Photo Tourism:
Exploring Photo Collections in 3D

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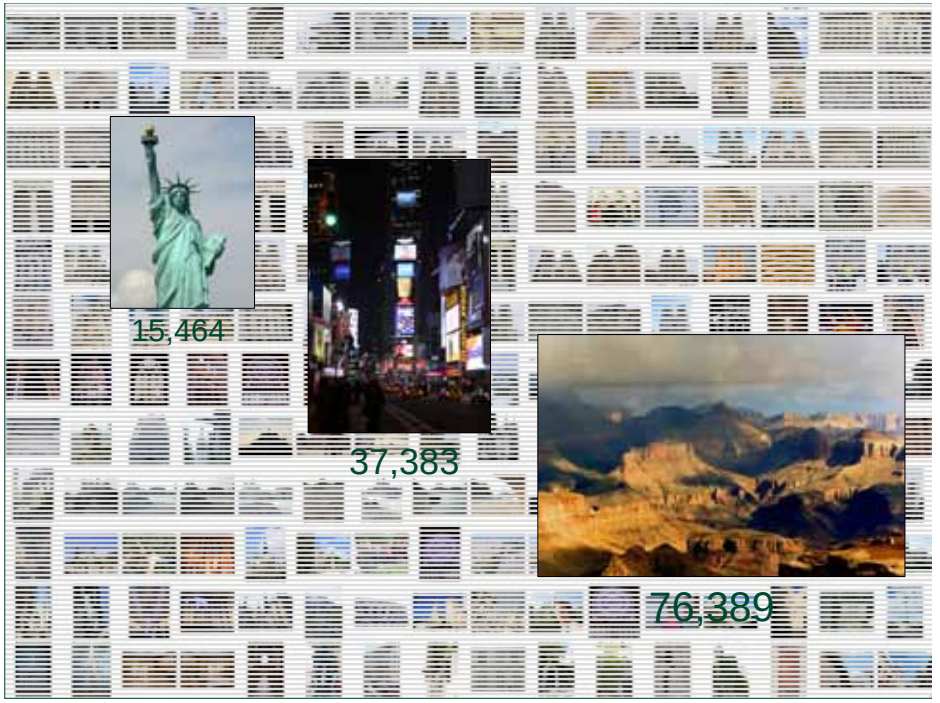



15,464


37,383


76,389

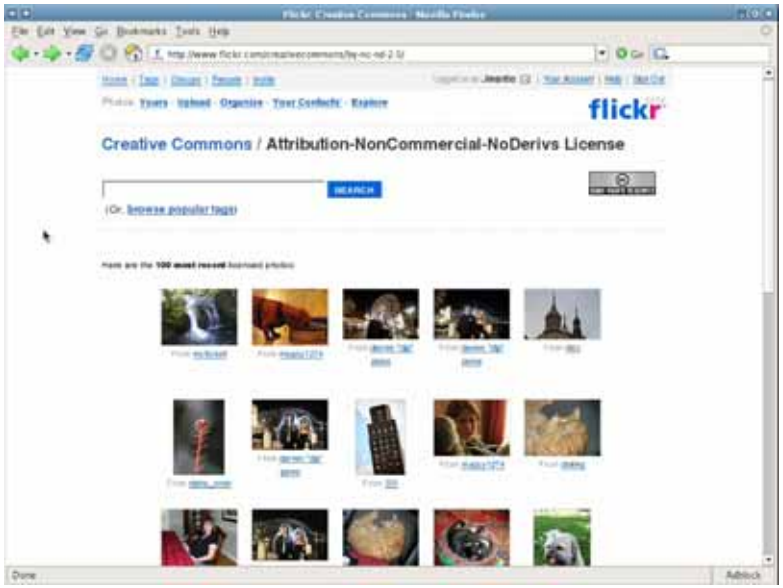


Photo Tourism

Photo Tourism overview

Input photographs

Scene reconstruction

Relative camera positions and orientations

Point cloud

Sparse correspondence

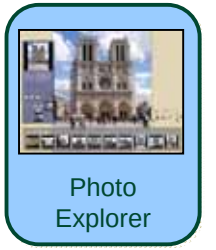


Photo Explorer

Related work

- Image-based modeling

Debevec, *et al.*
SIGGRAPH 1996

Schaffalitzky and Zisserman
ECCV 2002

Brown and Lowe
3DIM 2005

- Image-based rendering

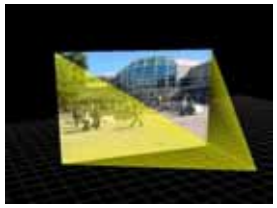
Aspen Movie Map
Lippman, *et al.*, 1978

Photorealistic IBR:
Levoy and Hanrahan, SIGGRAPH 1996
Gortler, *et al*, SIGGRAPH 1996
Seitz and Dyer, SIGGRAPH 1996
Aliaga, *et al*, SIGGRAPH 2001
and many others

