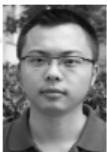


# Big Snapshot Stitching with Scarce Overlap

IEEE HPEC 2013, Waltham, MA



Alexandros-Stavros Iliopoulos<sup>1</sup>   Jun Hu<sup>1</sup>   Nikos Pitsianis<sup>2,1</sup>   Xiaobai Sun<sup>1</sup>



Mike Gehm<sup>1</sup>   David Brady<sup>1</sup>



<sup>1</sup>Duke University

<sup>2</sup>Aristotle University of Thessaloniki



September 12, 2013

# Outline

## 1 Introduction

## 2 De-ghosting

- Overview
- Pairwise registration
- Global bundle adjustment
- Fusion

## 3 Illustrations

## 4 Discussion

## 5 Acknowledgments

# Example Multi-Camera Systems

- Higher-end performance through lower-end cameras

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



<sup>1</sup> B. Wilburn *et al.* *ACM Transactions on Graphics* 24:3, 2005.

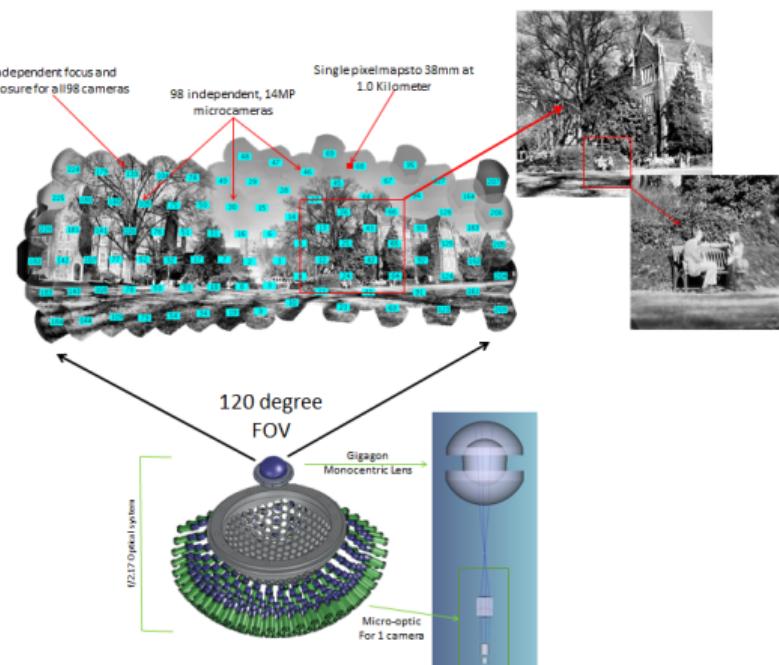
<sup>3</sup> F.R. Golish *et al.* *Optics Express* 20:20, 2012.

<sup>5</sup> J. Kopf *et al.* *ACM Transactions on Graphics* 26:3, 2007.

<sup>2</sup> D.J. Brady *et al.* *Nature* 486:7403, 2012.

<sup>4</sup> B. Leininger *et al.* *SPIE* 6981, 2008.

# AWARE-2 Prototype: 2 Gigapixels, 120° FOV



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

D.J. Brady *et al.* *Nature* 486:7403, 2012.  
 D.R. Golish *et al.* *Optics Express* 20:20, 2012.  
 E.J. Tremblay *et al.* *Applied Optics* 51:20, 2012.

AWARE-2 image acquisition outline. Image taken from <http://www.mosaic.disp.duke.edu/AWARE/index.html>.

# Ghosting & De-ghosting

Ghosted image



De-ghosted using our pipeline



Both results from the AWARE-2 dataset

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Ghosted image



De-ghosted using our pipeline



Both results from the AWARE-2 dataset

# 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

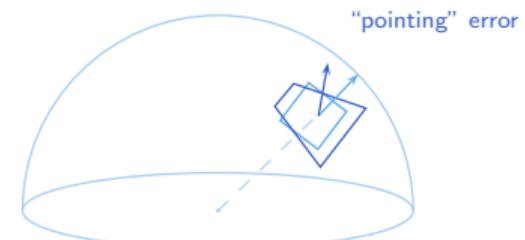


---

\* The AWARE-2 design is parallax-free

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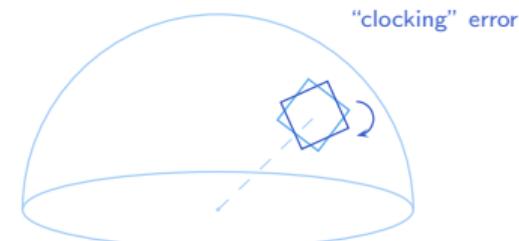
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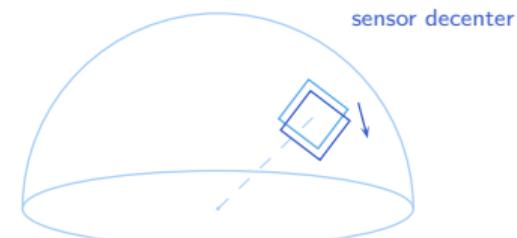
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  - Independent camera parameters & settings
  - Thermal & mechanical drift



---

\* The AWARE-2 design is parallax-free

# Gigapixel Imaging Applications

- Survey, cataloging and monitoring of:
  - urban and suburban development<sup>1</sup>
  - wild-life habitats<sup>2</sup>
  - cultural legacy<sup>3,4</sup>
- Exploration and dynamics of celestial bodies<sup>5,6</sup>
- Recognition<sup>7</sup>
- Surveillance<sup>8</sup>

<sup>1</sup> M.A. Smith. *Fine International Conference on Gigapixel Imaging for Science*, 2010.

<sup>2</sup> M.H. Nichols *et al.* *Rangeland Ecology & Management* 62, 2009.

<sup>3</sup> M. Seidl and C. Breiteneder. *VAST*, 2011.

<sup>4</sup> M. Ben-Ezra. *IEEE Computer Graphics and Applications* 31, 2011.

<sup>5</sup> A. McEwen *et al.* *Journal of Geophysical Research: Planets* 115, 2007.

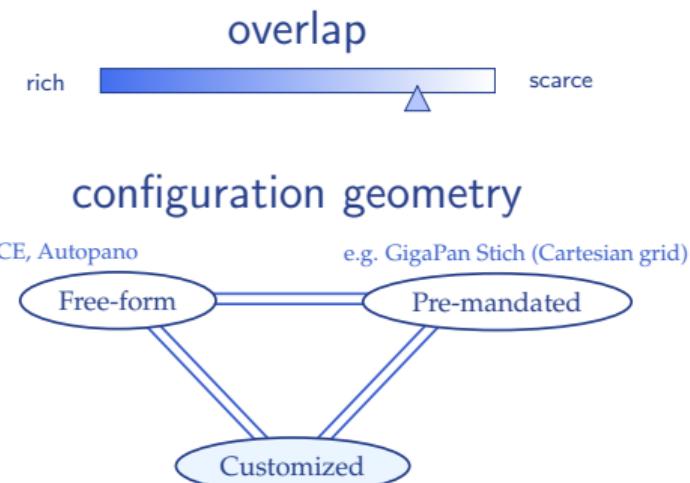
<sup>6</sup> M.R. Balme *et al.* *Icarus* 221, 2012.

<sup>7</sup> L. Gueguen *et al.* *IGARSS*, 2011.

<sup>8</sup> B. Leinenen *et al.* *SPIE* 6981, 2008.

# Stitching Software

- GigaPan Stitch<sup>1</sup>
  - Autopano Giga<sup>2</sup>
  - Microsoft ICE<sup>3</sup>
  - Autostitch<sup>4</sup>
  - Panorama Tools<sup>5</sup>
  - Fiji<sup>6</sup>
  - ...
- 
- Challenged by sparse, irregular, and noisy overlap



<sup>1</sup> [gigapan.com/](http://gigapan.com/)

<sup>3</sup> [research.microsoft.com/en-us/UM/redmond/groups/IVM/ICE/](http://research.microsoft.com/en-us/UM/redmond/groups/IVM/ICE/)

