Distortion-Robust Spherical Camera Motion Estimation via Dense Optical Flow

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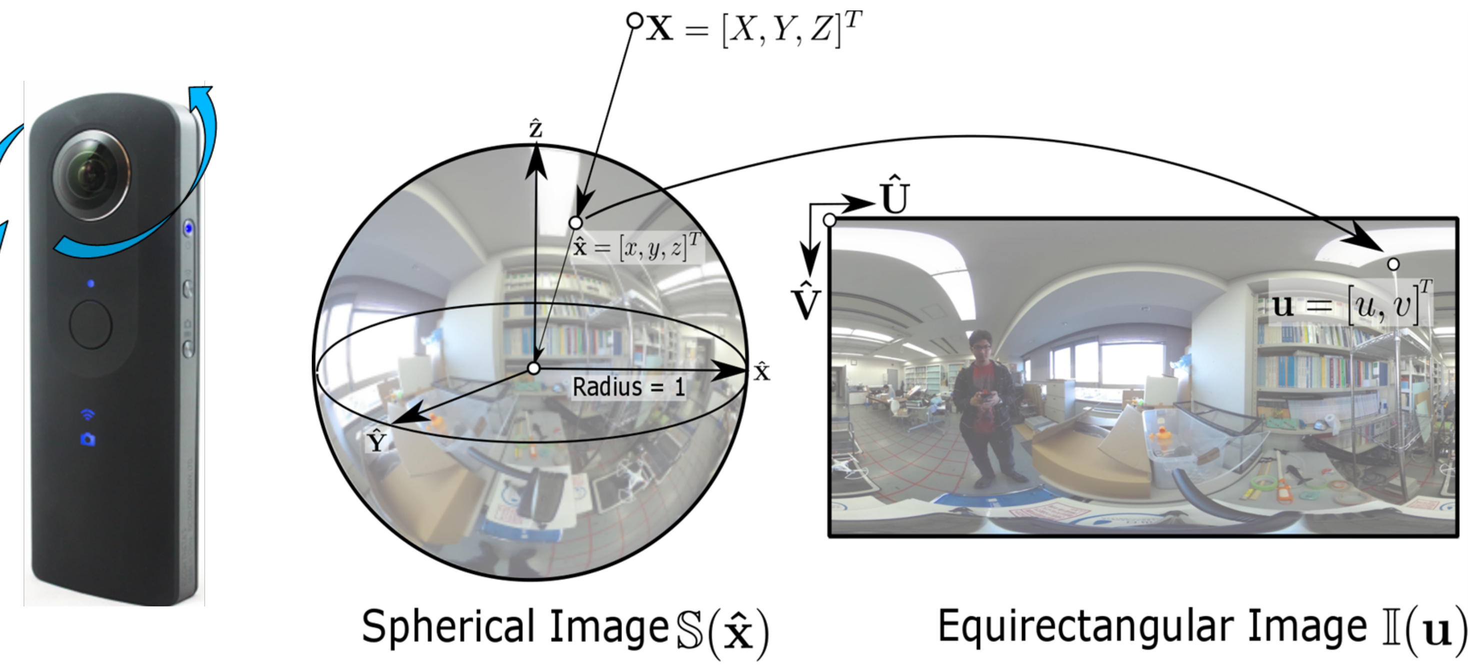
Background