Related work

- Image browsing

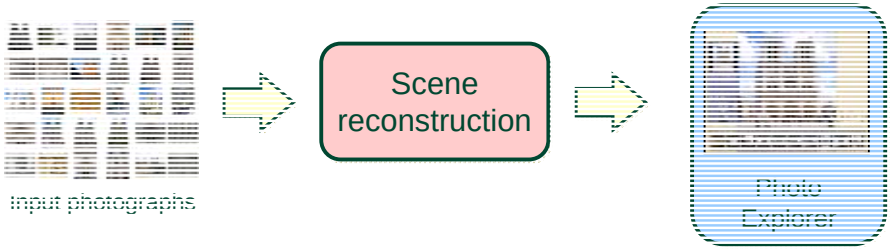
Toyama, *et al*,
Int. Conf. Multimedia, 2003



McCurdy and Griswold
Mobisys 2003

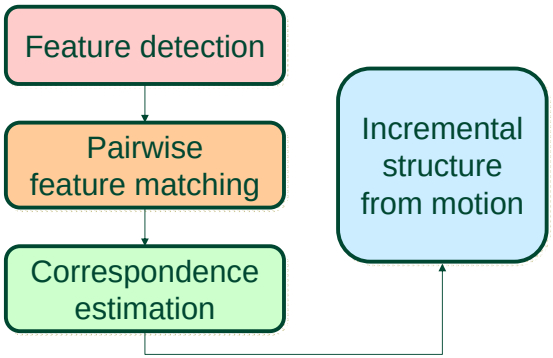
Sivic and Zisserman
ICCV 2003

Photo Tourism overview



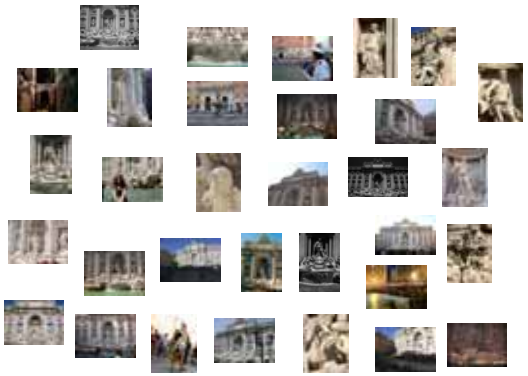
Scene reconstruction

- Automatically estimate
  - position, orientation, and focal length of cameras
  - 3D positions of feature points



Feature detection

- Detect features using SIFT [Lowe, IJCV 2004]

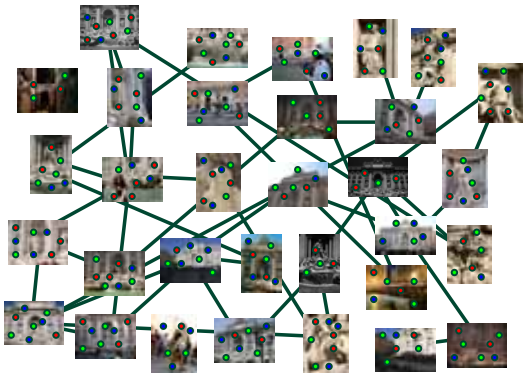


Feature detection

- Detect features using SIFT [Lowe, IJCV 2004]

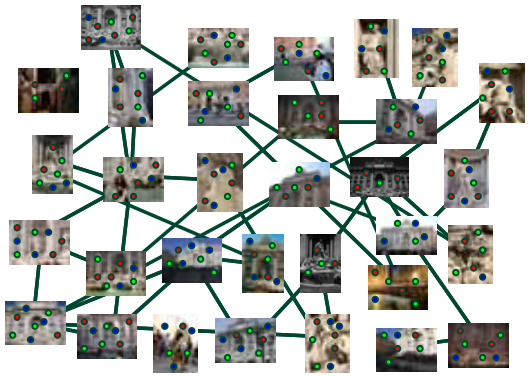
Pairwise feature matching

- Match features between each pair of images



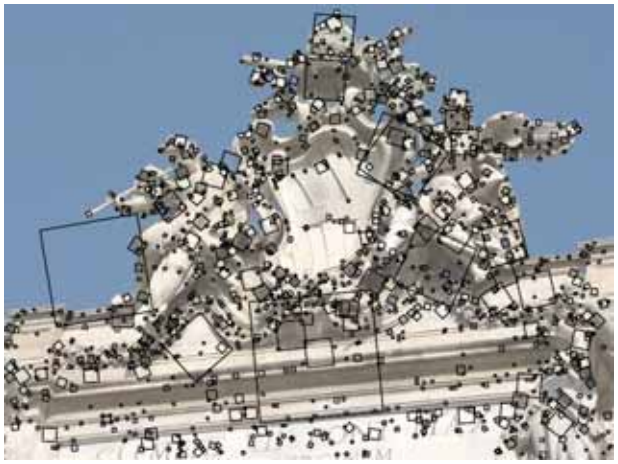
Pairwise feature matching

- Refine matching using RANSAC [Fischler & Bolles 1987] to estimate fundamental matrices between pairs



Feature detection

Detect features using SIFT [Lowe, IJCV 2004]