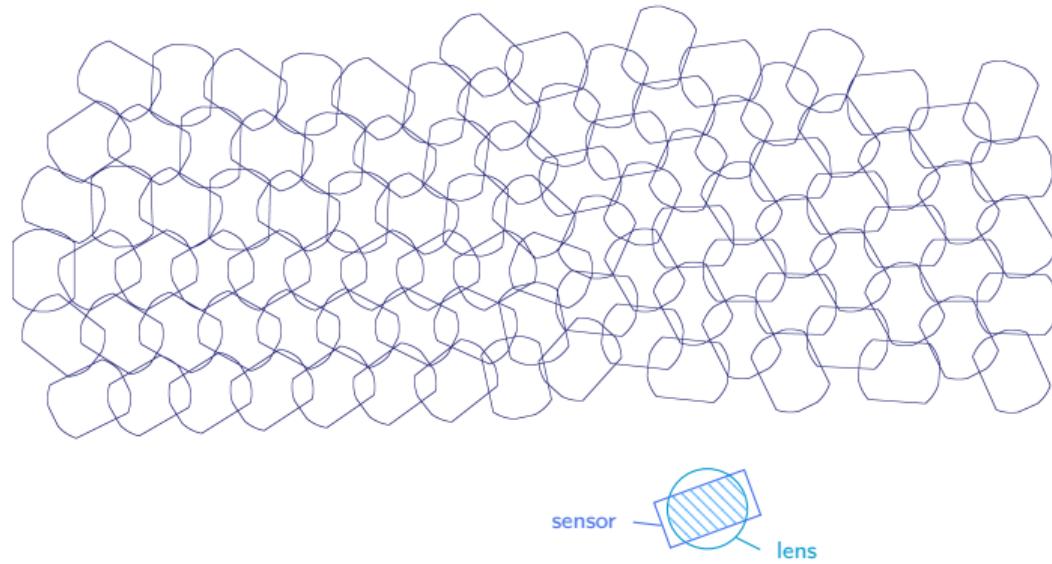
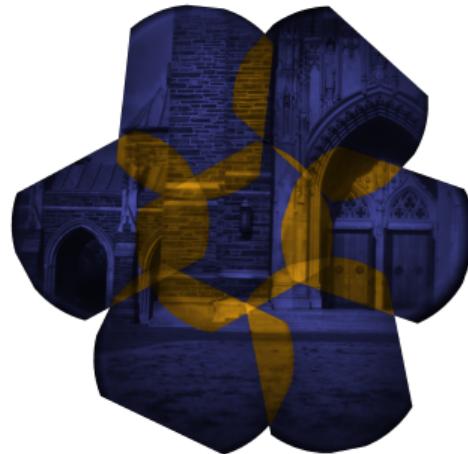
<sup>5</sup> [panotools.sourceforge.net/](http://panotools.sourceforge.net/)

<sup>2</sup> [autopano.net/](http://autopano.net/)

<sup>4</sup> [www.cs.bath.ac.uk/brown/autostitch/autostitch.html](http://www.cs.bath.ac.uk/brown/autostitch/autostitch.html)

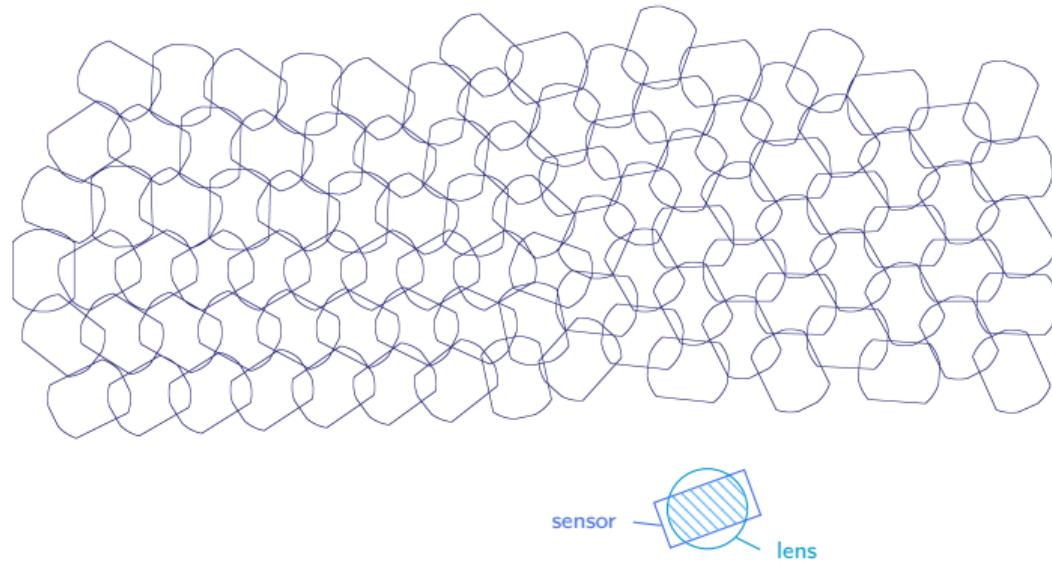
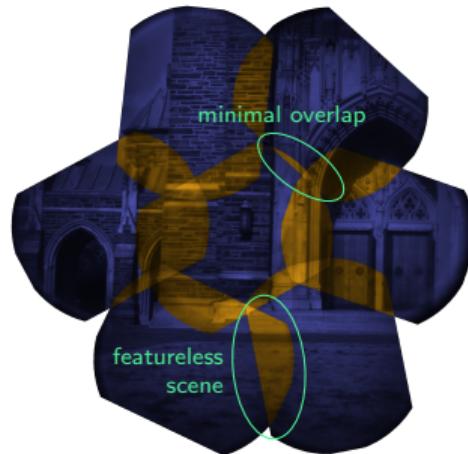
<sup>6</sup> <http://fiji.sc/>

# 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

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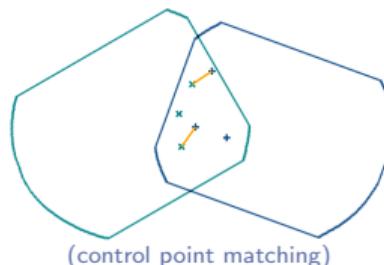
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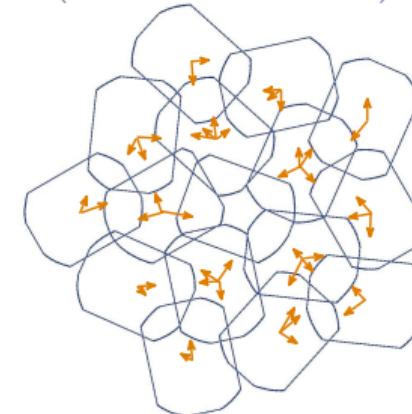
# De-ghosting: 3 Key Steps

- Pairwise registration

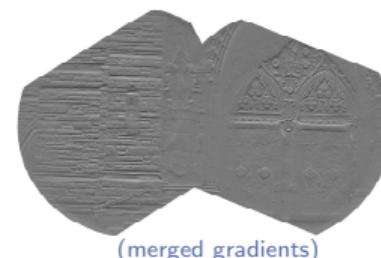


- Global bundle adjustment among multiple images

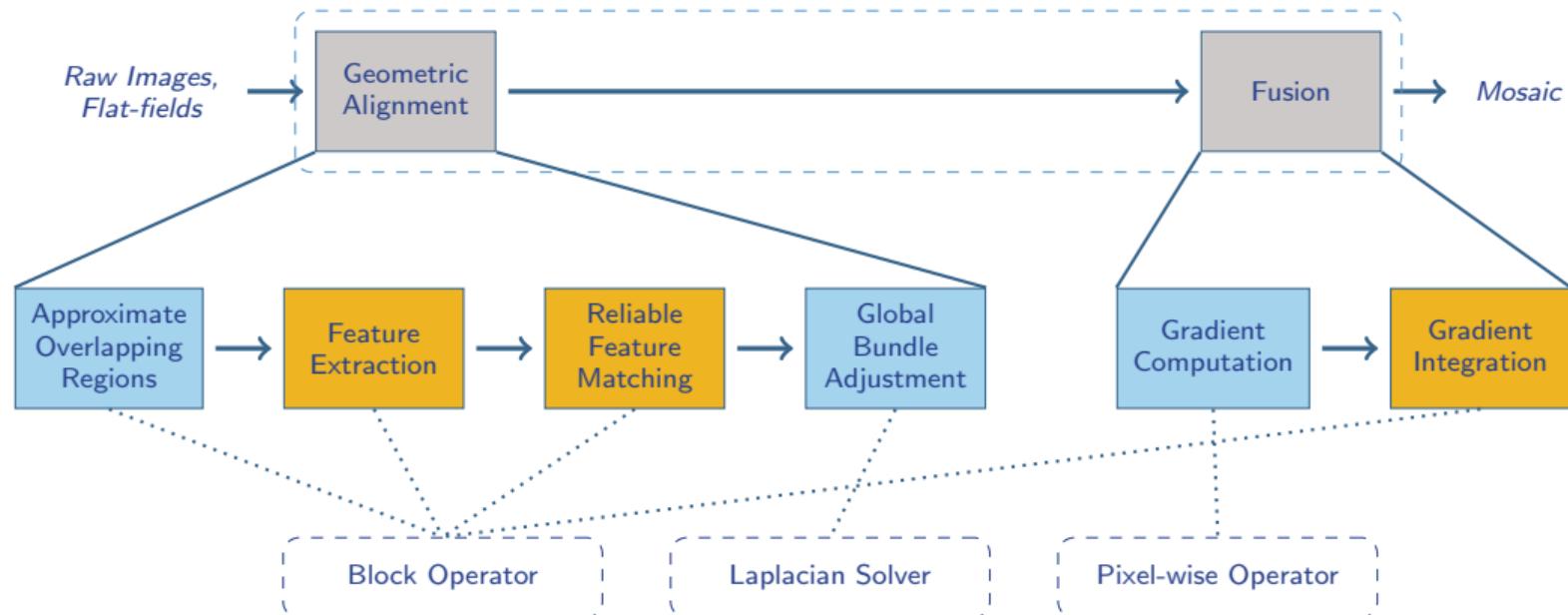
(simultaneous transformations)



