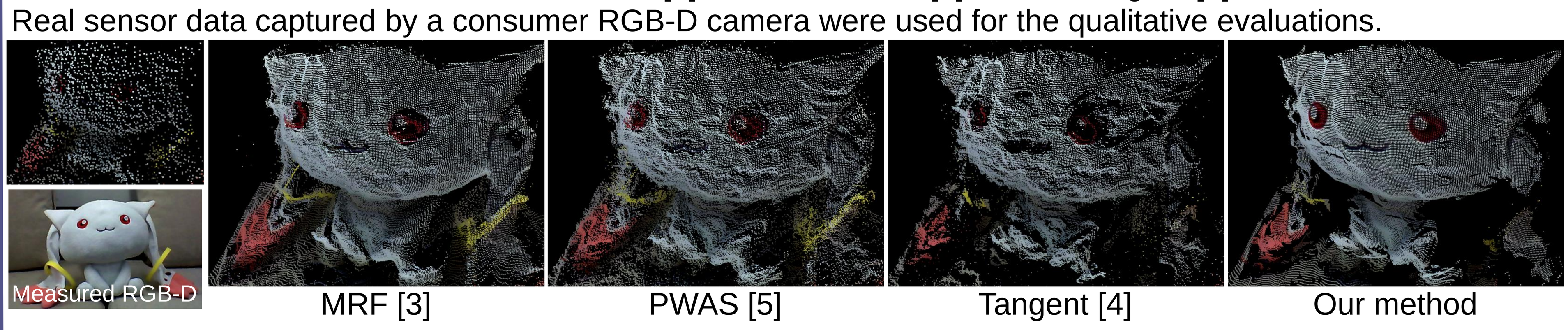
Experimental Results

The quantitative evaluations were performed using Middlebury datasets [1] and a measurement model [2] to simulate measurement noise. There images are colored by depth error at each pixel.



Scene | bilinear | MRF [3] | PWAS [5] | Tangent [4] | Our method

Real sensor data captured by a consumer RGB-D camera were used for the qualitative evaluations.



MRF [3] | PWAS [5] | Tangent [4] | Our method

The interior regions of surfaces were reconstructed more accurately.

[1] D. Scharstein and C. Pal. "Learning conditional random fields for stereo", CVPR2007.
[2] D. Anderson et al. "Experimental characterization of commercial flash ladar devices", International Conference of Sensing and Technology2005
[3] J. Diebel and S. Thrun. "An application of markov random fields to range sensing", NIPS2006
[4] K. Matsuo and Y. Aoki. "Depth interpolation via smooth surface segmentation using tangent planes based on the superpixels of a color image" ,ICCVW2013
[5] F. Garcia et al. "Pixel weighted average strategy for depth sensor data fusion", ICIP2010