Feature detection

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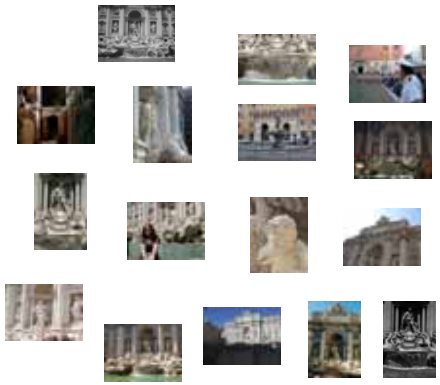

Feature detection

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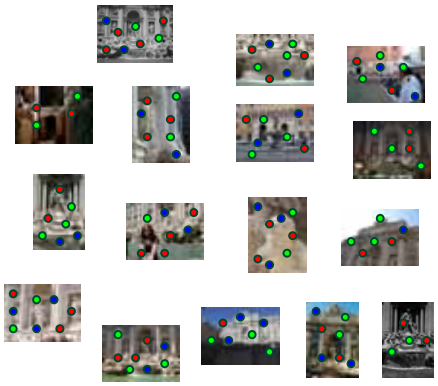
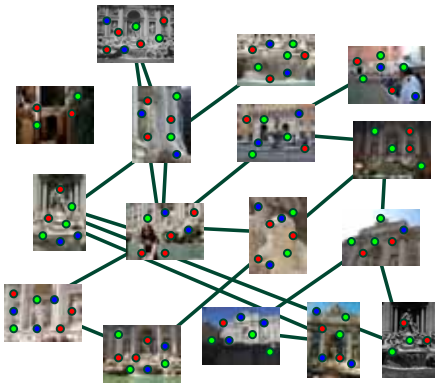


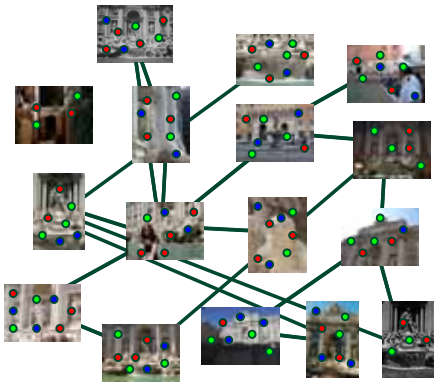
Feature matching

Match features between each pair of images



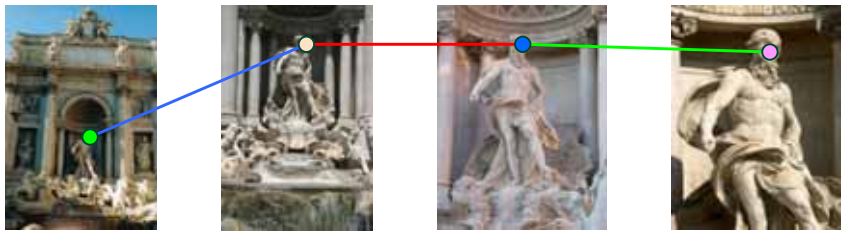
Feature matching

Refine matching using RANSAC [Fischler & Bolles 1987] to estimate fundamental matrices between pairs

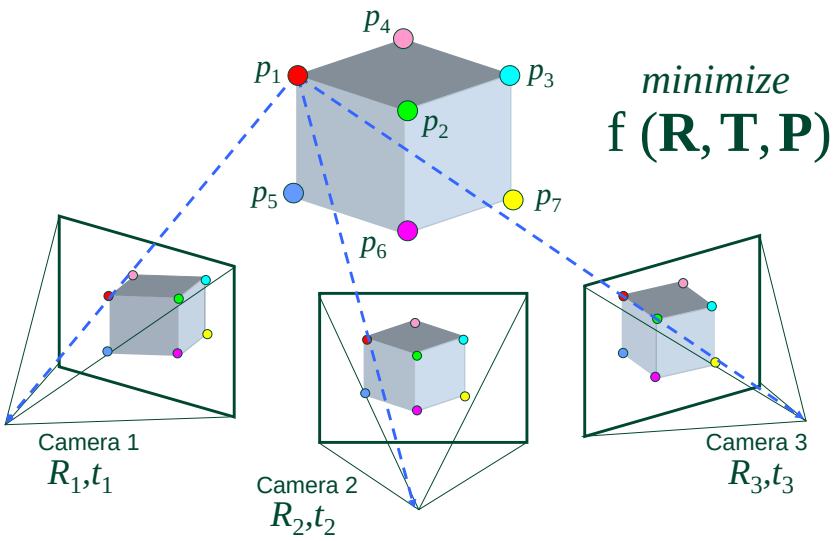


Correspondence estimation

- Link up pairwise matches to form connected components of matches across several images



Structure from motion



minimize

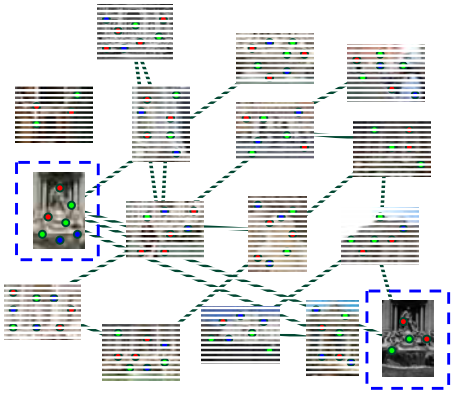
$$f(\mathbf{R}, \mathbf{T}, \mathbf{P})$$