Spherical cameras: 360 degrees in real-time



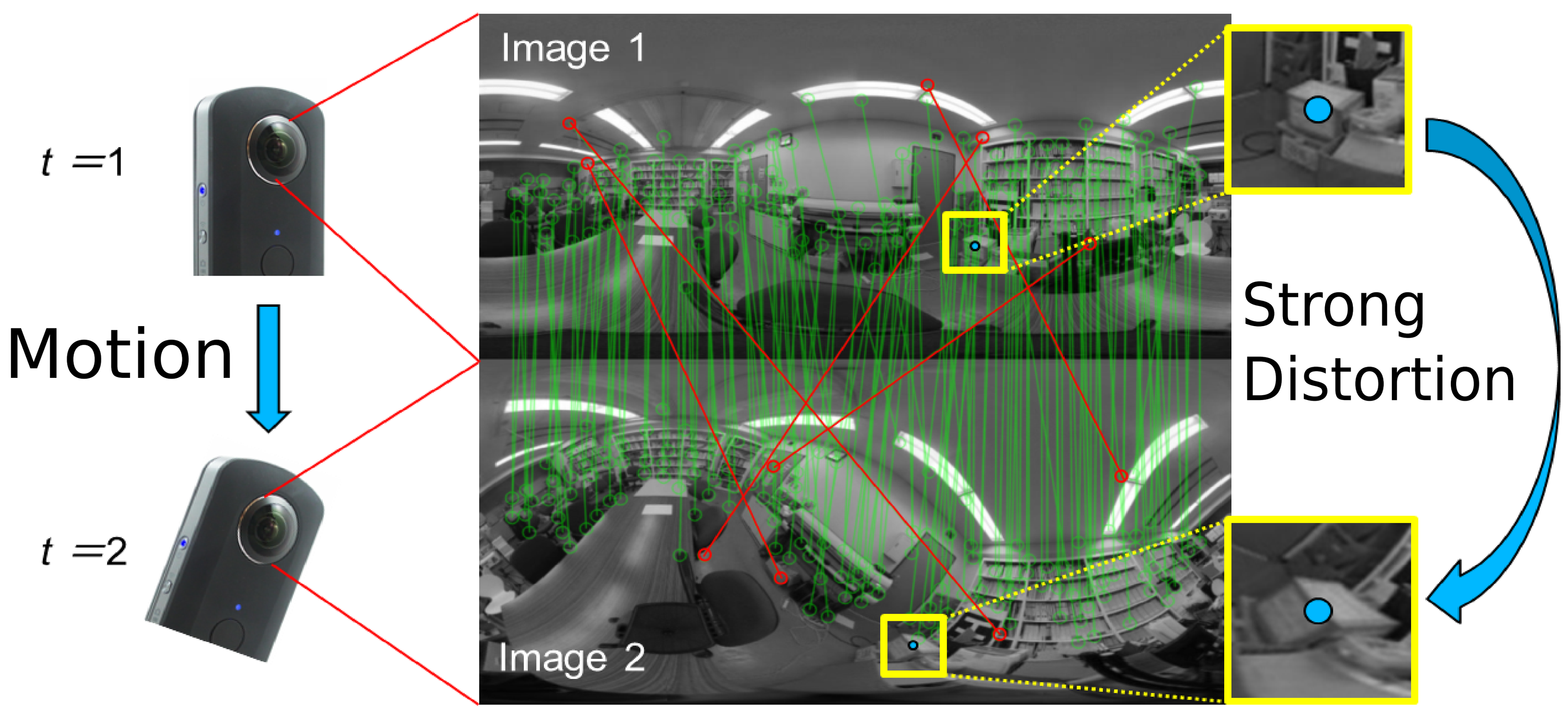
Effective at SfM/VSLAM in enclosed, indoor spaces

Projected as distorted, 2D equirectangular images

Basic steps of SfM: 1. Track features 2. Triangulate 3D points 3. Track camera motion

However, strong distortion induces mistakes.

=> Low robustness and accuracy



Aim and Approach

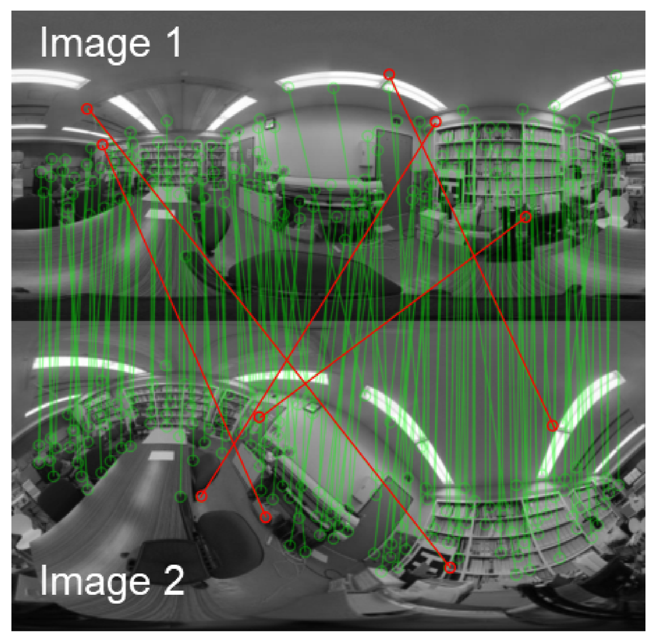
Aim: Robust, accurate Motion Estimation

According to [1], using **dense optical flow** is highly robust and acccurate for small displacements.

Reason: Smoothing in variational optimization -> No outliers

Approach: Combination of **sparse and dense information**

Sparse | Dense



Feature Points
- Large image displacements okay
- Outliers, low robustness

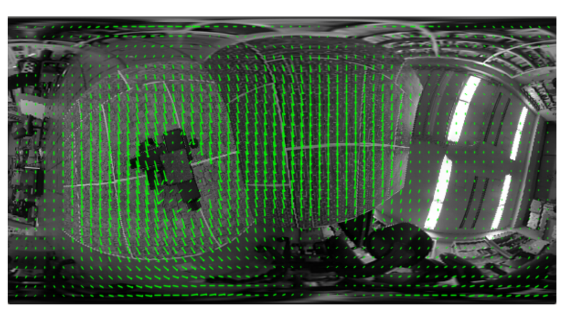
Dense Optical Flow
- No outliers, robust
- Large displacements not okay

