Big Snapshot Stitching with Scarce Overlap
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September 12, 2013
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### Example Multi-Camera Systems

**Higher-end performance through lower-end cameras**

<table>
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<th>System</th>
<th>Overlap ratio</th>
<th>Key feature</th>
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<tr>
<td>A Stanford Multi-Camera Array (mode 1)</td>
<td>~ 90%</td>
<td>high frame-rate video; synthetic aperture</td>
<td>1</td>
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<tr>
<td>B Stanford Multi-Camera Array (mode 2)</td>
<td>~ 50%</td>
<td>high resolution eFOV</td>
<td>1</td>
</tr>
<tr>
<td>C AWARE-2</td>
<td>~ 10%</td>
<td>high resolution eFOV</td>
<td>2, 3</td>
</tr>
<tr>
<td>D ARGUS-IS</td>
<td>~ 5%</td>
<td>high resolution eFOV</td>
<td>4</td>
</tr>
<tr>
<td>Single-camera sweep over stationary scene</td>
<td>variable</td>
<td>high resolution eFOV</td>
<td>5</td>
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**overlap**

- A: large, dense
- B: small, dense
- C: small, sparse
- D: small, sparse

---

AWARE-2 Prototype: 2 Gigapixels, 120° FOV

- Gigapixel-resolution snapshots
- Independent focus & exposure
- Complex configuration on a hemisphere
- Parallax-free design


Ghosting & De-ghosting

Ghosted image

De-ghosted using our pipeline

Both results from the AWARE-2 dataset
Ghosting & De-ghosting

Both results from the AWARE-2 dataset

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Ghosting & De-ghosting

Ghosted image

De-ghosted using our pipeline

Both results from the AWARE-2 dataset
Ghost Sources

- Static/systematic:
  - Deviations from design during manufacturing
  - Displacement in array mounting

- Transient/scene-dependent:
  - Variable camera viewpoints*
  - Independent camera parameters & settings
  - Thermal & mechanical drift

* The AWARE-2 design is parallax-free
Ghost Sources

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*The AWARE-2 design is parallax-free

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1 D.R. Golish *et al.* *Optics Express* 20:20, 2012
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*The AWARE-2 design is parallax-free*
Gigapixel Imaging Applications

- Survey, cataloging and monitoring of:
  - urban and suburban development\(^1\)
  - wild-life habitats\(^2\)
  - cultural legacy\(^3,4\)

- Exploration and dynamics of celestial bodies\(^5,6\)

- Recognition\(^7\)

- Surveillance\(^8\)

---

Stitching Software

- GigaPan Stitch\textsuperscript{1}
- Autopano Giga\textsuperscript{2}
- Microsoft ICE\textsuperscript{3}
- Autostitch\textsuperscript{4}
- Panorama Tools\textsuperscript{5}
- Fiji\textsuperscript{6}
- ...

Challenged by sparse, irregular, and noisy overlap

---

1 gigapan.com/
2 autopano.net/
3 research.microsoft.com/en-us/UM/redmond/groups/IVM/ICE/
4 www.cs.bath.ac.uk/brown/autostitch/autostitch.html
5 panotools.sourceforge.net/
6 http://fiji.sc/
FoV Overlap: Sparse, Irregular, Noisy (S.I.N.)

Note: AWARE-10 is coming out
FoV Overlap: Sparse, Irregular, Noisy (S.I.N.)

Note: AWARE-10 is coming out
Introduction

2 De-ghosting
   ■ Overview
   ■ Pairwise registration
   ■ Global bundle adjustment
   ■ Fusion

3 Illustrations

4 Discussion

5 Acknowledgments
De-ghosting: 3 Key Steps

- Pairwise registration
- Global bundle adjustment among multiple images
- Blending/fusion in the gradient domain
De-ghosting Pipeline

**Raw Images, Flat-fields**

1. **Geometric Alignment**
2. **Feature Extraction**
3. **Reliable Feature Matching**
4. **Global Bundle Adjustment**

**Approximate Overlapping Regions**

- **Block Operator**
- **Pixel-wise Operator**

**Gradient Computation**

**Gradient Integration**

**Fusion** → **Mosaic**

Computational bottlenecks

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Big Snapshot Stitching with Scarce Overlap