Incremental structure from motion

Incremental structure from motion

Incremental structure from motion

Incremental structure from motion



Incremental structure from motion

Incremental structure from motion

Reconstruction performance

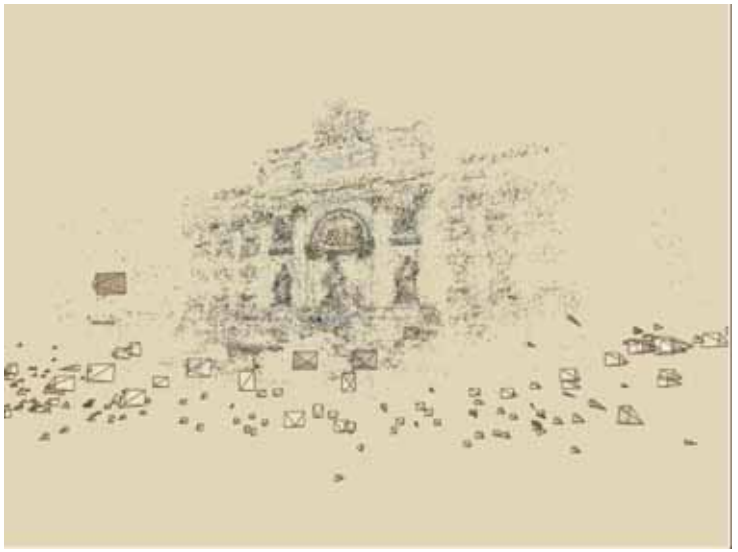
- For photo sets from the Internet, 20% to 75% of the photos were registered
- Most unregistered photos belonged to different connected components

- Running time: < 1 hour for 80 photos

  > 1 week for 2600 photo

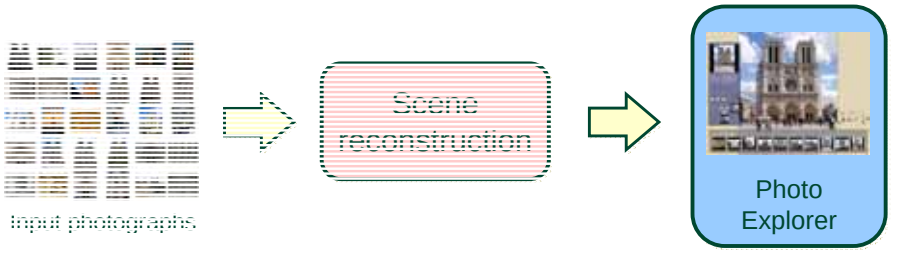
Photo Tourism overview

Photo Explorer



Demo

Photo Tourism overview

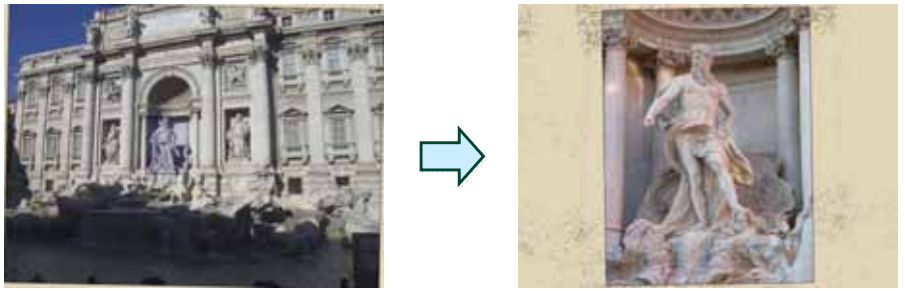


- Navigation
- Rendering
- Annotations

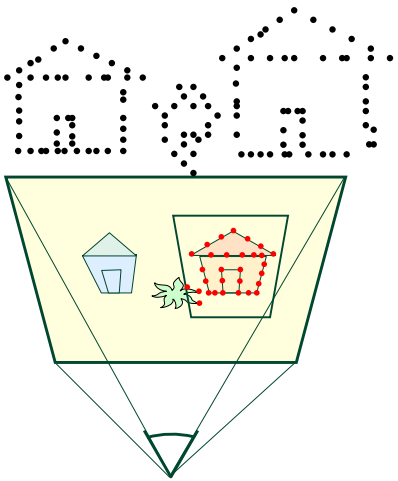
Navigation controls

- Free-flight navigation
- Object-based browsing
- Relation-based browsing
- Overhead map

