Depth Image Enhancement Using Local Tangent Plane Approximations

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Project page

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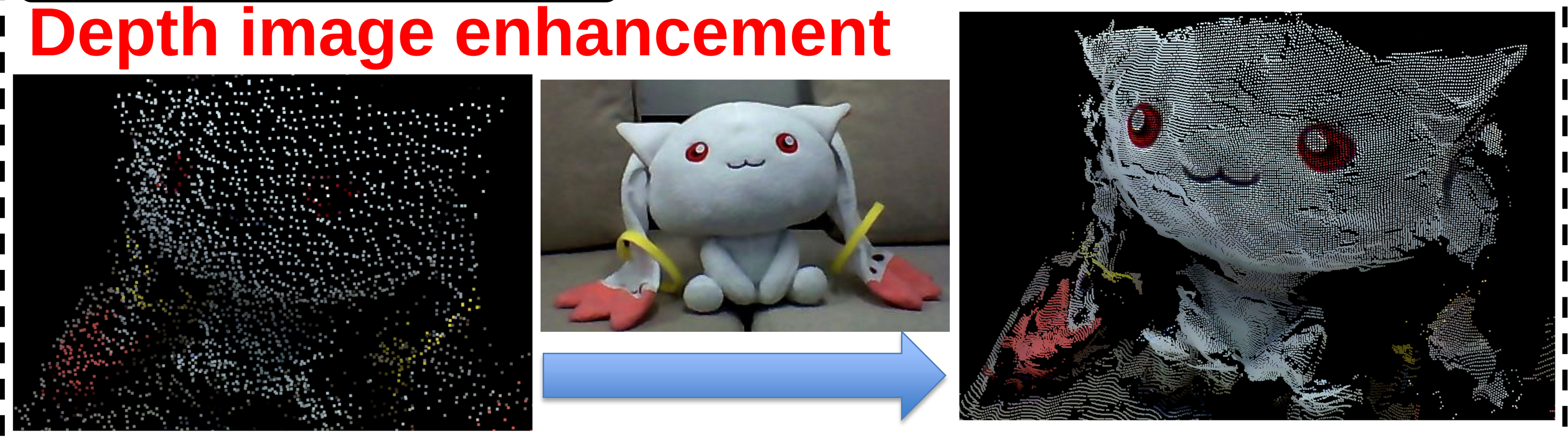
Introduction

Problem

Depth image enhancement



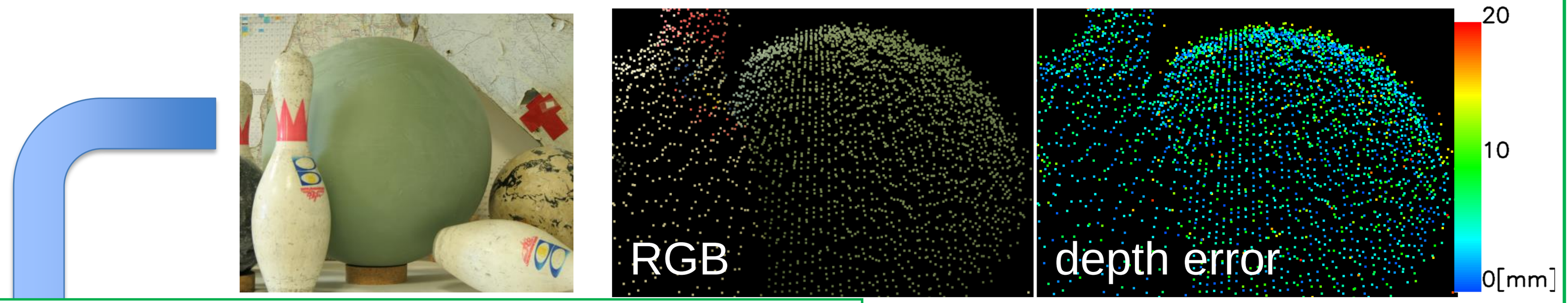
Input : A pair of images captured by a consumer RGB-D camera
Output : A high-resolution and accurate depth image

Background

Most existing previous methods use the **pixel-coordinates** of the aligned color image to smooth and upsample the surfaces.
But global coordinates are not suitable to handle the geometries.

