Motion Estimation of Multiple Depth Cameras Using Spheres

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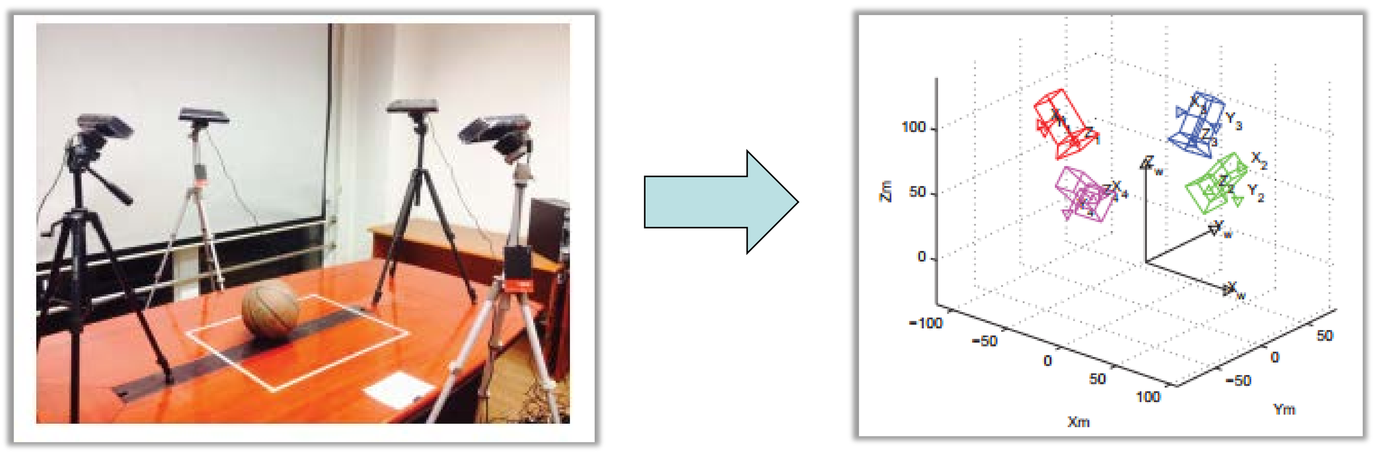
Introduction

Problem: Previous motion estimation methods for Kinect-like cameras are all plane-based methods, with the simultaneous visibility problem in calibrating multiple depth cameras

Goal: Estimate motions between multiple depth cameras automatically

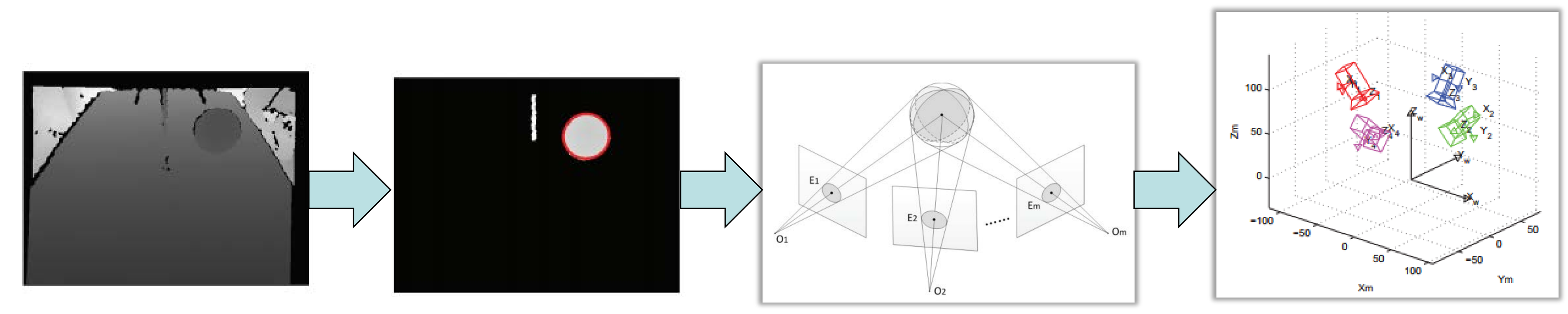
Solution: Use spherical objects to estimate motions between multiple depth cameras, and avoid simultaneous visibility problem due to the symmetry of sphere object



Overview

Pipeline

- Sphere contour detection and get sphere center in each view
- Motion estimation using factorization approach with sphere centers in each camera view as correspondences
- Refine motion parameters by using bundle adjustment