- Blending/fusion in the gradient domain

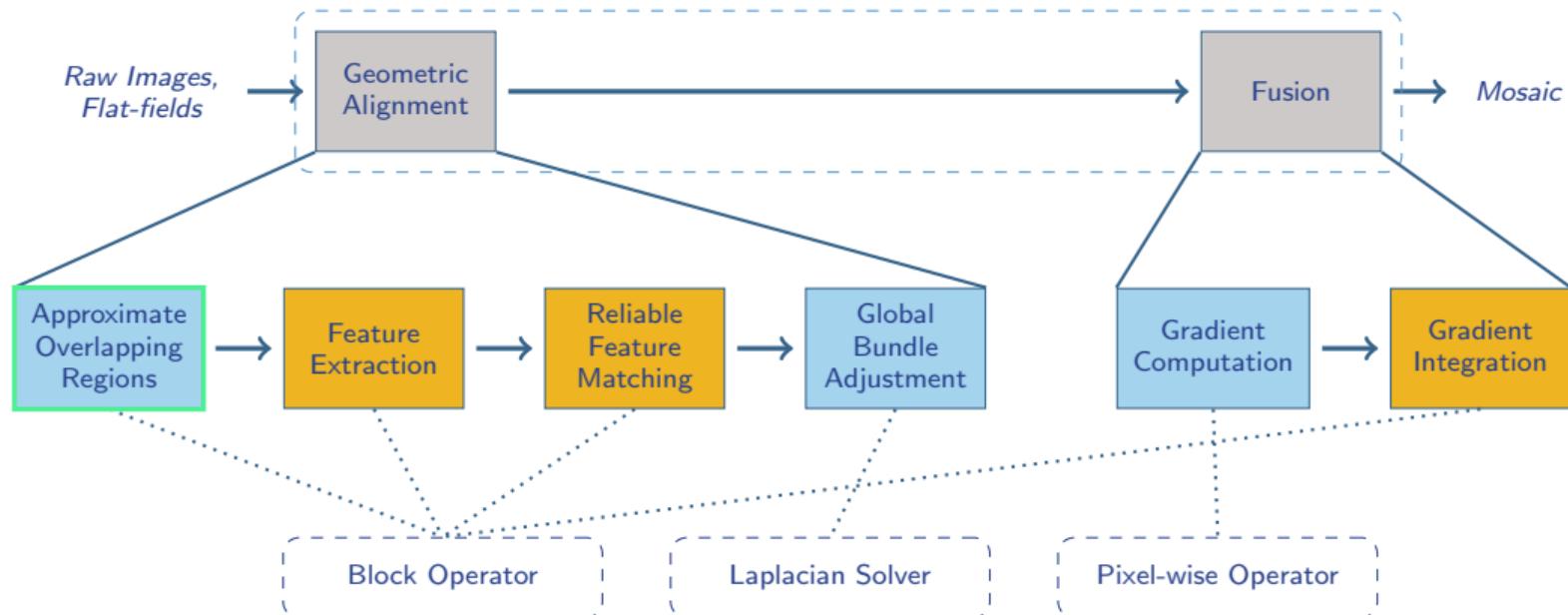


# De-ghosting Pipeline



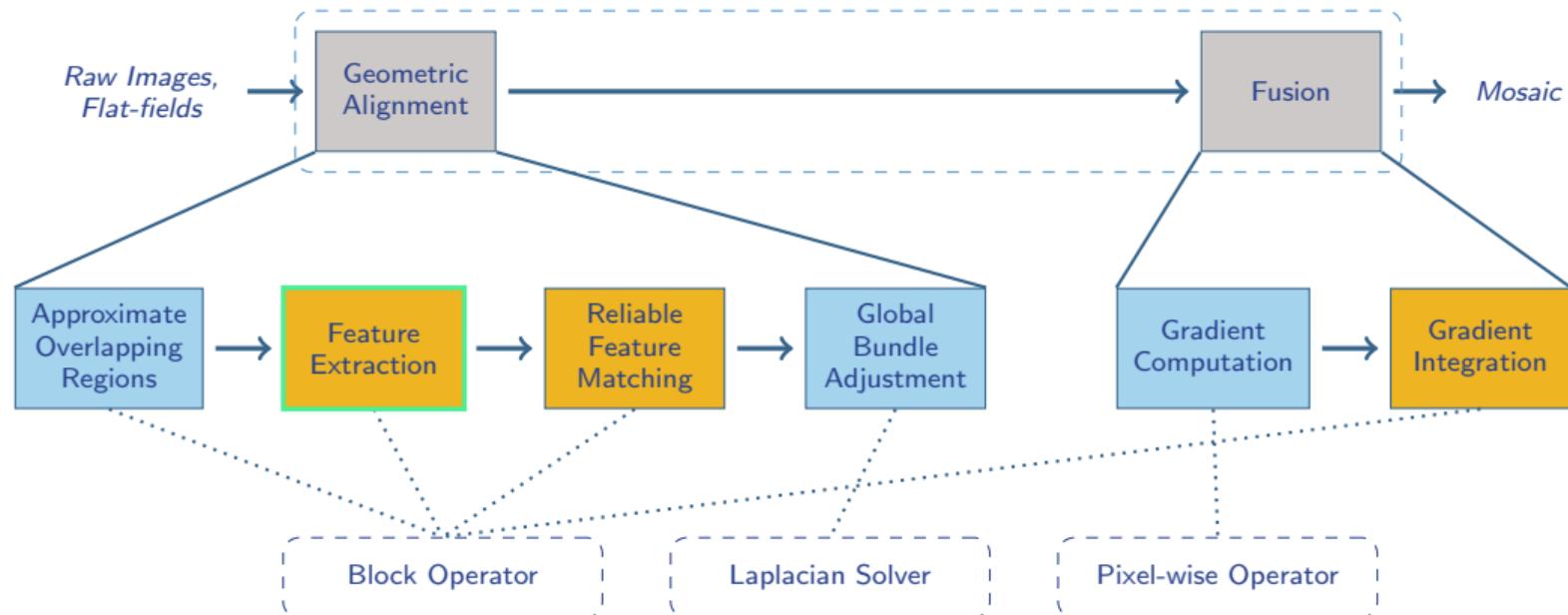
computational bottlenecks

# De-ghosting Pipeline



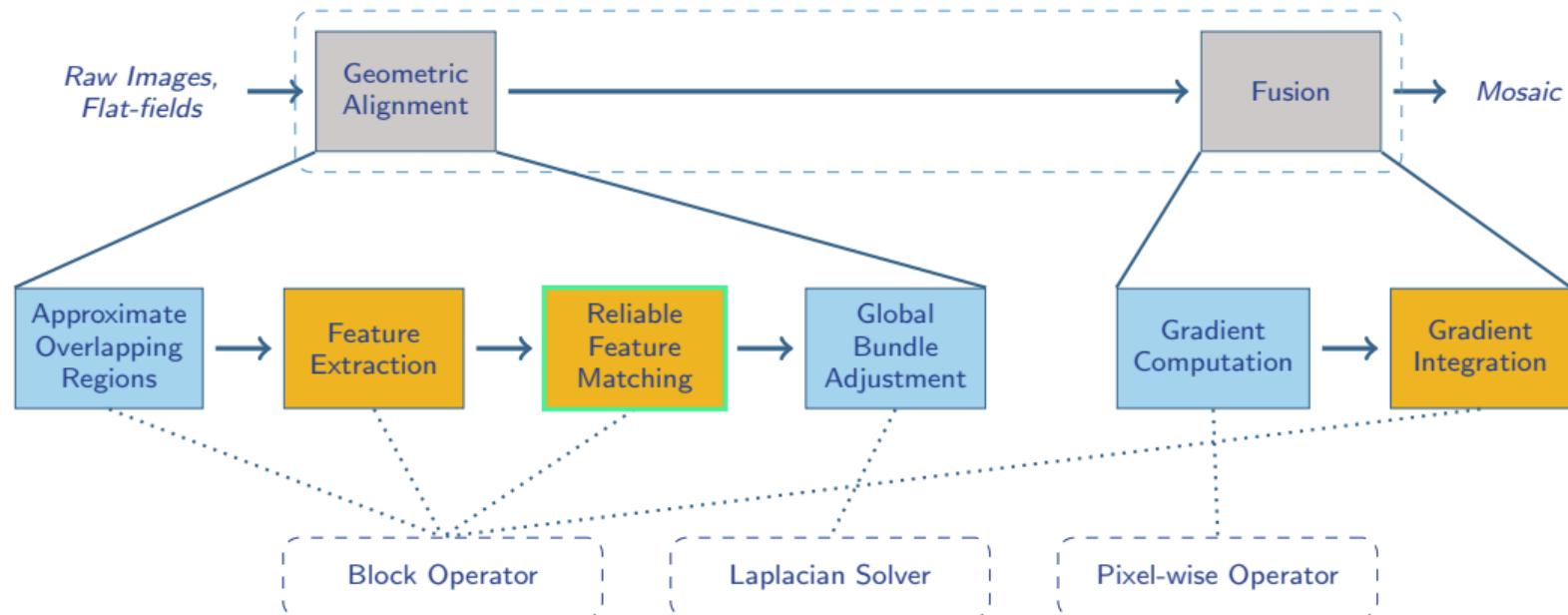
computational bottlenecks

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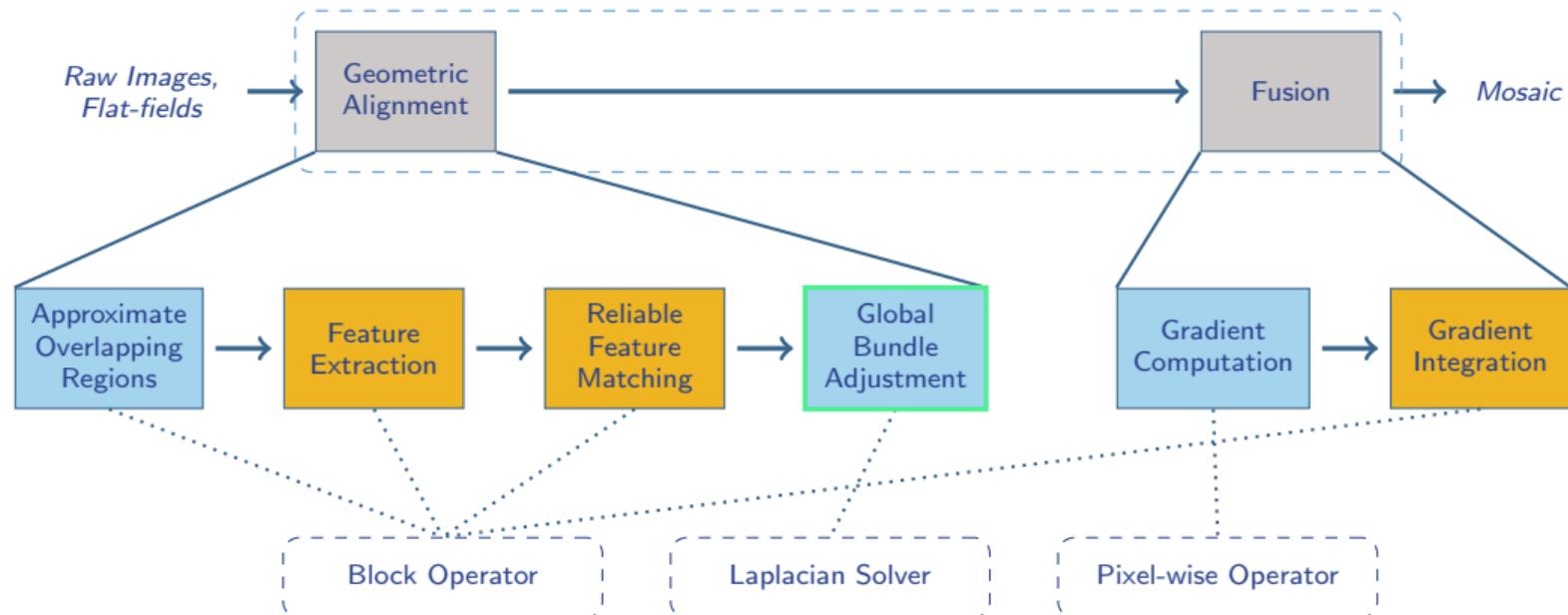
computational bottlenecks