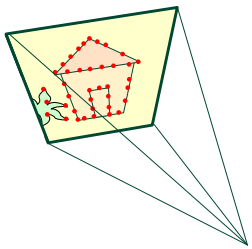
Object-based browsing



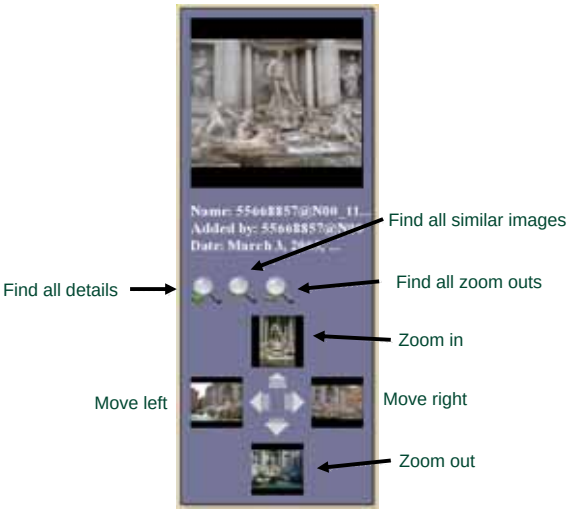
Object-based browsing



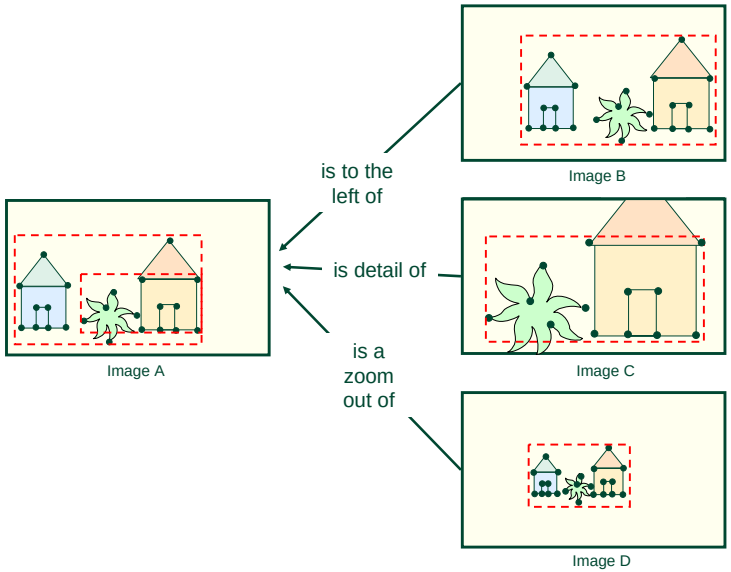
- Visibility
- Resolution
- Head-on view



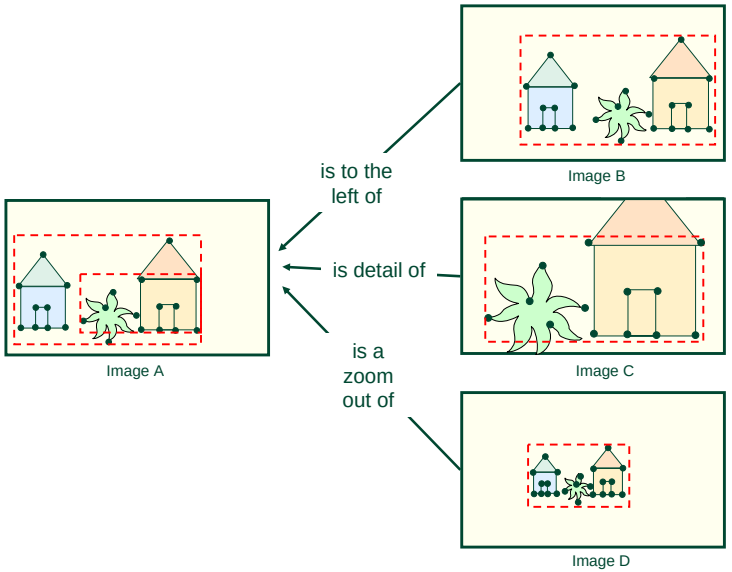
Relation-based browsing



Relation-based browsing



Relation-based browsing



Relation-based browsing

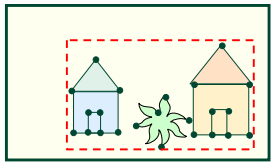


Image A

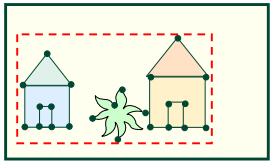


Image B

Relation-based browsing

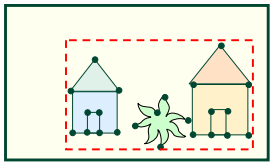


Image A

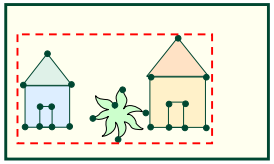
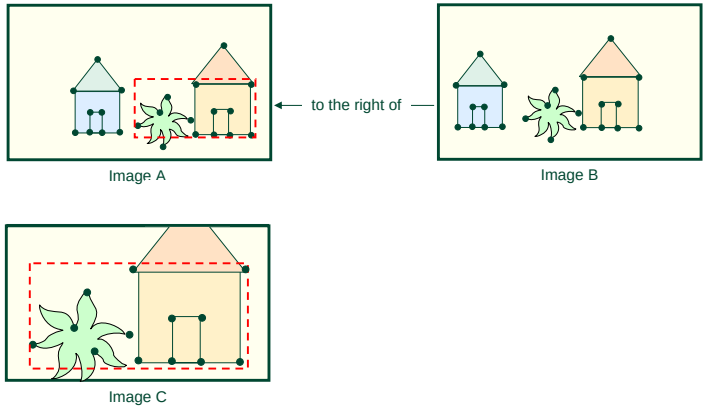