Preliminary evaluation of a previous global-coordinate-based method

"*Bowling2*" from dataset [1] corrupted by simulated measurement noise [2]



Enhancement by MRF based method [3]

Granular noises are remained even on simple smooth surfaces.

More precise geometries of the measured surfaces should be taken into account to recover smooth surfaces.

Contributions

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

[Challenging points]

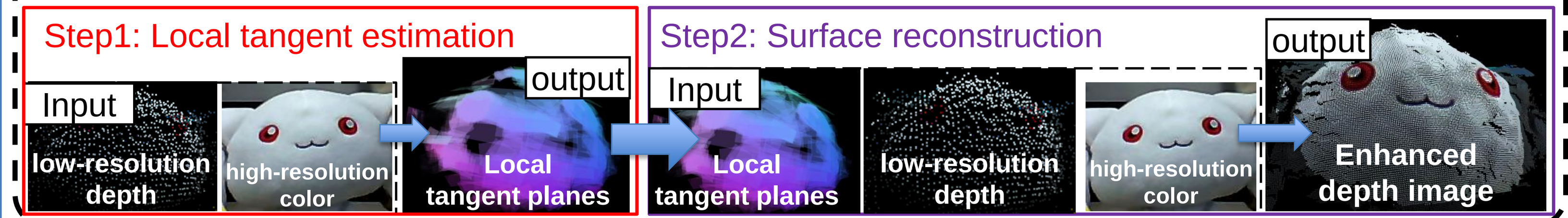
1. Estimation of **the local tangent planes of the uncorrupted surfaces** from **a noisy low-resolution depth image**
2. Reconstruction of the smooth surfaces from the estimated local tangent planes and a noisy low-resolution depth image

Proposed Method

Overview

Proposed method is composed of following two steps :

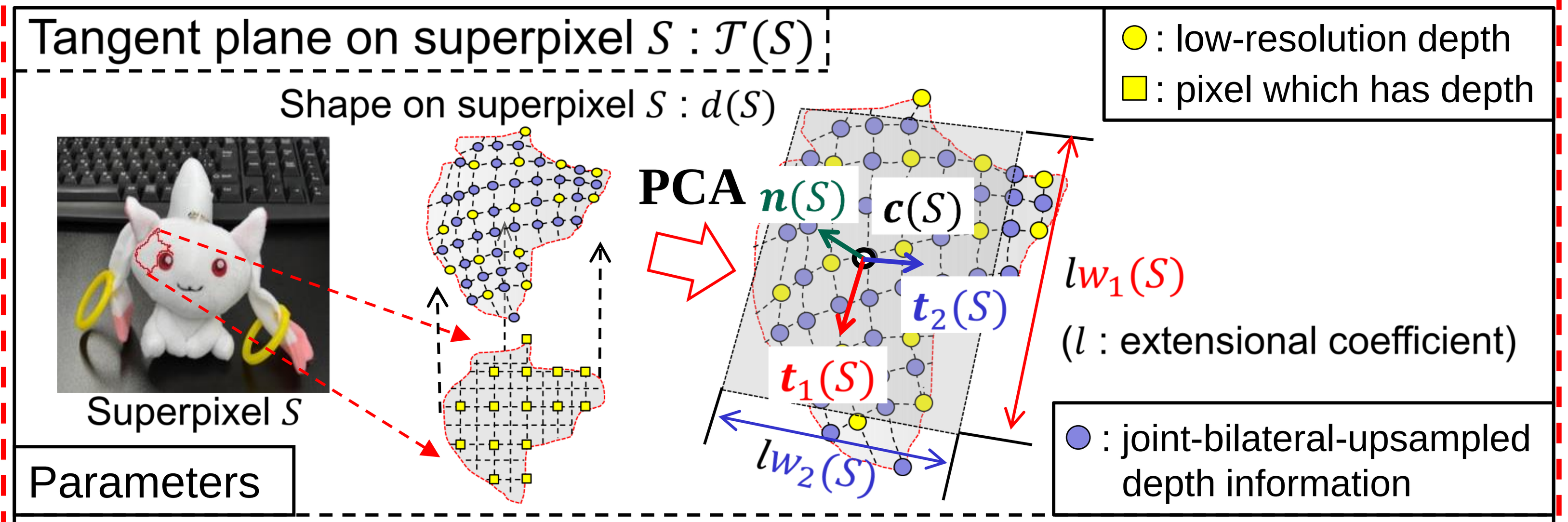
1. Step that estimates the local tangent planes
2. Step that reconstructs surfaces using estimated local tangents