Complementary information

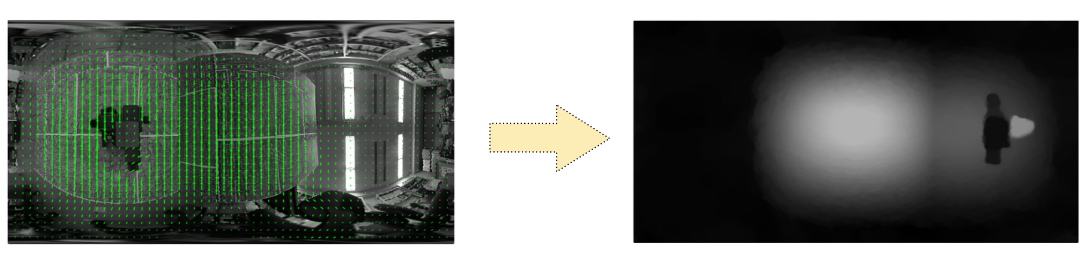
Advantages:
1. Highly robust to distortion, accurate
2. Work completely within equirectangular images
3. Handle distortion in natural, geometric manner

Overview

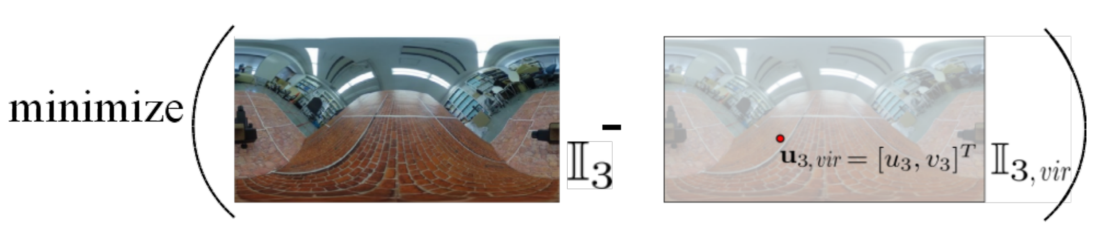
1. **Cover large displacements** with **sparse feature points**, and estimate Dense Optical Flow.



2. **Decompose Optical Flow** to **Dense Disparity** (stereo rectification).



3. **Reproject** to arbitrary pose. **Minimize dense reprojection error** with real image, over 6 DoF motion.