Image B

Relation-based browsing



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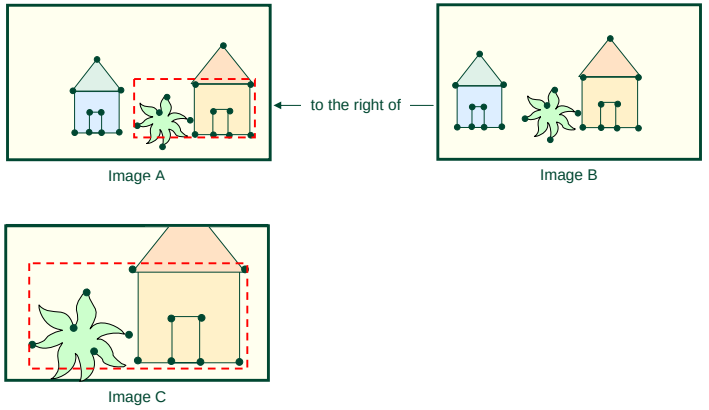

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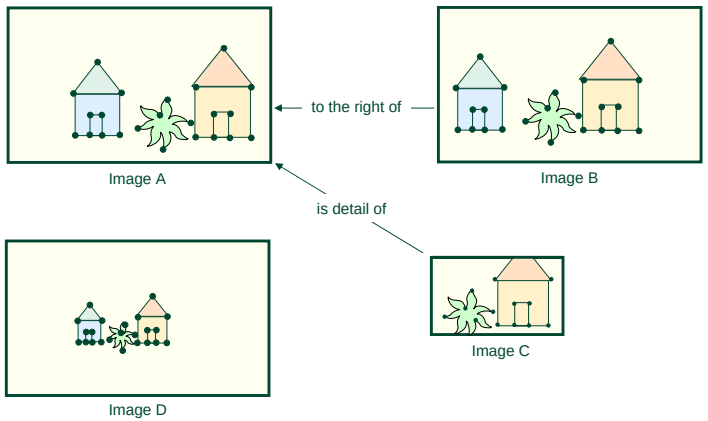
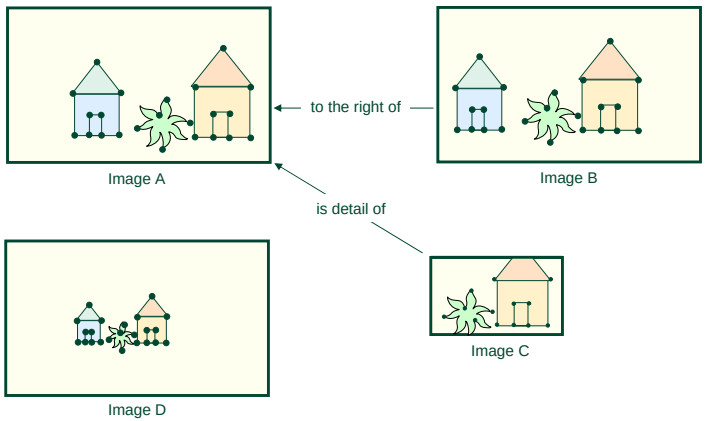
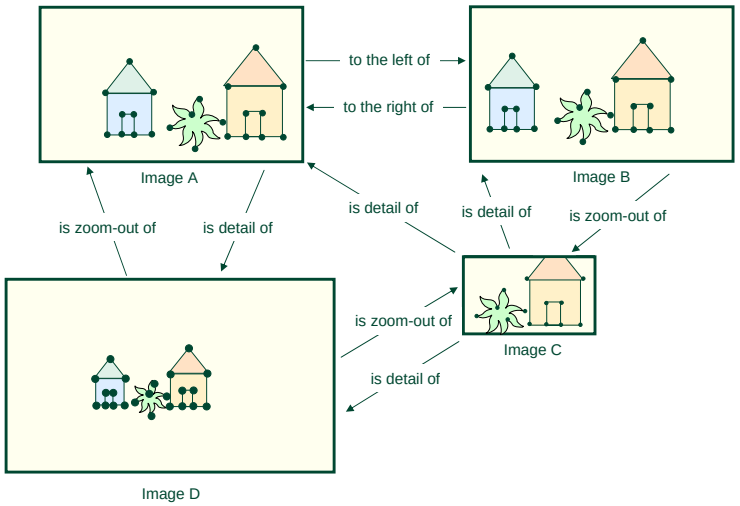