Duke, AUTh

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De-ghosting Pipeline

- **Raw Images, Flat-fields**
- **Geometric Alignment**
- **Fusion**

**Steps:**
- **Approximate Overlapping Regions**
- **Feature Extraction**
- **Reliable Feature Matching**
- **Global Bundle Adjustment**
- **Gradient Computation**
- **Gradient Integration**

**Computational Bottlenecks:**
- **Block Operator**
- **Laplacian Solver**
- **Pixel-wise Operator**

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Big Snapshot Stitching with Scarce Overlap
De-ghosting Pipeline

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Block Operator
Laplacian Solver
Pixel-wise Operator

Fusion

Gradient Computation
Gradient Integration
Mosaic

computational bottlenecks

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Duke, AUTh
De-ghosting Pipeline

Raw Images, Flat-fields

- Geometric Alignment
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- Feature Extraction
  - Block Operator
- Reliable Feature Matching
  - Laplacian Solver
- Global Bundle Adjustment
- Gradient Computation
  - Pixel-wise Operator
- Mosaic

Approximate overlapping regions lead to reliable feature matching, which in turn leads to global bundle adjustment. This process is part of the de-ghosting pipeline, with computational bottlenecks highlighted.

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Big Snapshot Stitching with Scarce Overlap
De-ghosting Pipeline

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**Block Operator**

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computational bottlenecks

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- **Computational Bottlenecks**
  - Block Operator
  - Laplacian Solver
  - Pixel-wise Operator

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Pipeline Performance

- Approaching real-time performance is important
- Moving cameras
- Video applications
- Utilization of modern architectures: multi-core and GPU
- Algorithms tailored for bridging applications and architectures
- Processing a mosaic of $\sim 100$ MP (10 micro-cameras)
  - $24 \times$ AMD Opteron @1.9 MHz, 64 GB RAM, NVIDIA Tesla K20c
  - Naïve serial implementation: 3.5 hours
  - Current pipeline: 50 seconds*

* $\sim 25$ seconds are overhead related to MATLAB-CUDA communication
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Textbook Alignment: Features

- Find similar-looking locally distinctive image regions, or “features”
- But there are mismatches, or “outliers”
Textbook Alignment: RANSAC

- Correct matches are consistent with a single transformation (ideally)
- Determine transformations from small random subsets
- Choose transformation with most consenting feature matches


Pairwise Registration

Sparse, Irregular, Noisy overlapping regions

SIFT

“broken”

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Big Snapshot Stitching with Scarce Overlap
Pairwise Registration

Sparse, Irregular, Noisy overlapping regions

Geometric configuration

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Big Snapshot Stitching with Scarce Overlap
Pairwise Registration

Speed-up by algorithm & GPU: >1000x!

SIFT

computation-intensive SiftGPU by C.C. Wu

PG-RANSAC

Sparse, Irregular, Noisy overlapping regions

anchor points

reliable control points

preconditioning

Geometric configuration

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1 http://cs.unc.edu/~ccwu/siftgpu

Big Snapshot Stitching with Scarce Overlap
Placement Geometry preserving RANSAC (PG-RANSAC)

- RANSAC variants minimize a ranking function $r$:
  \[ \theta_* = \arg \min_{\theta} \sum_{i=1}^{N} r(d_i, M(\theta), \theta_0) \]

- PG-RANSAC ranking:
  \[ r(d, M(\theta), \theta_0) = f(\theta, \theta_0) \cdot \frac{\rho(d, M(\theta))}{\tau_\theta N} \]

rank points & models
Placement Geometry preserving RANSAC (PG-RANSAC)

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 rank points & models

---

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  \]

- PG-RANSAC ranking:
  \[
  r(d, M(\theta), \theta_0) = f(\theta, \theta_0) \cdot \frac{\rho(d, M(\theta))}{\tau_\theta N}
  \]
  
  \( \rho(d, M(\theta)) \) is the normalization factor.