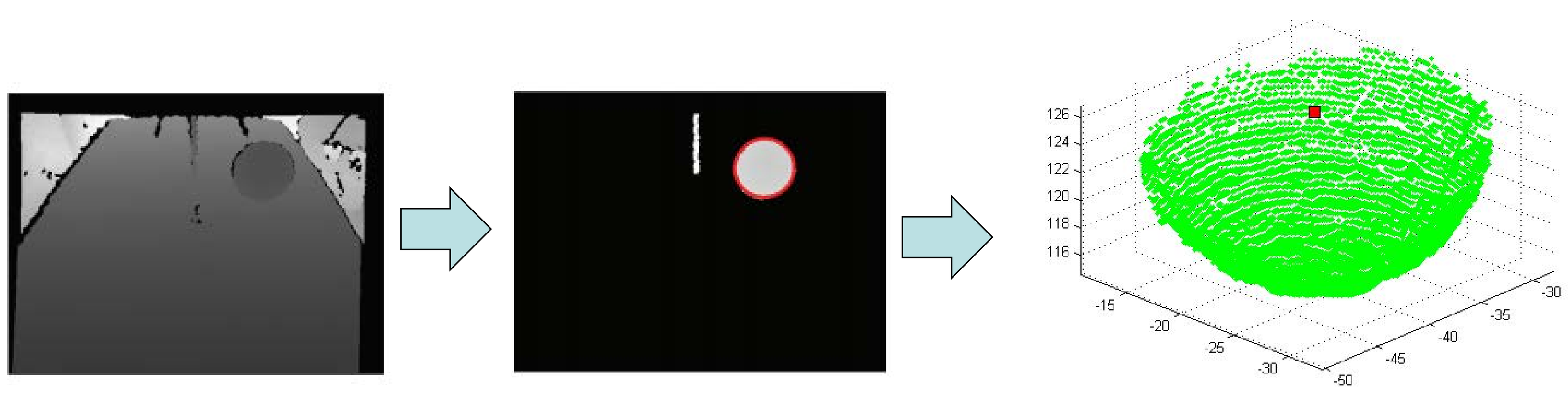


Sphere Center Estimation

Main idea: 2D image of a sphere contour is an ellipse, use Hough transform for robust ellipse detection, and then select proper sphere image with RANSAC and known sphere radius.

Solution:

- Use Hough transform for ellipse detection
- Based on the detected sphere contour images, we fit the sphere with the point clouds by lifting the pixels within the sphere contour images to 3D, and remove infeasible candidates with sphere radius
- Recover the sphere center



$\mathbf{O}_{i,j}$: sphere center in the i-th camera system with sphere's j-th movement

Camera Motion Estimation

Solution: Recover motion parameters of multiple depth cameras from spheres' centers by using a factorization method for 3D point sets. The factorization method is advantageous over other methods in that it treats each view equally and recover all the camera motion matrices simultaneously

Estimate translations: $\boxed{\mathbf{t}_i = \frac{1}{n}\sum_{j=1}^{n}\mathbf{O}_{i,j}}$

Centre the data: $\tilde{\mathbf{O}}_{i,j} = \mathbf{O}_{i,j} - \mathbf{t}_i$

Estimate rotations:

$$\underbrace{\begin{bmatrix} \tilde{\mathbf{O}}_{11} & \tilde{\mathbf{O}}_{12} & \cdots & \tilde{\mathbf{O}}_{1n} \\ \tilde{\mathbf{O}}_{21} & \tilde{\mathbf{O}}_{22} & \cdots & \tilde{\mathbf{O}}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{\mathbf{O}}_{m1} & \tilde{\mathbf{O}}_{m2} & \cdots & \tilde{\mathbf{O}}_{mn} \end{bmatrix}}_{\mathbf{W}} = \underbrace{\begin{bmatrix} \hat{\mathbf{R}}_1 \\ \hat{\mathbf{R}}_2 \\ \vdots \\ \hat{\mathbf{R}}_m \end{bmatrix}}_{\mathbf{Q}} \underbrace{[\hat{\mathbf{O}}_1, \hat{\mathbf{O}}_1, ..., \hat{\mathbf{O}}_n]}_{\mathbf{S}}$$