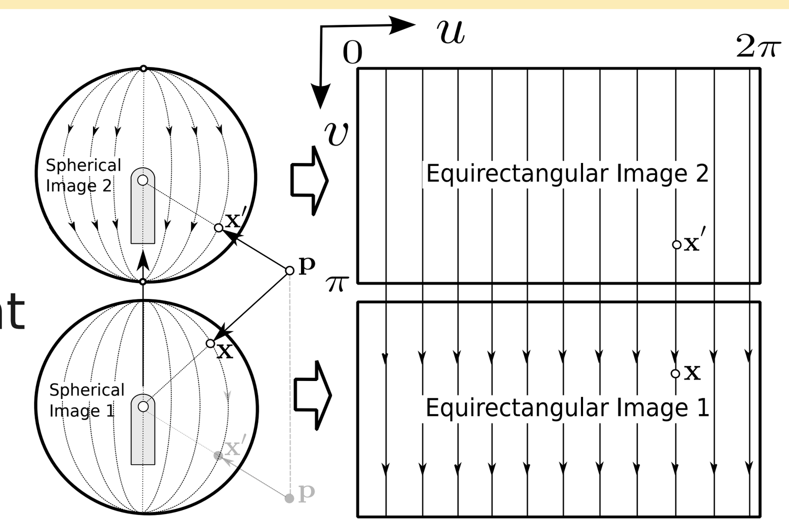


Analogous to the conventional sparse method, but with dense information

Equirectangular Rectification and Disparity Estimation

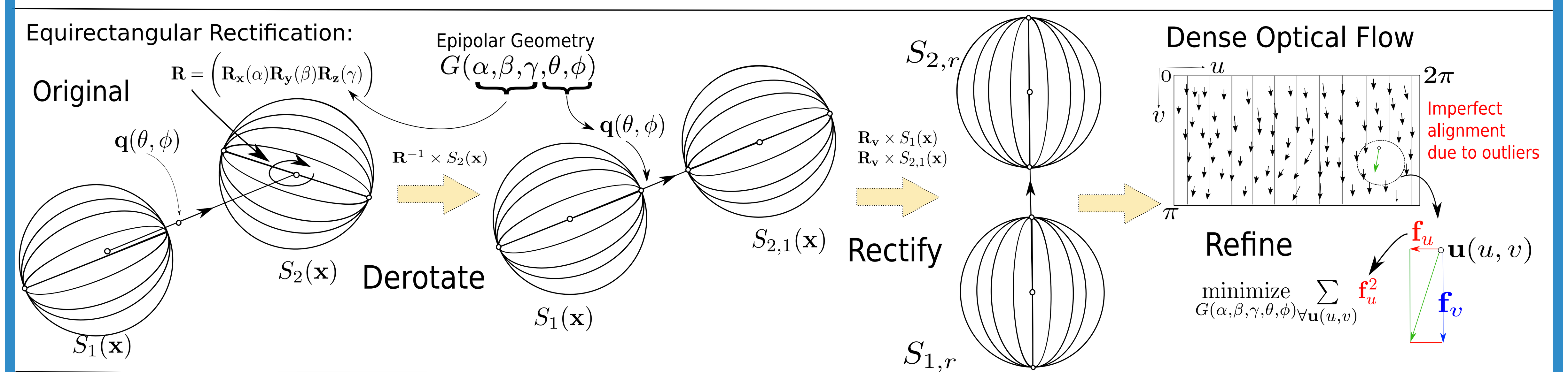
Concept:
Equirectangular Stereo Rectification

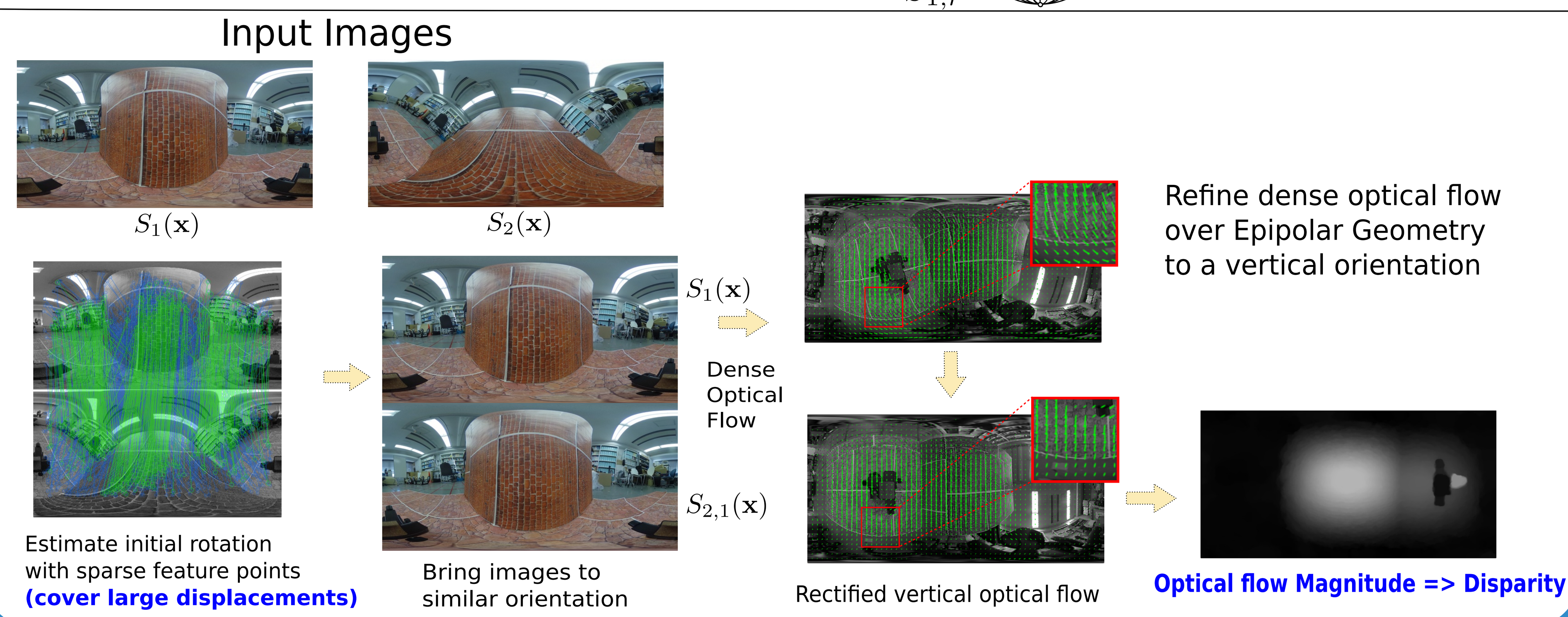
Only vertical displacement
=> All pixels have vertical displacement in the equirectangular projection [4]



Spherical images can be rotated to any orientation
=>Rotate arbitrary images to vertical alignment.