Step1. Local tangent estimation

Superpixels of a color image are used as shape-linear regions.

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



Parameters

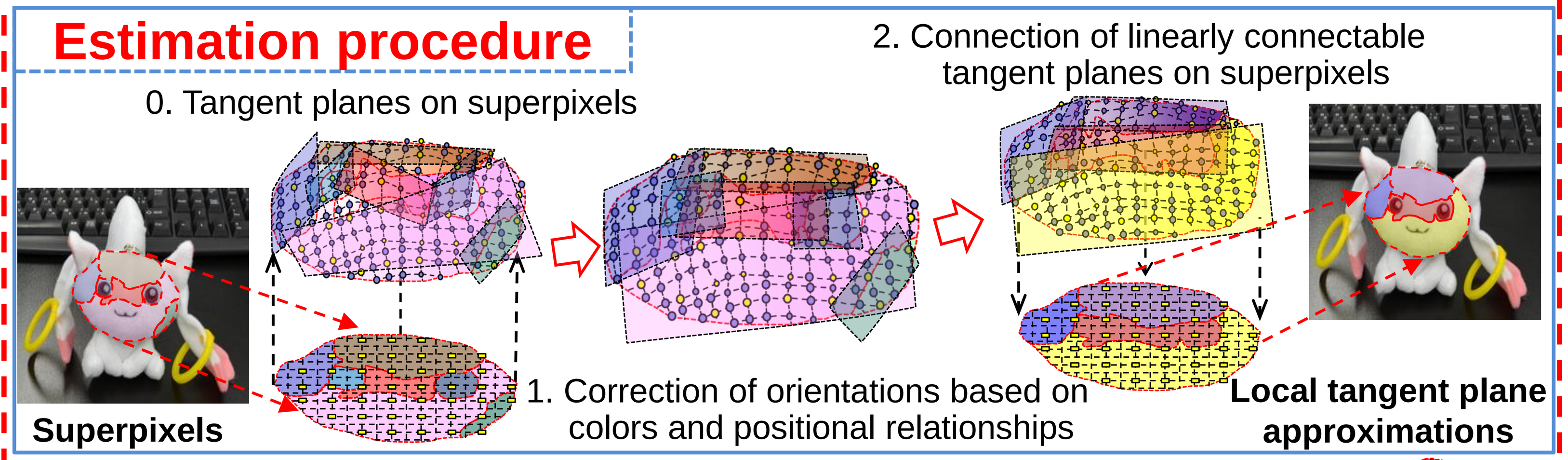
$n(S)$: normal vector $t_1(S)$: tangent vector1 $w_1(S)$: square root of largest eigen value
$c(S)$: center $t_2(S)$: tangent vector2 $w_2(S)$: square root of second largest eigen value

We use tangent planes on superpixels[4] to detect local tangents.
Merit : data-driven accurate approximations of smooth surfaces
Demerit : unstable on the shape-boundaries and noise sensitive

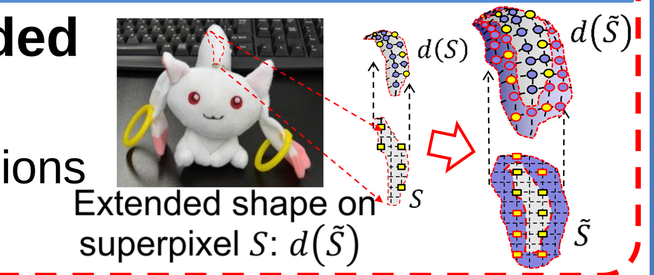
To overcome these disadvantages, two processes are added.