Relation-based browsing



Relation-based browsing



Overhead map

Prague Old Town Square

Photo Tourism overview

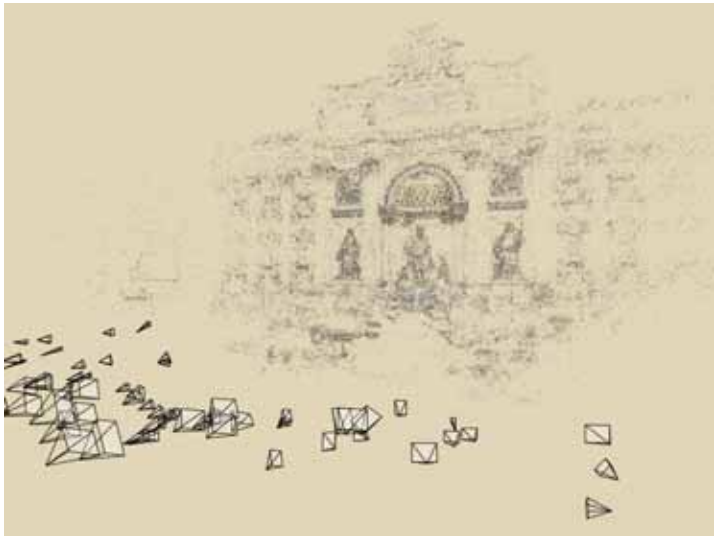
input photographs

Scene reconstruction

Photo Explorer

- Navigation
- Rendering
- Annotations

Rendering



Rendering

Rendering

Rendering transitions

Rendering transitions

Rendering transitions

Rendering transitions

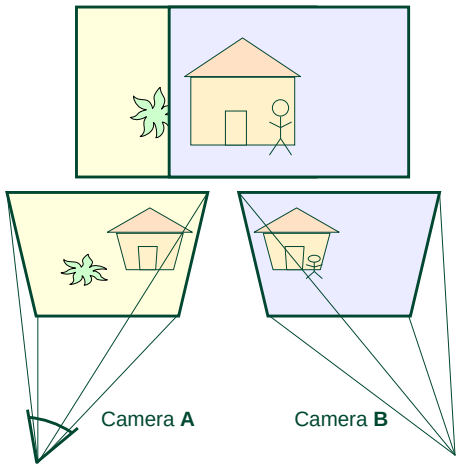


Photo Tourism overview

input photographs

- Navigation
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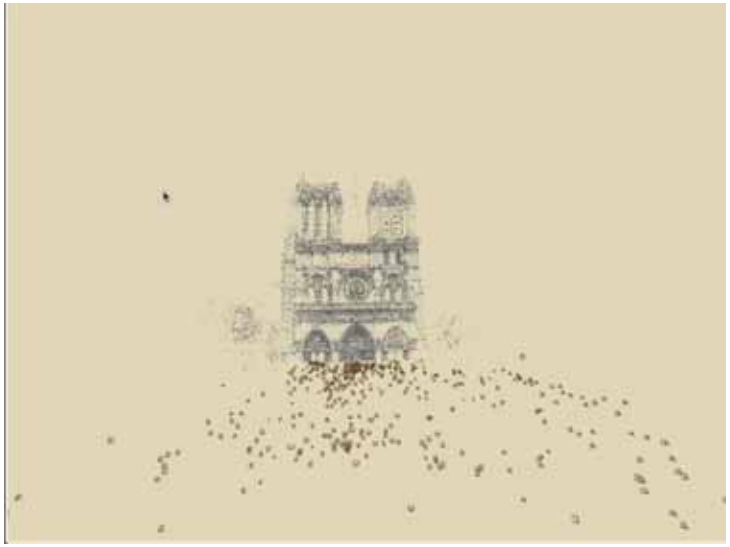
Annotations



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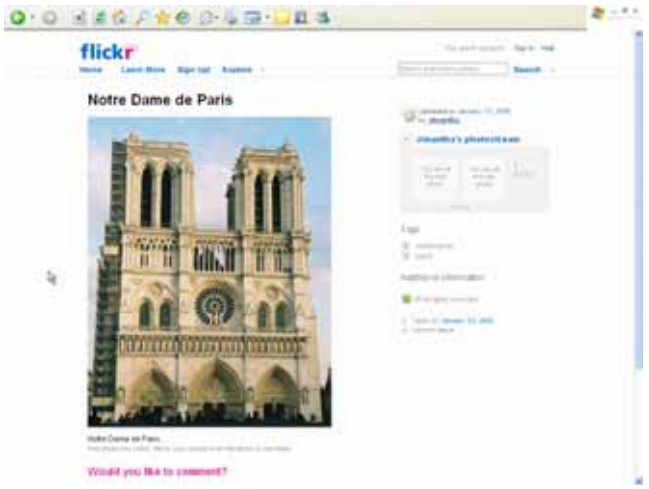
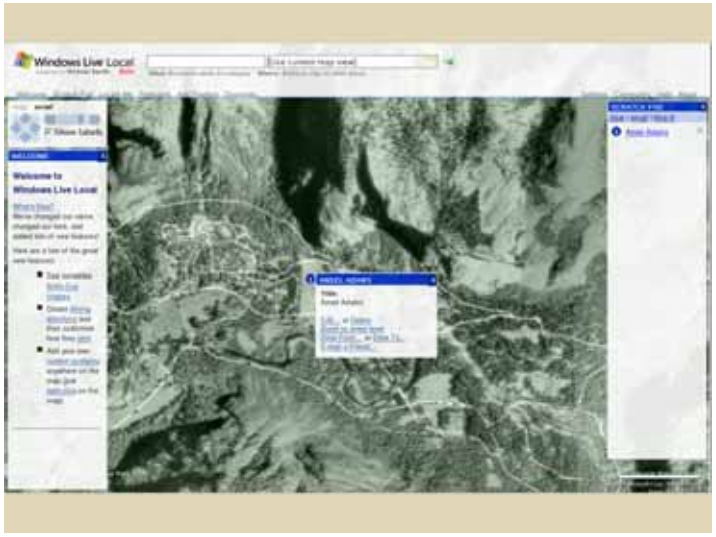