⇓ SVD with rank 3 constraint

$$\mathbf{W} = \mathbf{QS} = (\mathbf{QT})(\mathbf{T}^{-1}\mathbf{S})$$

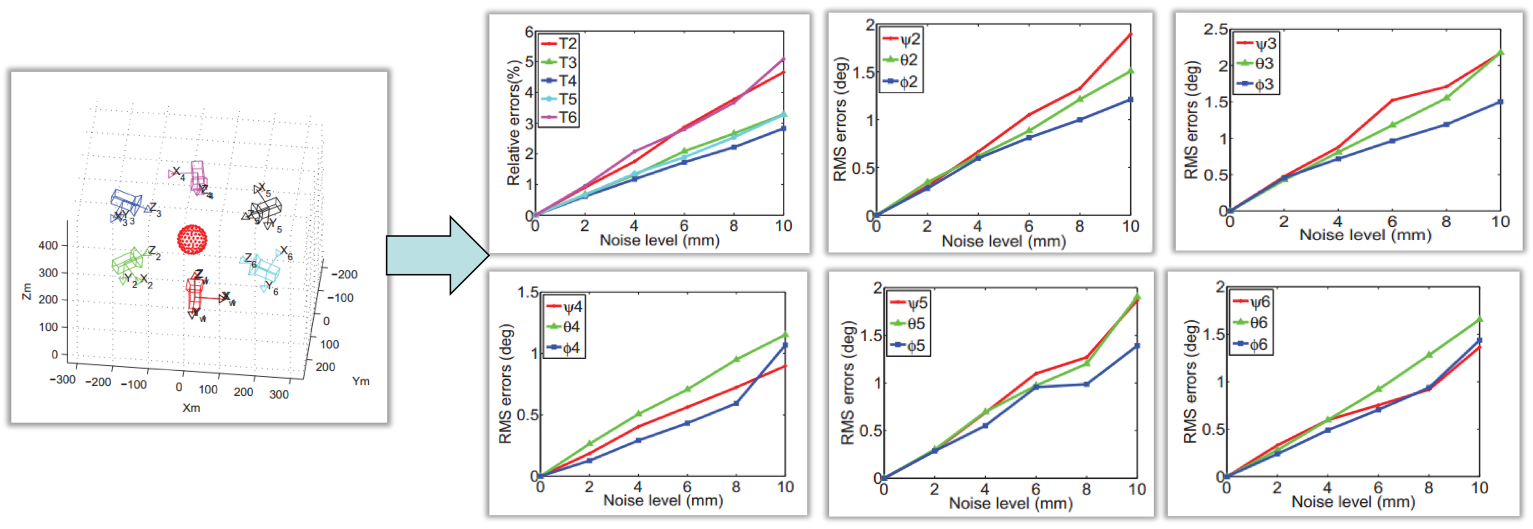
⇓ orthogonality constraints of rotation matrix

$$\begin{aligned} \mathbf{Q}_{[3k+1:3k+3,:]}\mathbf{T}(\mathbf{Q}_{[3k+1:3k+3,:]}\mathbf{T})^T &= \\ \mathbf{Q}_{[3k+1:3k+3,:]}\underbrace{\mathbf{TT}^T}_{\mathbf{\Omega}}\mathbf{Q}^T_{[3k+1:3k+3,:]} &= \mathbf{I}_{3\times 3} \end{aligned}$$

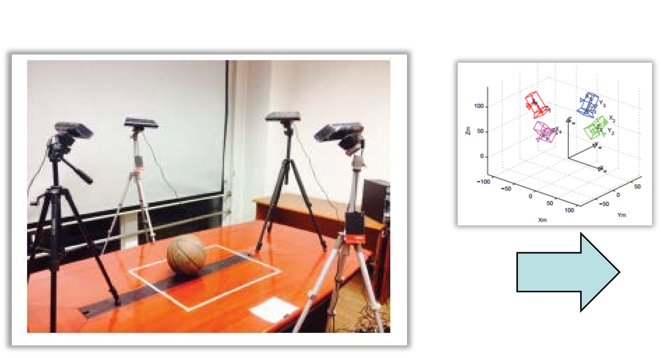
⇒ $\mathbf{A}\mathrm{vec}(\mathbf{\Omega}) = \mathbf{0}$ ↓ SVD $\mathbf{\Omega} = \mathbf{U\Lambda U}^T = \mathbf{U\Lambda}^{1/2}(\mathbf{U\Lambda}^{1/2})^T$ ⇒ $\mathbf{T} = \mathbf{U\Lambda}^{1/2}$ ⇒ $\boxed{\{\hat{\mathbf{R}}_i\}_{i=1}^{m} = \mathbf{QT}}$

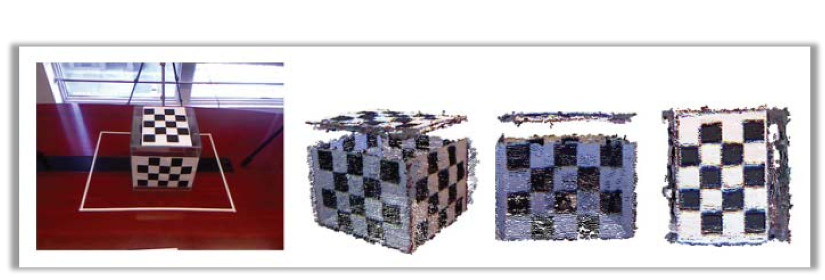
Experiments

Simulated experiments



Real experiments





Method	θ(degrees)	σ_θ (degrees)
Our method	89.8	1.1
Planar-based method	89.7	1.5

Conclusions

- Accurate and automatic method
- Adaptable to different depth sensors
- Achieved accurate calibration of multiple Kinect-like sensors

References

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