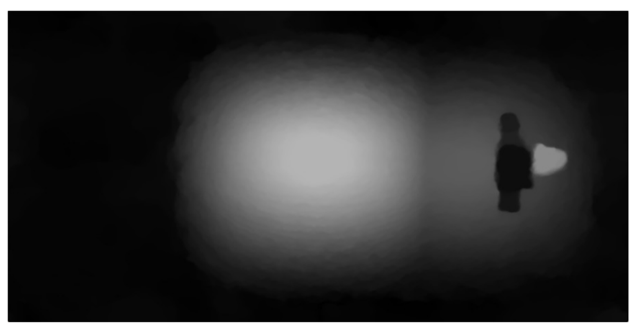
Equirectangular Rectification
=>Can ignore distortion





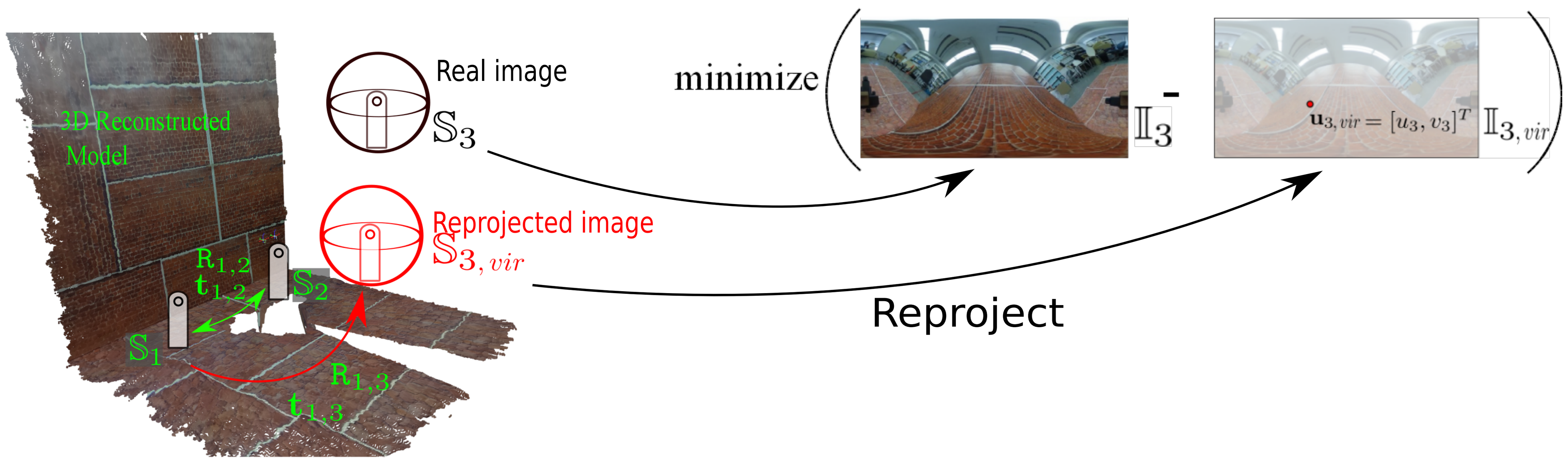
Motion Estimation via Dense Reprojection of Optical Flow