# De-ghosting Pipeline

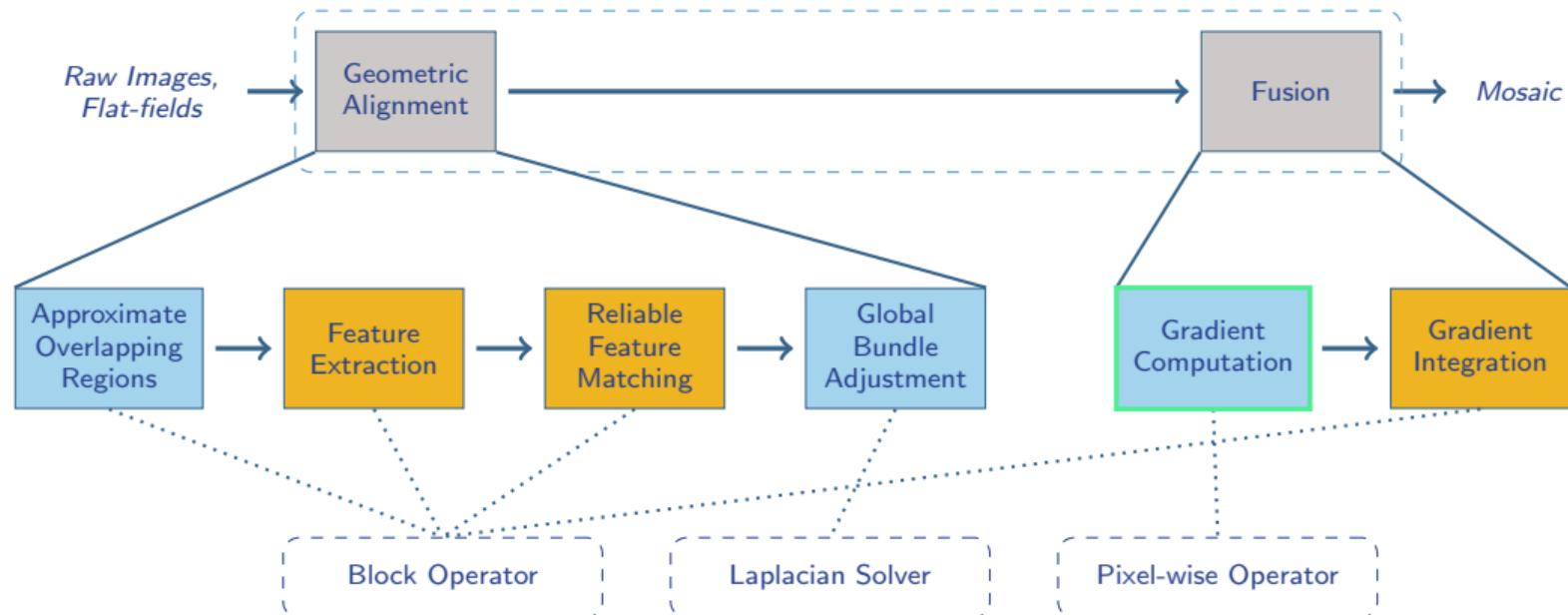


  computational bottlenecks

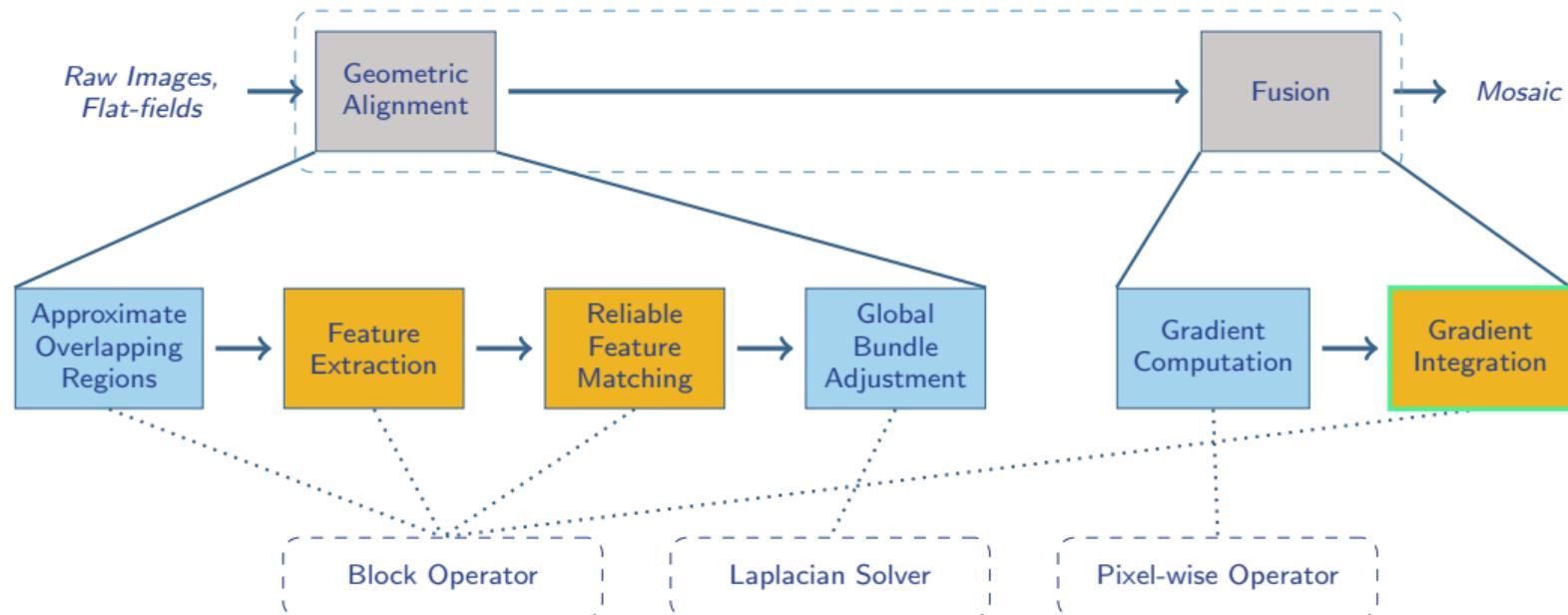
# De-ghosting Pipeline



# De-ghosting Pipeline



# De-ghosting Pipeline



computational bottlenecks

# 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×AMD Opteron @1.9 MHz, 64 GB RAM, NVIDIA Tesla K20c
  - Naïve serial implementation: 3.5 hours
  - Current pipeline: **50 seconds\***