---

RANSAC variants minimize a ranking function $r$:

$$\theta_* = \arg \min_{\theta} \sum_{i=1}^{N} r(d_i, \mathcal{M}(\theta), \theta_0)$$

PG-RANSAC ranking:

$$r(d, \mathcal{M}(\theta), \theta_0) = f(\theta, \theta_0) \cdot \frac{\rho(d, \mathcal{M}(\theta))}{\tau_\theta N}$$

where $f(\theta, \theta_0) = \frac{1}{1 + e^{-\alpha[(\theta - \theta_0) - \tau \theta]}} \cdot \frac{1}{1 + e^{\alpha[(\theta - \theta_0) - \tau \theta]}}$ (logistic “box”)

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Global Bundle Adjustment*

- Adhere to geometric configuration

  (variational 1) \( \min_{\{H_i\}} \sum_{D_{ij} \neq \emptyset} \sum_{x_k \in D_{ij}} w_{ij} \left\| x_{k,i}^T H_i - x_{k,j}^T H_j \right\|_2 \)

  (variational 2) \( \min_H \|W E_x H\|_2 \)

  Edge incidence block-matrix

- Weights: \( w_{ij} = \frac{1}{|D_{ij}|} \)

  - Normalize edge contribution to solution
  - “Weak” edges may be down-weighted

* Note that here we are only concerned with the 2D mosaic, not the 3D structure of the scene
Global Bundle Adjustment – Fast & Robust Solution

\[
\begin{bmatrix}
W_{R,2} \\
W_{R,3} \\
\vdots \\
W_{R,6} \\
W_{2,3} \\
W_{2,6}
\end{bmatrix}
\begin{bmatrix}
x_{R,2} \\
x_{R,3} \\
\vdots \\
x_{R,6} \\
x_{2,3} \\
x_{2,6}
\end{bmatrix}
- \begin{bmatrix}
x_{2,R} \\
0 \\
\vdots \\
0 \\
x_{3,2} \\
0
\end{bmatrix}
- \begin{bmatrix}
x_{3,R} \\
0 \\
\vdots \\
0 \\
x_{6,2} \\
0
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
\vdots \\
0 \\
x_{6,R} \\
x_{6,2}
\end{bmatrix}
\]

\[
\begin{bmatrix}
X_{R,2} \\
X_{R,3} \\
\vdots \\
X_{R,6} \\
X_{2,3} \\
X_{2,6}
\end{bmatrix}
- \begin{bmatrix}
x_{2,R} \\
0 \\
\vdots \\
0 \\
x_{3,2} \\
0
\end{bmatrix}
= \begin{bmatrix}
x_{3,R} \\
0 \\
\vdots \\
0 \\
x_{6,2} \\
0
\end{bmatrix}
\]

Fix frame \( R \); normal/Laplace equation, \( \mathbf{L}_{\tilde{R}} \mathbf{H}_{\tilde{R}} = \mathbf{B}_R \)

\[
\mathbf{L}_{\tilde{R}} =
\begin{bmatrix}
\sum_j (x_{2,j}^\top w_{2,j}^2 x_{j,2}) \\
-x_{3,2}^\top w_{2,3}^2 x_{3,2} \\
\sum_j (x_{3,j}^\top w_{3,j}^2 x_{j,3}) \\
-x_{6,2}^\top w_{2,6}^2 x_{2,6} \\
\sum_j (x_{6,j}^\top w_{6,j}^2 x_{j,6})
\end{bmatrix}
\]

\[
\mathbf{H}_{\tilde{R}} =
\begin{bmatrix}
H_{R} \\
H_{2} \\
H_{3} \\
H_{6}
\end{bmatrix}
\]

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Big Snapshot Stitching with Scarce Overlap
Global Bundle Adjustment – Fast & Robust Solution

- **W**
  \[
  \begin{pmatrix}
  W_{R,2} \\
  W_{R,3} \\
  \vdots \\
  W_{R,6} \\
  W_{2,3} \\
  W_{2,6}
  \end{pmatrix}
  \]
  - **E**
  \[
  \begin{pmatrix}
  x_{R,2} & -x_{2,R} & 0 & \cdots & 0 \\
  0 & x_{2,3} & -x_{3,2} & \cdots & 0 \\
  0 & 0 & x_{3,6} & \cdots & -x_{6,2} \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  \end{pmatrix}
  \]
  - **H**
  \[
  \begin{pmatrix}
  H_R \\
  H_2 \\
  H_3 \\
  H_6
  \end{pmatrix}
  \]