Concept: Dense Photometric Minimization



Optical Flow Disparity

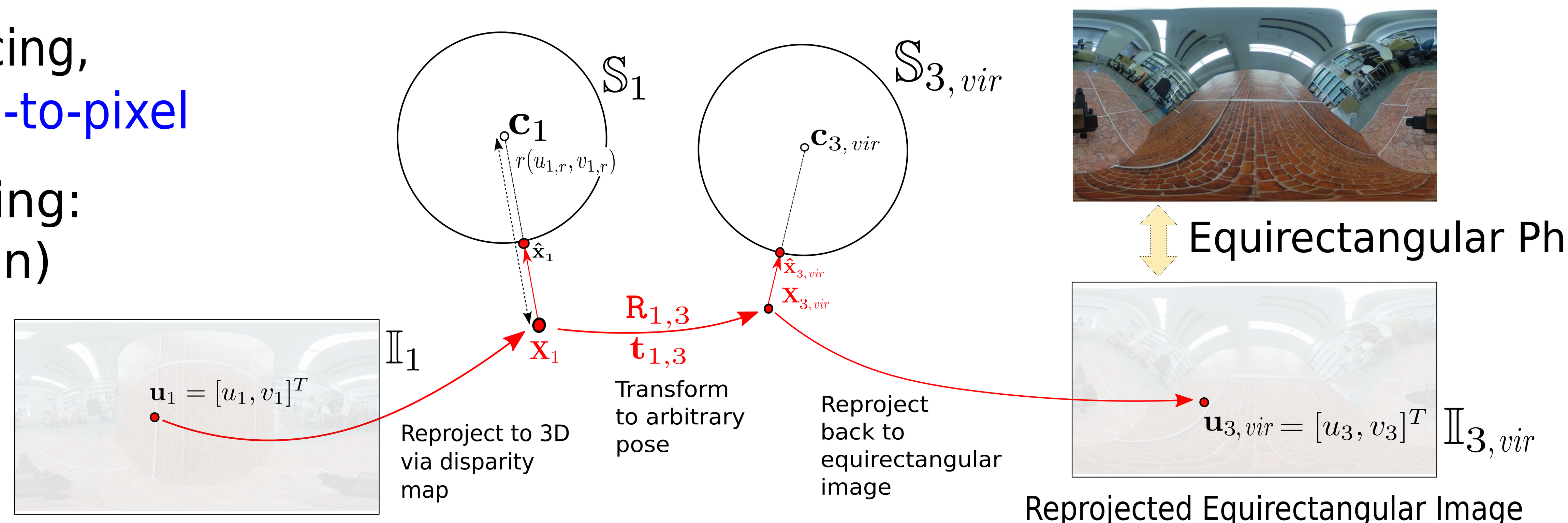
3D Model



Position & Orientation

Instead of ray tracing,
=> reproject pixel-to-pixel

Pixelwise mapping:
(via interpolation)



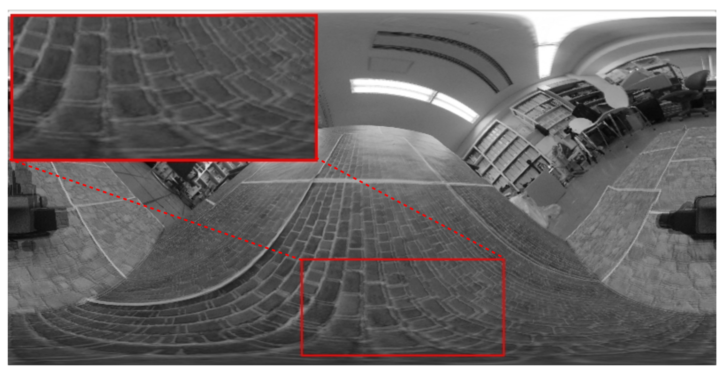
Original Image

Equirectangular Photometric Minimization

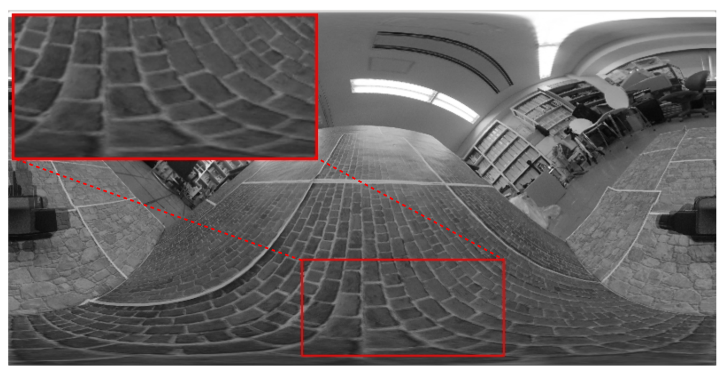
Reprojected Equirectangular Image

$$(x, y, z, \alpha, \beta, \gamma)$$

6 DoF Motion



Before photometric minimization

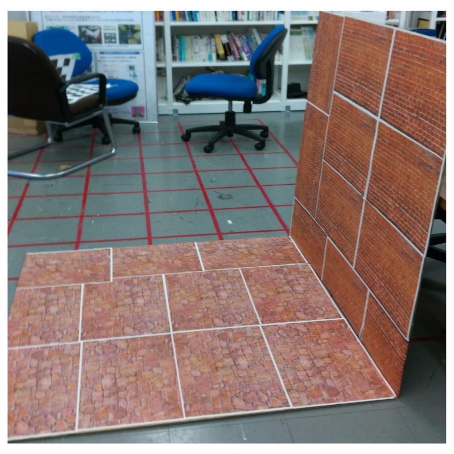


After photometric minimization

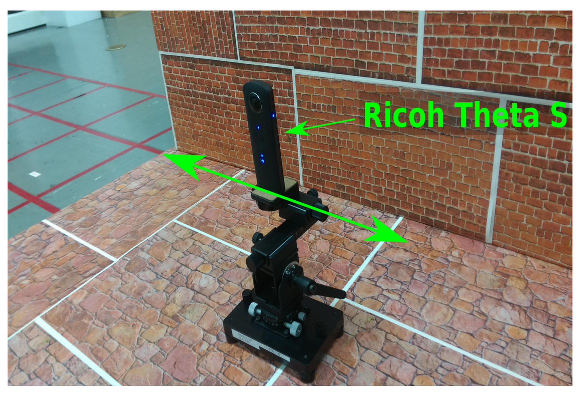
For further images in the sequence,
reproject the disparity map from the closest two.

=> Can also be used for dense, photometric bundle adjustment.