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\*  $\sim 25$  seconds are overhead related to MATLAB-CUDA communication

# Outline

## 1 Introduction

## 2 De-ghosting

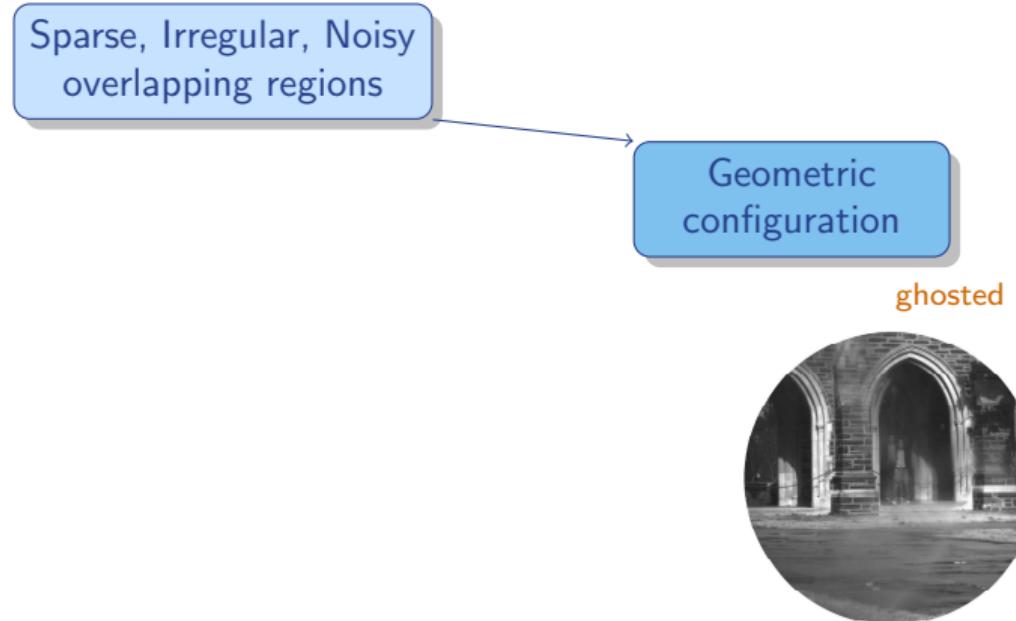
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# Pairwise Registration



# Pairwise Registration

Sparse, Irregular, Noisy  
overlapping regions

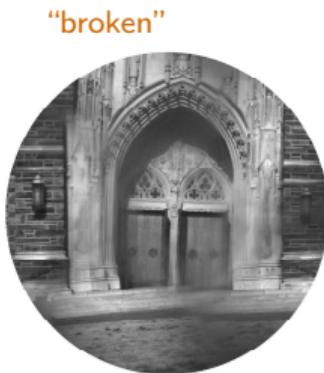
SIFT

"broken"