- Fix frame $R$; normal/Laplace equation, $L_{\bar{R}} H_{\bar{R}} = B_R$

$$
L_{\bar{R}} = \begin{pmatrix}
\sum_j \left( x_{2,j}^T w_{2,j}^2 x_{j,2} \right) & -x_{2,3}^T w_{2,3}^2 x_{3,2} & \cdots & -x_{2,6}^T w_{2,6}^2 x_{6,2} \\
-x_{3,2}^T w_{3,2}^2 x_{3,2} & \sum_j \left( x_{3,j}^T w_{3,j}^2 x_{j,3} \right) & \cdots & \cdots \\
\vdots & \vdots & \ddots & \vdots \\
-x_{6,2}^T w_{6,2}^2 x_{2,6} & 0 & \cdots & \sum_j \left( x_{6,j}^T w_{6,j}^2 x_{j,6} \right)
\end{pmatrix}
$$

Strong overlap

Weak overlap
Global Bundle Adjustment – Fast & Robust Solution

\[
\begin{pmatrix}
W_{R,2} \\
W_{R,3} \\
\vdots \\
W_{R,6} \\
W_{2,3} \\
W_{2,6}
\end{pmatrix}
\begin{pmatrix}
x_{R,2} \\
x_{R,3} \\
\vdots \\
x_{R,6} \\
x_{2,3} \\
x_{2,6}
\end{pmatrix}
\begin{pmatrix}
x_{2,R} & 0 & -x_{3,R} & \cdots & 0 \\
0 & x_{2,3} & -x_{3,2} & \cdots & 0 \\
0 & 0 & x_{2,6} & \cdots & -x_{6,2} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\end{pmatrix}
\begin{pmatrix}
H_R \\
H_2 \\
H_3 \\
\vdots \\
H_6
\end{pmatrix}
\]

Fix frame \( R \); normal/Laplace equation, \( \mathbf{L}_{\bar{R}} \mathbf{H}_{\bar{R}} = \mathbf{B}_R \)

\[
\mathbf{L}_{\bar{R}} = \begin{pmatrix}
\sum_j \left( x_{2,j}^T W_{2,j} x_{j,2} \right) & -x_{2,3}^T W_{2,3} x_{j,3} & \cdots & -x_{2,6}^T W_{2,6} x_{6,2} \\
-x_{3,2}^T W_{3,2} x_{2,3} & \sum_j \left( x_{3,j}^T W_{3,j} x_{j,3} \right) & \cdots & \sum_j \left( x_{3,j}^T W_{3,j} x_{j,3} \right) \\
\vdots & \vdots & \ddots & \vdots \\
-x_{6,2}^T W_{6,2} x_{2,6} & 0 & \cdots & \sum_j \left( x_{6,j}^T W_{6,j} x_{j,6} \right)
\end{pmatrix}
\]
Fusion in the Gradient Domain: Advantages

- Smooths intensity seams
- Preserves high-frequency information
- Invariant to camera sensor bias
平行融合操作在拼贴画布上
- 将图像分组并打包成非重叠集—图着色问题
- 用于CUDA内核的自定义
- 转换反投射；插值
- 二进制图像侵蚀以移除多余的梯度边界

- **加速打包与GPU**：40倍
Gradient-domain Blending

- Computation-intensive integration
  \[ \nabla I(x) = \sum_{x \in D_i} w_i(x) \nabla I_i(x) \]

- Green’s function (\(G\)) is factored approximately via a convolution pyramid.\(^1\)
- **Speed-up** by algorithm & GPU: 30x

---

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Illustrations I

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Illustrations II

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Illustrations IV

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Illustrations V

Big Snapshot Stitching with Scarce Overlap
Illustrations VI

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Recap

- Unconventional projective layout:
  - Sparse, irregular and noisy (S.I.N.) overlap among multiple FoVs
- Combine static spatial/geometric knowledge and scene-dependent parameters & features
- Computation-intensive steps made tractable through GPU
- Potential other applications include:
  - Sparse and adaptive sampling in video data
  - Individual tracking among a crowd
Future Work

- Develop a statistical foundation for the PG-RANSAC framework
  - Currently investigating a scheme based on matrix perturbation\(^1\) and adaptive sample weighting\(^2\)
- Allow arbitrary reference planes in GBA
- Investigate flat-field weighting schemes to remove “rings”
- Extend to color stitching for big snapshots

\(^1\) A. Criminisi et al. *Image and Video Computing* 17, 1999.  
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