Annotations

Yosemite

Yosemite



Topographic data courtesy USGS

Contributions

- Automated system for registering photo collections in 3D for interactive exploration
- Structure from motion algorithm demonstrated on hundreds of photos from the Internet
- Photo exploration system combining new image-based rendering and photo navigation techniques

Limitations / Future work

- Not all photos can be reliably matched

- Structure from motion scalability
  - → More
- Plane-base

Limitations / Future work

Limitations / Future work

- Not all photos can be reliably matched
  - → Better feature detection / matching
  - → Integrating GPS & other localization info.
- Structure from motion scalability
  - → More efficient (sparse) algorithms
- Plane-based transitions lack parallax
  - → Richer transitions
- Photo explorer scalability…

Future work

- Photo explorer scalability
  - Design client-server architecture for streaming images and geometry at required resolution
  - Scale to *all* of the world's photos (and videos…)
  - ***Photosynth*** project at Microsoft Live Labs (live demo)

Photosynth

Future work

- Photo explorer scalability
  - Scale to *all* of the world's photos (and videos…)
  - Computational complexity: avoid matching all images to all other images
    - vocabulary trees [Nister]
    - graphical models, nested dissection [Dellaert]
    - serendipitous (?) probabilistic inference

Acknowledgements

- National Science Foundation
- Achievement Rewards for College Scientists (ARCS)
- The many people who allowed use of their photos
- UW GRAIL Lab
- MSR Interactive Visual Media Lab
- Kevin Chiu and Andy Hou for writing the Java applet

Conclusion

Indexing the world's photos in 3D provides a new way to share and experience our world

To find out more:

- http://phototour.cs.washington.edu
- http://research.microsoft.com/IVM/PhotoTourism
- http://labs.live.com/photosynth


Saint Basil's Cathedral


Trafalgar Square


Rockefeller Center


Mount Rushmore

Statistics

Dataset	# input	# registered
Trevi Fountain	466	360
Yosemite	325	1,893
Notre Dame	597	2,635
Prague	197	235
Great Wall	82	120
Trafalgar Square	278	1,893

Reconstruction running time

- **Great Wall**: 82 / 120 photos registered

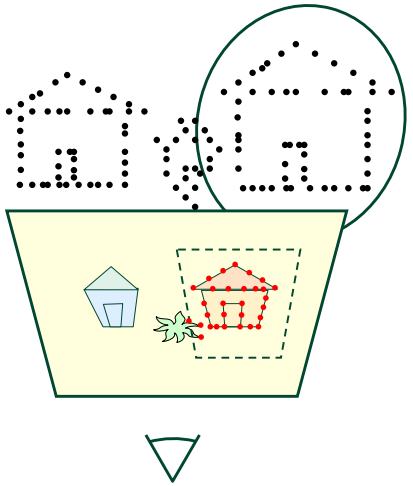
  Running time: ~ 3 hours
- **Notre Dame**: 597 / 2,635 photos registered

  Running time: ~ 2 weeks

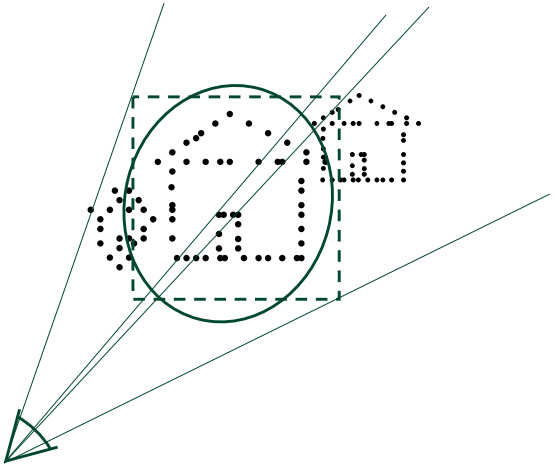
Future work

- Incorporate other metadata (e.g., time, photographer) and media (e.g., panoramas, video)
- Enhanced morphing
- Scale up structure from motion algorithm

Visibility



Visibility



Advantages of 3D over 2D

- 3D geometry has multi-image consistency
- Can annotate point cloud directly
- Can import annotations from georeferenced sources (e.g., landmark databases)
- Can use depth as cue for rejecting outliers in selection

Post-processing the reconstruction

- Compute gravity direction
- Center point cloud at the origin
- Scale model to unit variance