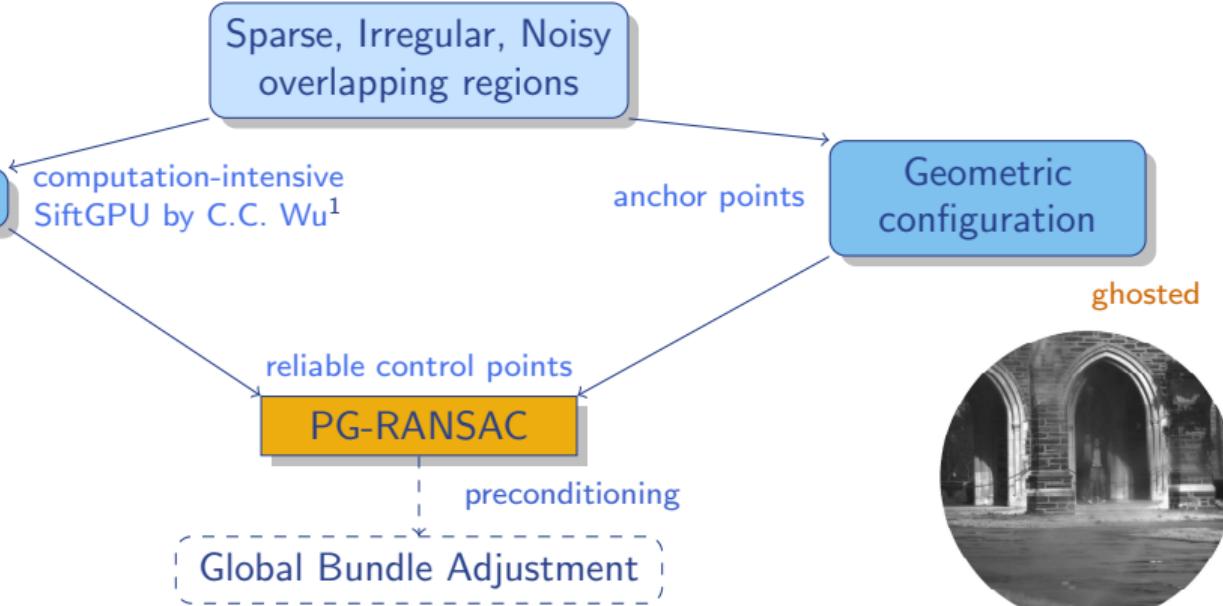


# Pairwise Registration

Speed-up by  
algorithm & GPU:  
 $>1000\times!$

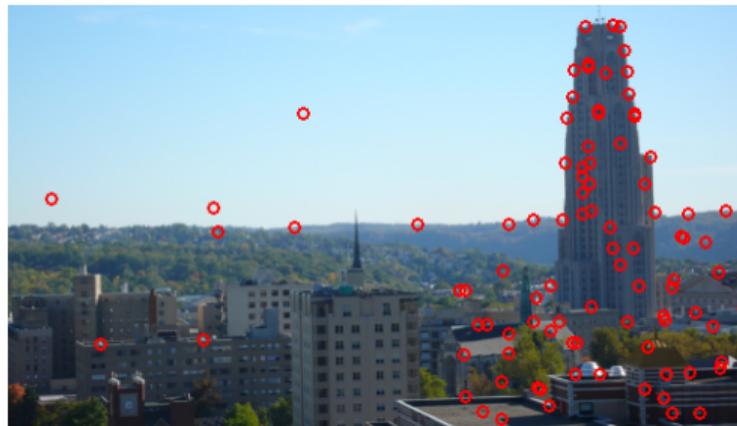


<sup>1</sup> <http://cs.unc.edu/~ccwu/siftgpu>

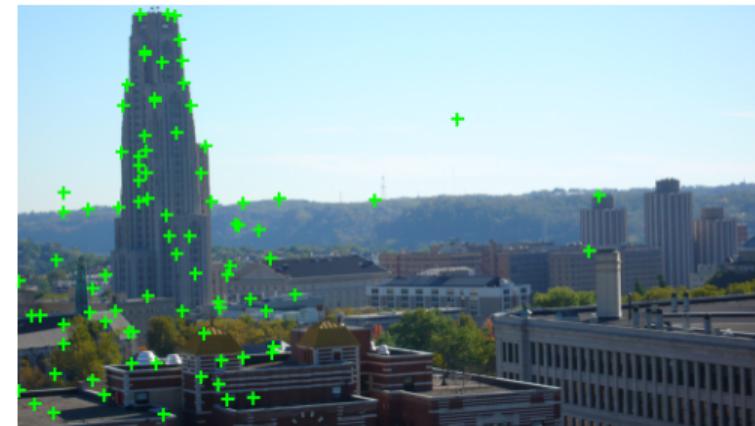


# Textbook Alignment: Features

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

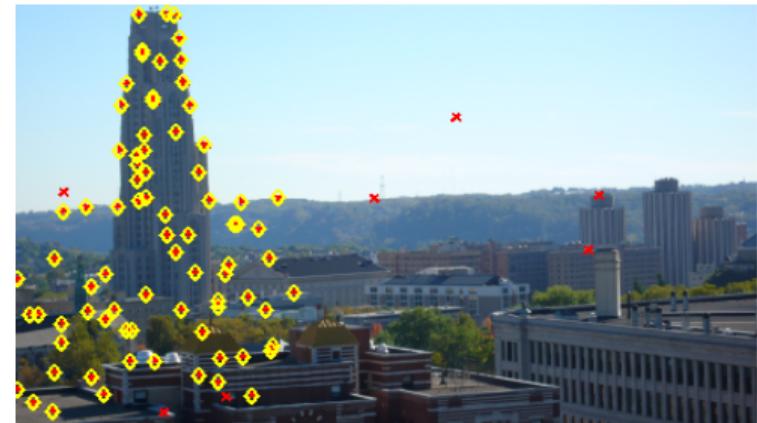
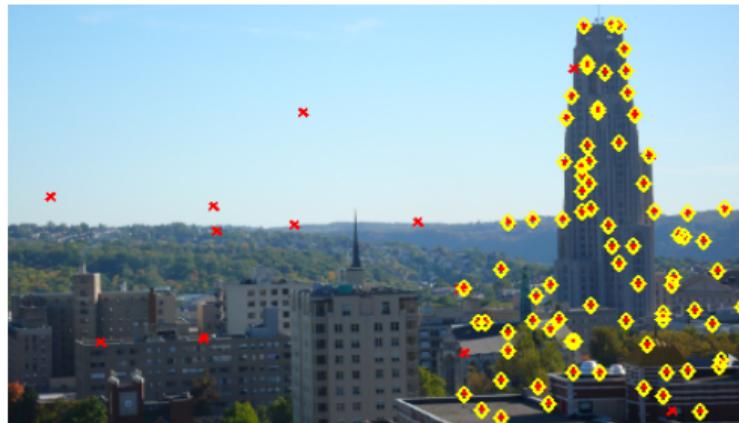


Images by William Wedler, <http://www.cs.cmu.edu/afs/andrew/scs/cs/15-463/f07/proj4/www/wwedler/>



# Textbook Alignment: RANSAC<sup>1</sup>

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



Images by William Wedler, <http://www.cs.cmu.edu/afs/andrew/scs/cs/15-463/f07/proj4/www/wwedler/>

<sup>1</sup> M. Fischler and R. Bolles. *Communications of the ACM* 24, 1981.

# Placement Geometry preserving RANSAC (PG-RANSAC)

- RANSAC variants minimize a ranking function:

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

- PG-RANSAC ranking:

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

rank points & models —————↑

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rank points & models —————↑————— RANSAC ranking (MSAC<sup>1</sup>)

<sup>1</sup> P. Torr et al. Computer Vision and Image Understanding 78, 2000.

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↑                                    ↓

rank points & models              RANSAC ranking (MSAC<sup>1</sup>)      normalization factor

<sup>1</sup> P. Torr et al. Computer Vision and Image Understanding 78, 2000.

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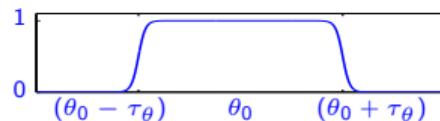
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- PG-RANSAC ranking:

rank points & models
RANSAC ranking (MSAC<sup>1</sup>)

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

capture geometric constraint
normalization factor



$$f(\theta, \theta_0) = \frac{1}{1 + e^{-\alpha[(\theta - \theta_0) - \tau_\theta]}} \cdot \frac{1}{1 + e^{+\alpha[(\theta - \theta_0) - \tau_\theta]}} \quad (\text{logistic "box"})$$

<sup>1</sup> P. Torr et al. Computer Vision and Image Understanding 78, 2000.

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# Global Bundle Adjustment\*

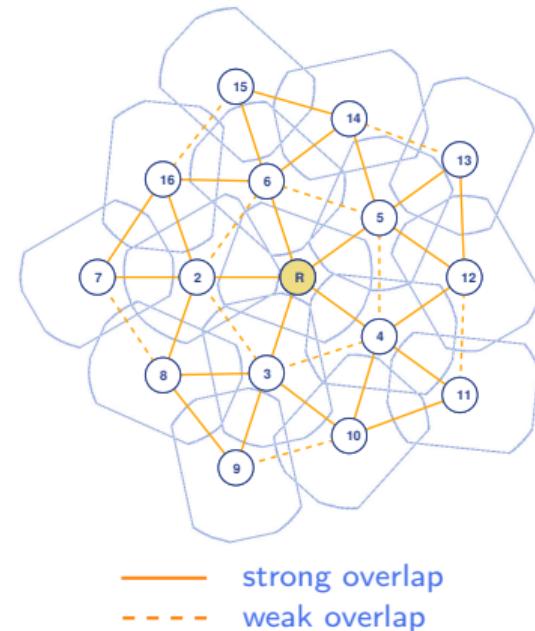
- Adhere to geometric configuration

$$\text{(variational 1)} \quad \min_{\{\mathbf{H}_i\}} \sum_{\mathcal{D}_{ij} \neq \emptyset} \sum_{\mathbf{x}_k \in \mathcal{D}_{ij}} w_{ij} \left\| \mathbf{x}_{k,i}^T \mathbf{H}_i - \mathbf{x}_{k,j}^T \mathbf{H}_j \right\|_2$$

$$\text{(variational 2)} \quad \min_{\mathbf{H}} \|\mathbf{W}\mathbf{E}_{\mathbf{x}}\mathbf{H}\|_2$$

Edge incidence block-matrix

- Weights:  $w_{ij} = \frac{1}{|\mathcal{D}_{ij}|}$ 
  - 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

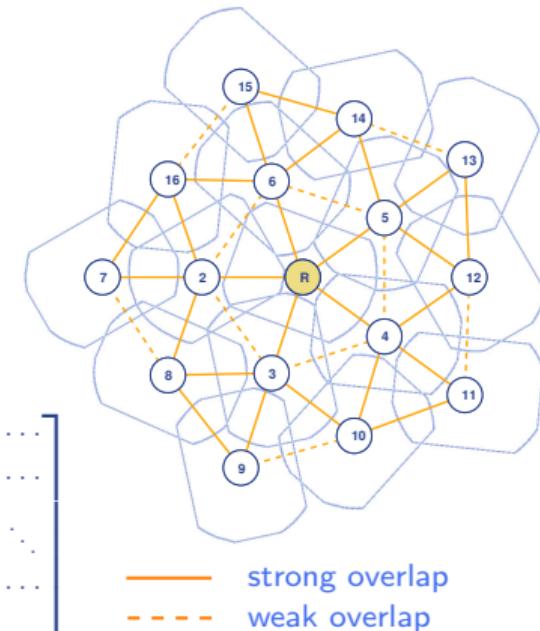
# Global Bundle Adjustment – Fast & Robust Solution



$$\text{diag} \left( \begin{bmatrix} \mathbf{W}_{R,2} \\ \mathbf{W}_{R,3} \\ \vdots \\ \mathbf{W}_{R,6} \\ \mathbf{W}_{2,3} \\ \mathbf{W}_{2,6} \\ \vdots \end{bmatrix} \right) \cdot \begin{bmatrix} \mathbf{x}_{R,2} & -\mathbf{x}_{2,R} & 0 & \cdots & 0 & \cdots \\ \mathbf{x}_{R,3} & 0 & -\mathbf{x}_{3,R} & \cdots & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{x}_{R,6} & 0 & 0 & \cdots & -\mathbf{x}_{6,R} & \cdots \\ 0 & \mathbf{x}_{2,3} & -\mathbf{x}_{3,2} & \cdots & 0 & \cdots \\ 0 & \mathbf{x}_{2,6} & 0 & \cdots & -\mathbf{x}_{6,2} & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \end{bmatrix} \cdot \begin{bmatrix} \mathbf{H}_R \\ \mathbf{H}_2 \\ \mathbf{H}_3 \\ \vdots \\ \mathbf{H}_6 \\ \vdots \end{bmatrix}$$

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

$$\mathbf{L}_{\bar{R}} = \begin{bmatrix} \sum_j (\mathbf{x}_{2,j}^\top \mathbf{w}_{2,j}^2 \mathbf{x}_{j,2}) & -\mathbf{x}_{2,3}^\top \mathbf{w}_{2,3}^2 \mathbf{x}_{3,2} & \cdots & -\mathbf{x}_{2,6}^\top \mathbf{w}_{2,6}^2 \mathbf{x}_{6,2} & \cdots \\ -\mathbf{x}_{3,2}^\top \mathbf{w}_{2,3}^2 \mathbf{x}_{3,2} & \sum_j (\mathbf{x}_{3,j}^\top \mathbf{w}_{3,j}^2 \mathbf{x}_{j,3}) & \cdots & 0 & \cdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -\mathbf{x}_{6,2}^\top \mathbf{w}_{2,6}^2 \mathbf{x}_{2,6} & 0 & \cdots & \sum_j (\mathbf{x}_{6,j}^\top \mathbf{w}_{6,j}^2 \mathbf{x}_{j,6}) & \cdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \end{bmatrix}$$



