Robust Non-Local Denoising of Colored Depth Data

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Motivation

- high noise-level of time-of-flight cameras
- **denoising in 2D** domain:
  - additive noise in viewing direction
  - known neighborhood structure
  - techniques from image restoration
- two kinds of noise:
  - inaccuracies
  - outliers
Overview

- previous work
  - outlier detection
  - smoothing algorithms
- robust non-local denoising of depth data
  - outlier detection for unbiased smoothing
  - smoothing (new variant of NL-means)
  - integration of color-data
- results
Tensor Voting

- **outlier detection** in the tensor voting framework
  - surfaceness
  - curveness
  - junctionness

- initialization similar to PCA on nearest neighbors
- voting of neighbored tensors
- inverse of junctionness ($\approx$ anisotropy of covariance)
Neighborhood Filters

Smith & Brady, 1995 / Tomasi & Manduchi, 1998

- bilateral filter:
  
  weight neighbors by distance in the range domain
  
  \[
  v'(i) = \frac{1}{Z_i} \sum_{j \in I} v(i) e^{-\frac{1}{\sigma_i^2} \|i-j\|^2} e^{-\frac{1}{\sigma_r^2} (v(i)-v(j))^2}
  \]

- influence function:

- cross/joint bilateral filter for multi-modal data
MRF-based Smoothing

• global optimization
• sum of potential functions:
  – data term
  – smoothing prior
• optimization difficult for non-convex potentials
• learned priors (*Fields of Experts*, Roth & Black, 2005)
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- sum of potential functions:
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- optimization difficult for non-convex potentials
- learned priors (*Fields of Experts*, Roth & Black, 2005)
- image gradients can support features (edges):
  - super-resolution application (Diebel & Thrun)
Non-Local Means Filter (NL-Means)

- patch-based extension of the bilateral filter
  \[ v'(i) = \sum_{j \in W_i} w(i, j)v(j) \]
- more robust similarity measure
  \[ w(i, j) = \frac{1}{Z_i} e^{-\frac{1}{h^2} \sum_{k \in N} G_{\alpha}(\|k\|_2)(v(i+k)-v(j+k))^2} \]
- related to texture synthesis (Efros & Leung, 1999)
- conserves repetitive fine detail structures
our approach

ROBUST NON-LOCAL DENOISING OF COLORED DEPTH DATA
Outlier Detection in the NL-Framework

- **NL-means:**
  - estimator of pixel value given its surrounding
    
    \[ p(v(i)|\{v(i + k)\}_{k \in \mathbb{N}}) \]

- **Idea:**
  - detect abnormalities (outliers) using this estimate
  - iterative algorithm (generalized EM), assuming

    \[ p_{mix}(v(i)|v(N_i^*)) = \alpha p_{inlier}(v(i)|v(N_i^*)) + p_{outlier}(v(i)|v(N_i^*)) \]
Smoothing with NL-Means

- artifacts on smooth surfaces near strong edges

- no smoothing perpendicular to near edges

- dilemma: big patches/smoothing near edges
A new variant of NL-Means

- intra-patch similarity:
  - additional weights

\[ \xi_{ik} = e^{-\frac{(v(i) - v(i+k))^2}{h}} \]

- distinguish distant regions (different surfaces)
Integration of Color-Data

- analog to joint bilateral filter (e.g. Kopf et al., 2007)
- make use of statistical dependence when estimating

\[ p(v(i)|\{v(i+k)\}_{k\in\mathbb{N}}) \]

- introducing additional weighting term

\[ v'_{uv}(i) = \sum_{j\in W_i} w(i,j) w^{(u)}(i,j) v(j) \]
Results: Our Setup

- time-of-flight camera PMD Vision 19k
  - 120x160 pixels, laterally calibrated
  - additional color camera

- GPU implementation:
  - CUDA on NVidia GeForce 8800GTX
  - 17x17 window, 7x7 patches
  - 10 iterations
  - 1.9 sec/frame
Results: Outlier Detection

tensor voting  

our approach
Results: Raw Input Data
Results: MRF-based Smoothing
Results: Joint Bilateral Smoothing
Results: Robust Non-Local Denoising
Results: Joint Bilateral, Detail View
Results: Robust NL, Detail View
Method Noise

- difference image (before/after denoising)

joint bilateral filter  robust NL
Conclusion

• new depth map denoising based on image restoration technique:

  **Robust Non-Local Denoising**
  – outlier detection for unbiased smoothing
  – intra-patch similarity for strong discontinuities
  – integration of color

• parallelized implementation
Thanks for your attention!