1. Correction of the orientations based on colors and positions
2. Connection of the linearly connectable tangents

Estimation procedure



To correct steep tangent planes, **extended shapes on superpixels** are used.
Tangent planes are recalculated on wider regions than superpixels to improve the accuracy.



Step1-1-1. Correction based on color

To prevent inaccurate estimation of tangents near surface-boundaries, we introduce a **color-heuristic PCA**.

Color heuristic covariance matrix (color-difference weighted covariance matrix)

$$\mathbf{A}_{\mathrm{color}}\left(d(\tilde{S})\right) = \frac{1}{W}\sum_{\boldsymbol{x}\in d(\tilde{S})} w(|\boldsymbol{i}(\boldsymbol{x}) - \boldsymbol{i}_S|_1)(\boldsymbol{x} - \boldsymbol{c}_{\mathrm{color}}(\tilde{S}))(\boldsymbol{x} - \boldsymbol{c}_{\mathrm{color}}(\tilde{S}))^T$$

$\boldsymbol{i}(\boldsymbol{x})$: RGB-color of point $\boldsymbol{x}$ — $\boldsymbol{i}_S$: average RGB-color on superpixel S
w : weight function, $w(t) = \exp(-t)$ — W : total weighted sum $W = \sum_{\boldsymbol{x}\in d(\tilde{S})} w(|\boldsymbol{i}(\boldsymbol{x}) - \boldsymbol{i}_S|_1)$
$\boldsymbol{c}_{\mathrm{color}}(\tilde{S})$: color-difference weighted center point of $d(\tilde{S})$

The tangent plane defined by this covariance matrix spreads to neighboring regions similarly-colored to the superpixel.
We use this tangent planes instead of steep tangent planes.

Step1-1-2. Correction based on positional relationships

To smooth connections between tangent planes on superpixels, we reapply PCA to only the center points of neighboring tangents.

Center points of spatially neighboring tangent planes

$$N(S, d_{\mathrm{th}}) = \{\boldsymbol{c}(S') \mid S' \in \mathcal{N}_{\mathcal{T}}(S, d_{\mathrm{th}})\}$$

$$\mathcal{N}_{\mathcal{T}}(S, d_{\mathrm{th}}) = \{S' : \text{superpixel} \mid d(\mathcal{T}(S), \mathcal{T}(S')) < d_{\mathrm{th}}\}$$

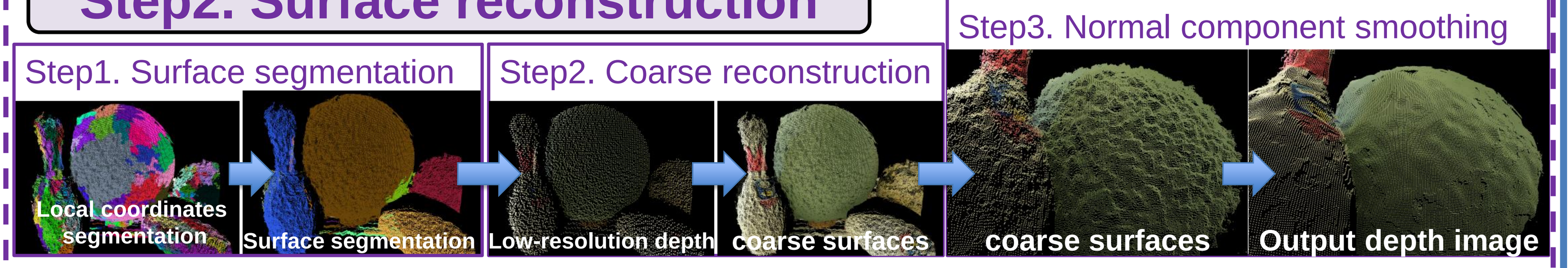
d : distance between planes measured by pixel-wise ray-tracing

Each center point is robust to measurement noise and are widely distributed on the surfaces that the tangents are approximating.
We simply apply PCA to only these center points to estimate local orientations of uncorrupted surfaces.