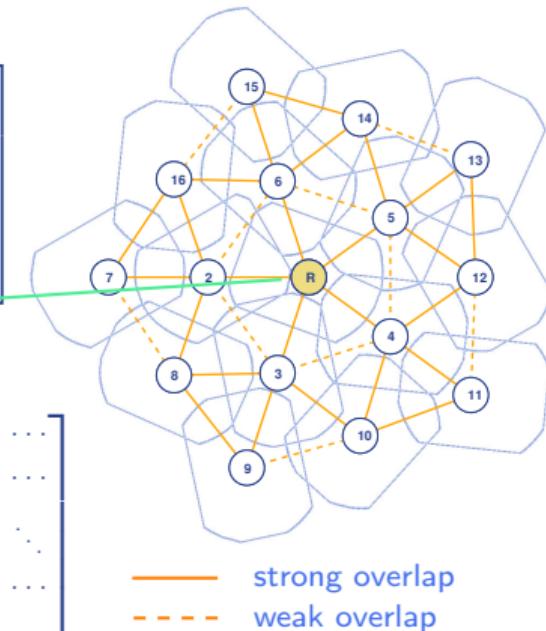
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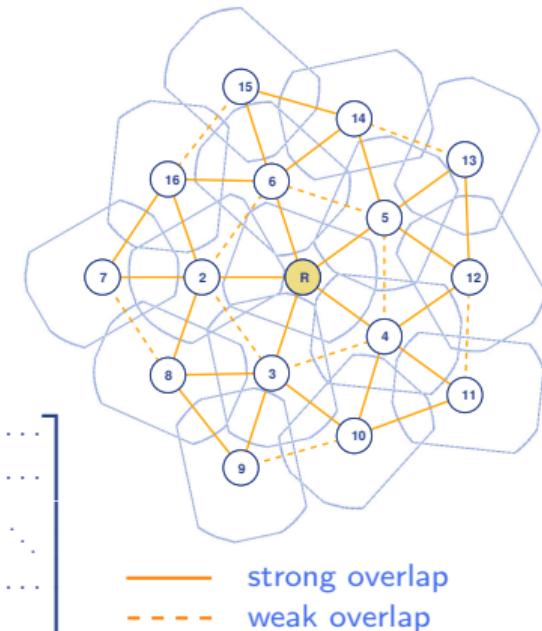
# Global Bundle Adjustment – Fast & Robust Solution



$$\text{diag} \left( \begin{bmatrix} \mathbf{W}_{R,2} \\ \mathbf{W}_{R,3} \\ \vdots \\ \mathbf{W}_{R,6} \\ \mathbf{W}_{2,3} \\ \mathbf{W}_{2,6} \\ \vdots \end{bmatrix} \right) \cdot \begin{bmatrix} \mathbf{x}_{R,2} & -\mathbf{x}_{2,R} & 0 & \cdots & 0 & \cdots \\ \mathbf{x}_{R,3} & 0 & -\mathbf{x}_{3,R} & \cdots & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{x}_{R,6} & 0 & 0 & \cdots & -\mathbf{x}_{6,R} & \cdots \\ 0 & \mathbf{x}_{2,3} & -\mathbf{x}_{3,2} & \cdots & 0 & \cdots \\ 0 & \mathbf{x}_{2,6} & 0 & \cdots & -\mathbf{x}_{6,2} & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \end{bmatrix} \cdot \begin{bmatrix} \mathbf{H}_R \\ \mathbf{H}_2 \\ \mathbf{H}_3 \\ \vdots \\ \mathbf{H}_6 \\ \vdots \end{bmatrix}$$

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

$$\mathbf{L}_{\bar{R}} = \begin{bmatrix} \sum_j (\mathbf{x}_{2,j}^\top \mathbf{w}_{2,j}^2 \mathbf{x}_{j,2}) & -\mathbf{x}_{2,3}^\top \mathbf{w}_{2,3}^2 \mathbf{x}_{3,2} & \cdots & -\mathbf{x}_{2,6}^\top \mathbf{w}_{2,6}^2 \mathbf{x}_{6,2} & \cdots \\ -\mathbf{x}_{3,2}^\top \mathbf{w}_{2,3}^2 \mathbf{x}_{3,2} & \sum_j (\mathbf{x}_{3,j}^\top \mathbf{w}_{3,j}^2 \mathbf{x}_{j,3}) & \cdots & 0 & \cdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -\mathbf{x}_{6,2}^\top \mathbf{w}_{2,6}^2 \mathbf{x}_{2,6} & 0 & \cdots & \sum_j (\mathbf{x}_{6,j}^\top \mathbf{w}_{6,j}^2 \mathbf{x}_{j,6}) & \cdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \end{bmatrix}$$



# Outline

## 1 Introduction

## 2 De-ghosting

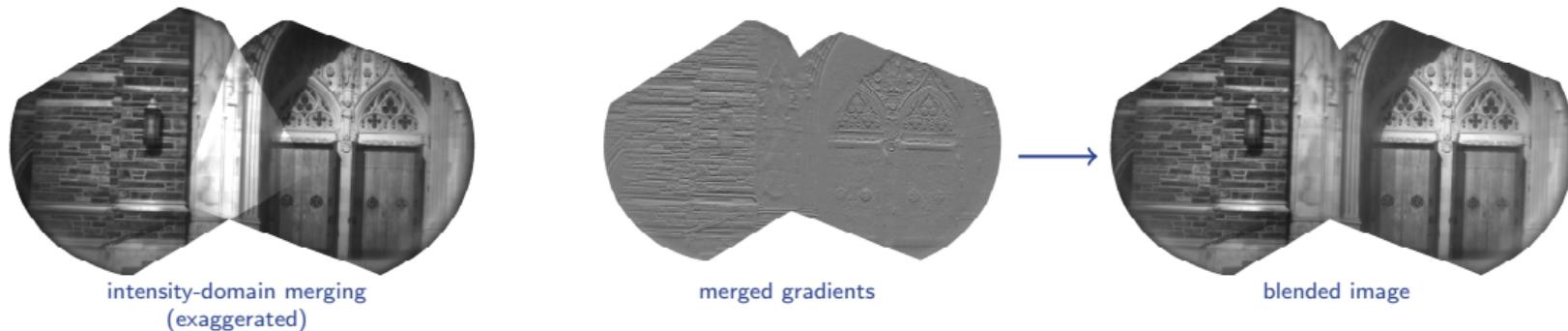
- Overview
- Pairwise registration
- Global bundle adjustment
- Fusion

## 3 Illustrations

## 4 Discussion

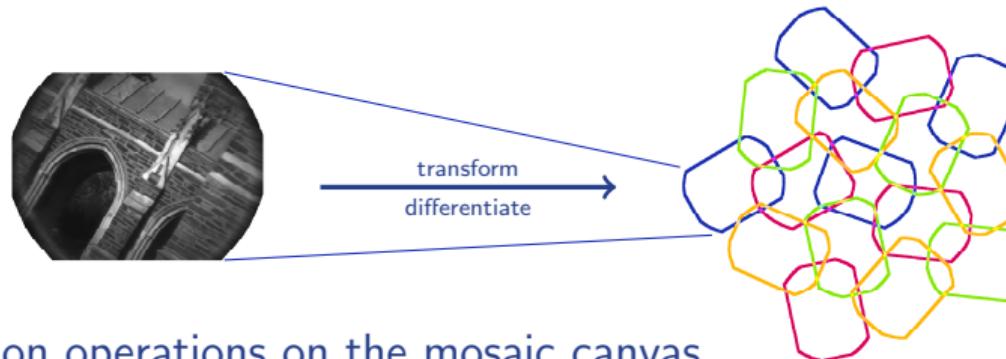
## 5 Acknowledgments

# Fusion in the Gradient Domain: Advantages



- Smooths intensity seams
- Preserves high-frequency information
- Invariant to camera sensor bias

# Gradient Re-projection



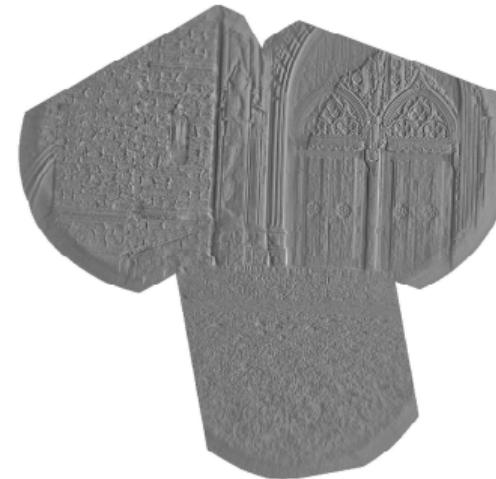
- Parallel fusion operations on the mosaic canvas
  - Group and pack images into non-overlapping sets—graph coloring problem
- Custom CUDA kernels
  - Transformation back-projection; interpolation
  - Binary image erosion to remove spurious gradient border
- **Speed-up by packing & GPU: 40x**

# Gradient-domain Blending

- Computation-intensive integration

$$\nabla I(x) = \sum_{x \in \mathcal{D}_i} w_i(x) \nabla I_i(x)$$

$$I = G * \text{div}(\nabla I)$$



- Green's function ( $G$ ) is factored approximately via a convolution pyramid.<sup>1</sup>
- Speed-up by algorithm & GPU: 30x

<sup>1</sup> Z. Farbman *et al.* ACM Transactions on Graphics 30, 2011.