Experimental Evaluation: Robustness to Distortions



Experimental Environment



Equipment: Ricoh Theta S

Image 1 was rotated with a pitch angle to induce distortions

Image 1

Image 2

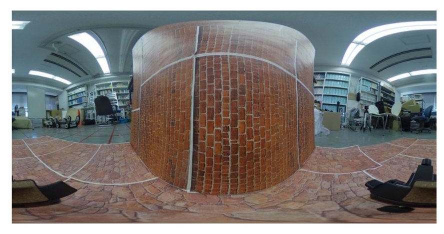


Image 3

Three images captured

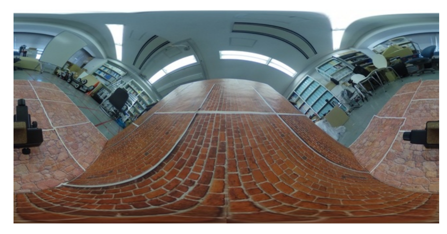


Image 4: Image 1 under pitch rotation, strong distortions

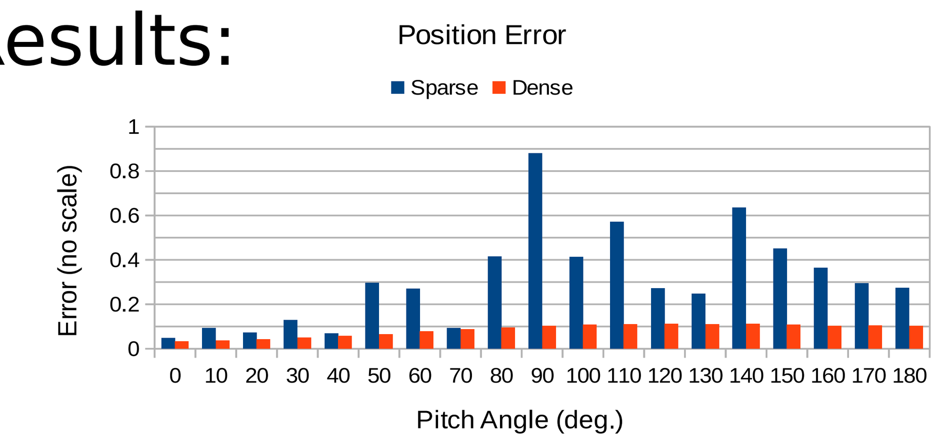
Motion was estimated according to the sequence: Image 1 > Image 2 > Image 3> Image 4
Groundtruth: Image 4, same position as Image 1, known rotation angle

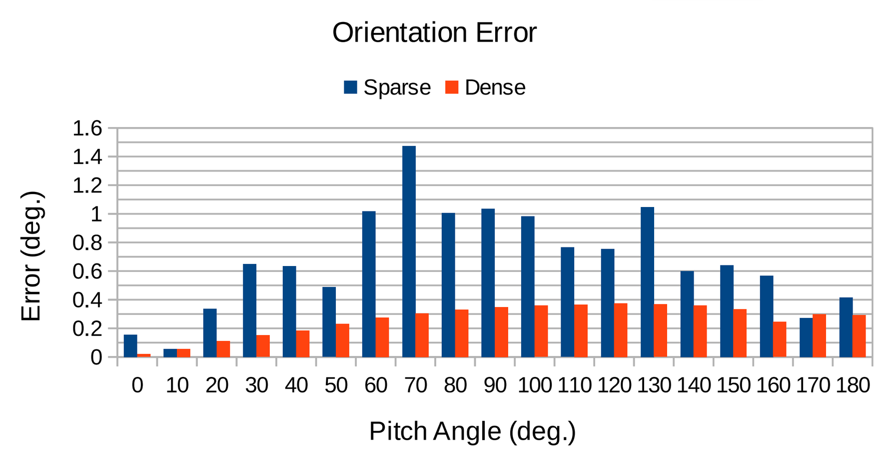
Pitch angle was varied from 0 to 180 degrees. Position and orientation errors were noted.
Compared to sparse feature points using a distortion resistant descriptor: A-KAZE [2]

Additional experiment:

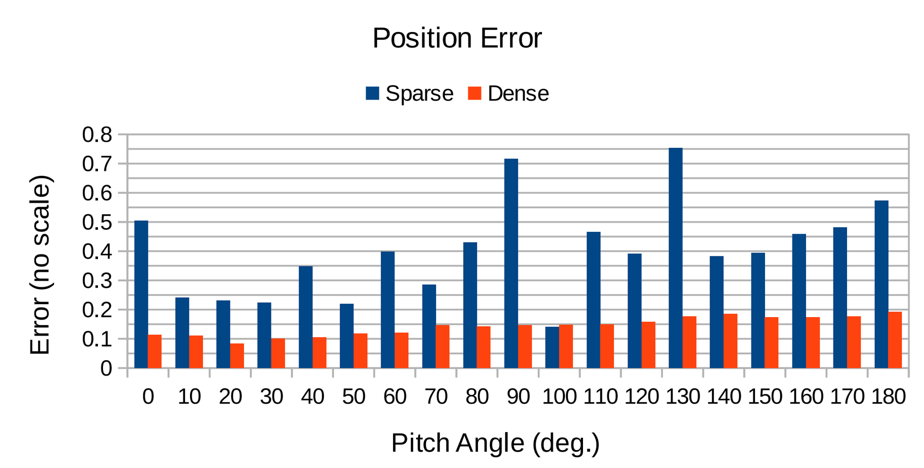
In highly cluttered room
(Disparity estimation difficult)