Step1-2. Connection of linearly connectable tangents

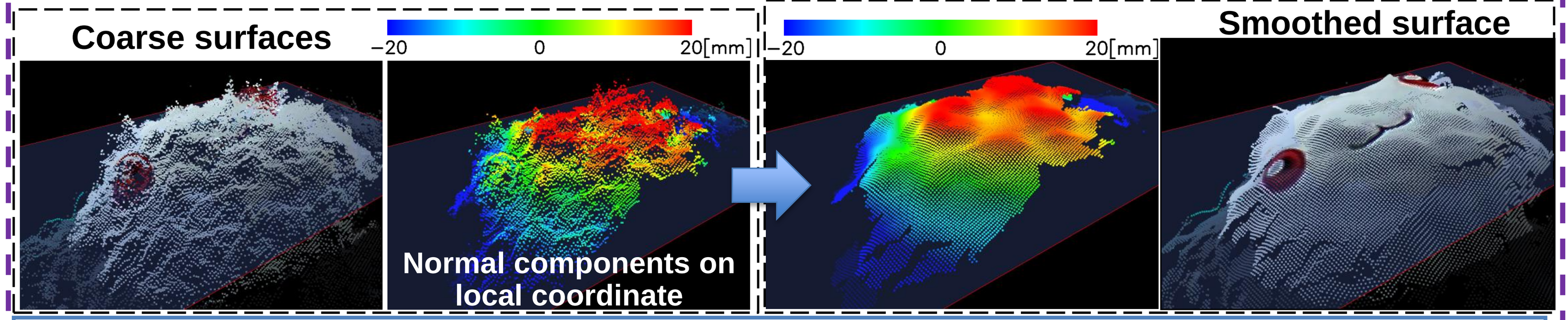
We connect superpixels that have spatially neighboring and similar normal tangent planes.
Shapes on the connected regions are almost linear and are approximated by local tangent planes.