# Outline

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## 5 Acknowledgments

# Illustrations I



# Illustrations II



# Illustrations III



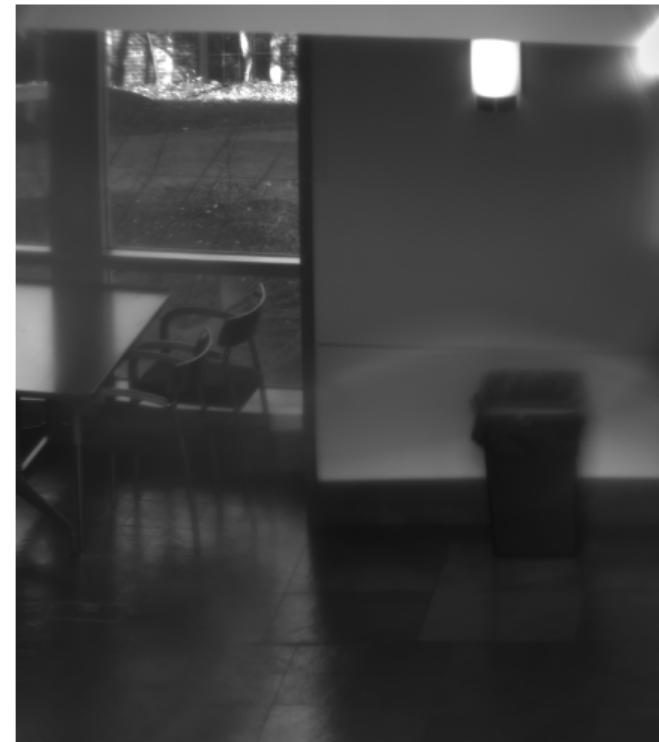
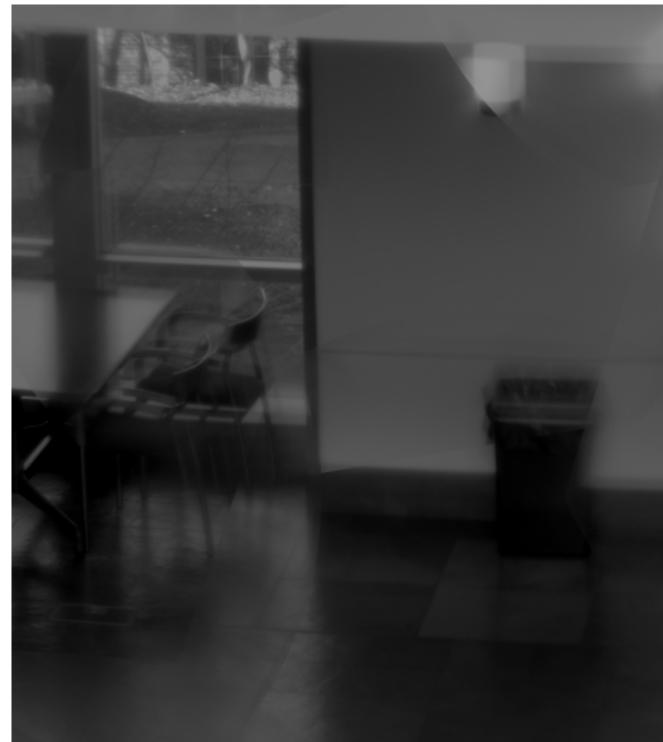
# Illustrations IV



# Illustrations V



# Illustrations VI



# Outline

## 1 Introduction

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- Overview
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- Fusion

## 3 Illustrations

## 4 Discussion

## 5 Acknowledgments

# 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<sup>1</sup> and adaptive sample weighting<sup>2</sup>
- Allow arbitrary reference planes in GBA
- Investigate flat-field weighting schemes to remove “rings”
- Extend to color stitching for big snapshots

<sup>1</sup> A. Criminisi *et al.* *Image and Video Computing* 17, 1999.

<sup>2</sup> O. Chum *et al.* *CVPR*, 2005.

# Outline

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## 5 Acknowledgments

# Acknowledgments I



# Acknowledgments II

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# Thank you!

# References I

- [1] M. R. Balme, A. Pathare, S. M. Metzger, M. C. Towner, S. R. Lewis, A. Spiga, L. K. Fenton, N. O. Renno, H. M. Elliott, F. A. Saca, T. Michaels, P. Russell, and J. Verdasca. Field measurements of horizontal forward motion velocities of terrestrial dust devils: Towards a proxy for ambient winds on mars and earth. *Icarus*, 221(2):632–645, Nov. 2012.
- [2] M. Ben-Ezra. A digital gigapixel large-format tile-scan camera. *IEEE Computer Graphics and Applications*, 31(1):49–61, Feb. 2011.
- [3] D. J. Brady, M. E. Gehm, R. A. Stack, D. L. Marks, D. S. Kittle, D. R. Golish, E. M. Vera, and S. D. Feller. Multiscale gigapixel photography. *Nature*, 486(7403):386–389, June 2012.
- [4] O. Chum and J. Matas. Matching with PROSAC – progressive sample consensus. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, volume 1 of *CVPR '05*, pages 220–226, San Diego, CA, USA, June 2005.

## References II

- [5] A. Criminisi, I. Reid, and A. Zisserman. A plane measuring device. *Image and Vision Computing*, 17(8):625–634, June 1999.
- [6] Z. Farbman, R. Fattal, and D. Lischinski. Convolution pyramids. *ACM Transaction on Graphics*, 30(6):175:1–175:8, Dec. 2011.
- [7] M. A. Fischler and R. C. Bolles. Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM*, 24(6):381–395, June 1981.
- [8] O. Gallo, N. Gelfand, W.-C. Chen, M. Tico, and K. Pulli. Artifact-free high dynamic range imaging. *IEEE International Conference on Computational Photography*, pages 1–7, Apr. 2009.
- [9] D. R. Golish, E. M. Vera, K. J. Kelly, Q. Gong, P. A. Jansen, J. M. Hughes, D. S. Kittle, D. J. Brady, and M. E. Gehm. Development of a scalable image formation pipeline for multiscale gigapixel photography. *Optics Express*, 20(20):22048–22062, Sept. 2012.

## References III

- [10] L. Gueguen, M. Pesaresi, and P. Soille. An interactive image mining tool handling gigapixel images. In *Proceedings of the 2011 IEEE International Geoscience and Remote Sensing Symposium, IGARGSS '11*, pages 1581–1584, July 2011.
- [11] J. Kopf, M. Uyttendaele, O. Deussen, and M. F. Cohen. Capturing and viewing gigapixel images. *ACM Transaction on Graphics*, 26(3), July 2007.
- [12] B. Leininger, J. Edwards, J. Antoniades, D. Chester, D. Haas, E. Liu, M. Stevens, C. Gershfield, M. Braun, J. D. Targove, S. Wein, P. Brewer, D. G. Madden, and K. H. Shafique. Autonomous real-time ground ubiquitous surveillance-imaging system (ARGUS-IS). *Proceedings of SPIE*, 6981:69810H–1–69810H–11, May 2008.
- [13] D. G. Lowe. Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision*, 60(2):91–110, Nov. 2004.

# References IV

- [14] A. S. McEwen, E. M. Eliason, J. W. Bergstrom, N. T. Bridges, C. J. Hansen, W. A. Delamere, J. A. Grant, V. C. Gulick, K. E. Herkenhoff, L. Keszthelyi, R. L. Kirk, M. T. Mellon, S. W. Squyres, N. Thomas, and C. M. Weitz. Mars reconnaissance orbiter's high resolution imaging science experiment (HiRISE). *Journal of Geophysical Research*, 112(E5), May 2007.
- [15] M. H. Nichols, G. B. Ruyle, and I. R. Nourbakhsh. Very-high-resolution panoramic photography to improve conventional rangeland monitoring. *Rangeland Ecology & Management*, 62(6):579–582, Nov. 2009.
- [16] M. Seidl and C. Breiteneder. Detection and classification of petroglyphs in gigapixel images – preliminary results. In *The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage*, VAST '11, pages 45–48, 2011.
- [17] M. A. Smith. A year in an urban forest: Dairy bush GigaPan 2009-2010. In *Proceedings of the Fine International Conference on Gigapixel Imaging for Science*, pages 1–10, Nov. 2010.

# References V

- [18] R. Szeliski. *Computer vision: Algorithms and applications*. Springer, London; New York, 2010.
- [19] P. H. Torr and A. Zisserman. MLESAC: a new robust estimator with application to estimating image geometry. *Computer Vision and Image Understanding*, 78(1):138–156, Apr. 2000.
- [20] E. J. Tremblay, D. L. Marks, D. J. Brady, and J. E. Ford. Design and scaling of monocentric multiscale imagers. *Applied Optics*, 51(20):4691–4702, July 2012.
- [21] A. Vedaldi and B. Fulkerson. VLFeat: An open and portable library of computer vision algorithms. <http://www.vlfeat.org/>, 2008.
- [22] B. Wilburn, N. Joshi, V. Vaish, E.-V. Talvala, E. Antunez, A. Barth, A. Adams, M. Horowitz, and M. Levoy. High performance imaging using large camera arrays. *ACM Transactions on Graphics*, 24(3):765, July 2005.
- [23] C. Wu. SiftGPU: A GPU implementation of scale invariant feature transform (SIFT), 2007.