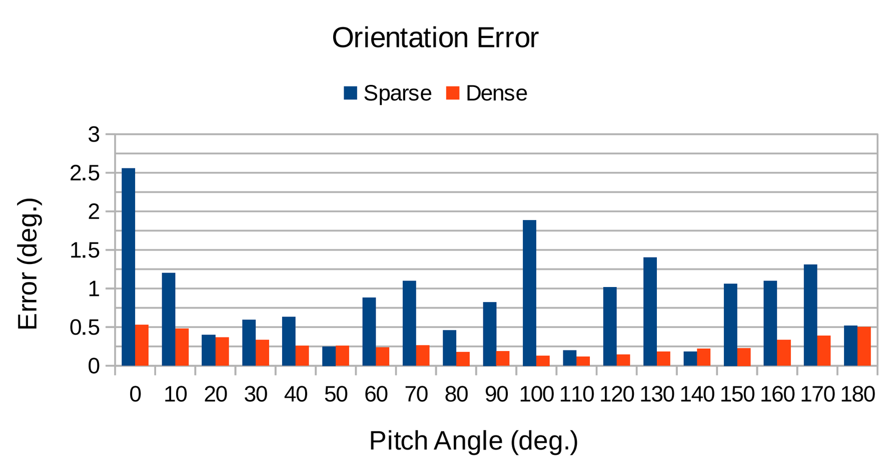
Results:





Results in highly cluttered room:

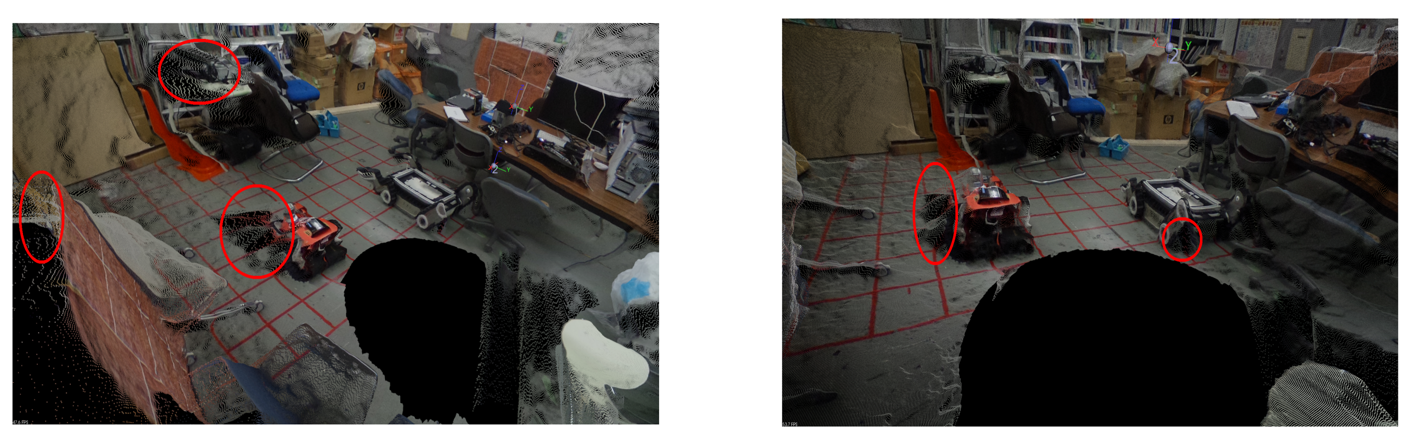




Conclusion: Proposed method is highly accurate and robust to distortion

Additional: 3D Reconstruction results (no mesh)

Cluttered environment:



References:
[1] Levi Valgaerts, Andrés Bruhn, Markus Mainberger, and Joachim Weickert, "Dense versus sparse approaches for estimating the fundamental matrix," *International Journal of Computer Vision*, vol. 96, pp. 212–234, January 2012

[2] Pablo Alcantarilla, Jesus Nuevo, and Adrien Bartoli, "Fast explicit diffusion for accelerated features in non-linear scale spaces," in *Proceedings of the British Machine Vision Conference*, September 2013, pp. 13.1–13.11.

Acknowledgements:

This work was in part supported by:
1. The Council for Science, Technology and Innovation, "Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management"
2. The Precise Measurement Technology Promotion Foundation (PMTP-F)

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