Step2. Surface reconstruction



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

Step2-4. Normal component smoothing



Gaussian smoothing of normal components of surfaces

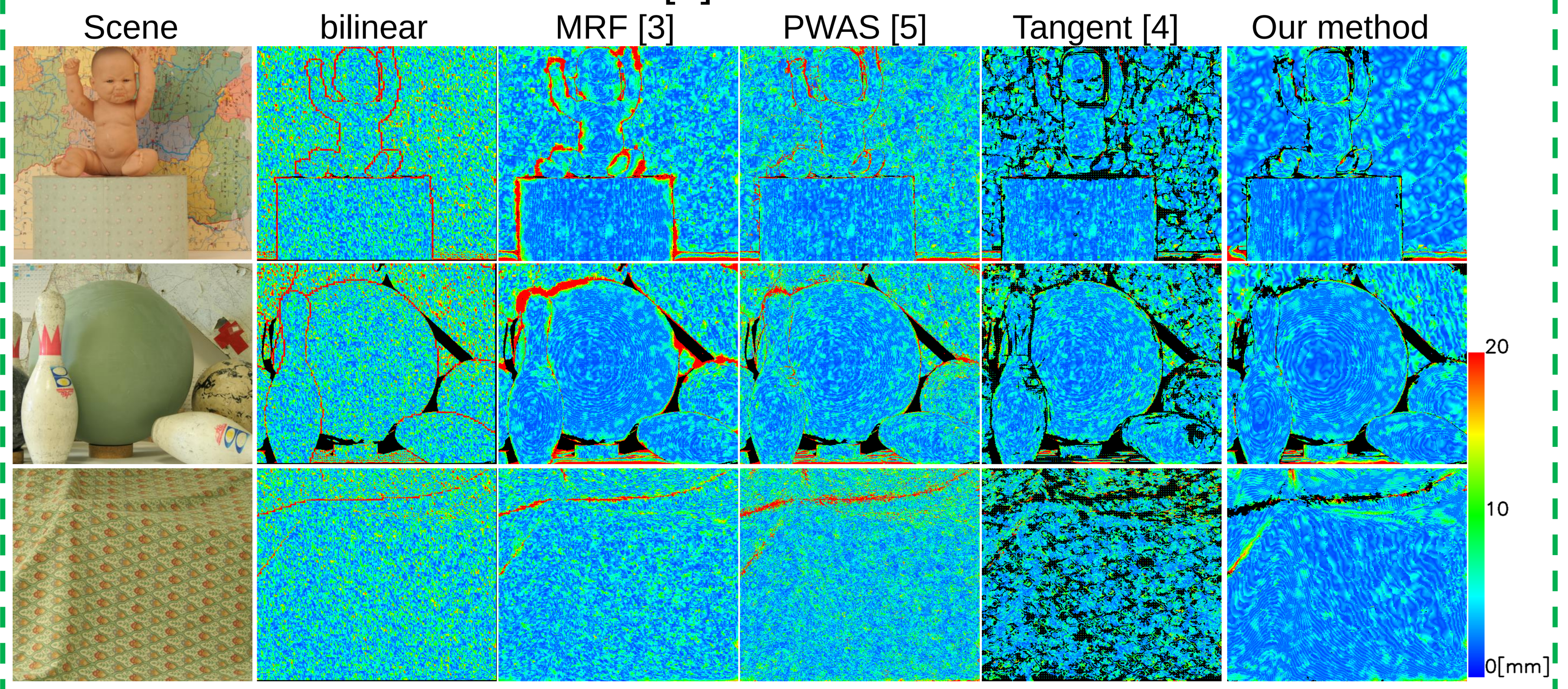
$$\tilde{\boldsymbol{x}} = \frac{1}{W}\sum_{\boldsymbol{x}'\in d(R)} w_{\mathrm{Gauss}}(|\boldsymbol{x} - \boldsymbol{x}'|_1)(\boldsymbol{x}', \boldsymbol{n}(R))\boldsymbol{n}(R) + \boldsymbol{x}_{\mathcal{T}}$$

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

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

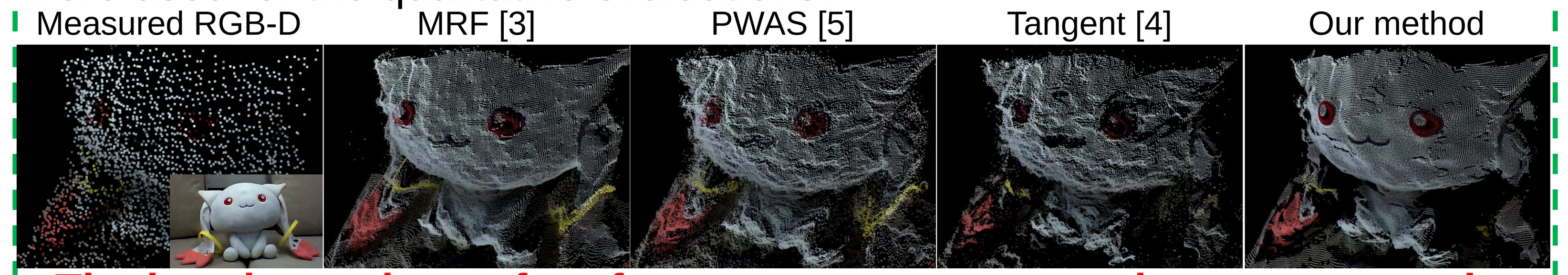
Experimental Results

The quantitative evaluations were performed using Middlebury datasets [1].
We used a measurement model [2] to simulate measurement noise.



Resulting enhancement error at each pixel (upsampling rate = x4x4).

Real sensor data captured by a consumer RGB-D camera (SoftKinetic DS311) were used for the qualitative evaluations.



The interior regions of surfaces were reconstructed more accurately.

Conclusions : We propose an estimation procedure for local tangents, and we show that accurate depth image enhancement is achieved by the local geometries approximated by the local tangent planes.

References:
[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