15-CVPR-Robust Reconstruction of Indoor Scenes

# Introduction

## ||High-fidelity reconstruction||

### High-fidelity reconstruction

###### 09-ICCV-Reconstructing building interiors from images

###### 12-IJRR-RGB-D mapping: Using Kinect-style depth cameras for dense 3D modeling of indoor environments

###### 12-ECCV-Reconstructing the world’s museums (Xiao Jianxiong)

###### 14-CVPR-Piecewise planar and compact floorplan reconstruction from images

### Make simplifying assumptions and forfeit detail in the reconstructed model

###### 09-ICCV-Reconstructing building interiors from images

###### 12-ECCV-Reconstructing the world’s museums (Xiao Jianxiong)

###### 14-CVPR-Piecewise planar and compact floorplan reconstruction from images

### Rely on user interaction

###### 11-UbiComp-Interactive 3D modeling of indoor environments with a consumer depth camera

### Both

###### 12-ICRA-Interactive acquisition of residential floor plans

### Rely on substantial hardware setups based on LiDAR scanners

###### 13-RS-Indoor localization algorithms for an ambulatory human operated 3D mobile mapping system

###### 15--Fast, automated, scalable generation of textured 3D models of indoor environments

## ||Large scene reconstruction||

### Views are acquired along a complex trajectory

### Each view expose only a small part of the environment

### Paths that thoroughly image all surfaces at close range lead to **significant odometry drift** and **the necessity to match and register different views globally**.

## ||Scene reconstruction with depth camera||

### Prior work

###### 12-IJRR-RGB-D mapping: Using Kinect-style depth cameras for dense 3D modeling of indoor environments

###### 14-TOR-3-D mapping with an RGB-D camera

###### 13-TOG-Dense scene reconstruction with points of interest

###### 13-IROS-Deformation-based loop closure for large scale dense RGB-D SLAM

###### 13-ICCV-SUN3D: A database of big spaces reconstructed using SfM and object labels

### Existing automatic reconstruction methods are not reliable enough for our purposes

###### 13-ICCV-SUN3D: A database of big spaces reconstructed using SfM and object labels

## ||Pipeline||

### Steps

##### Pairs of local scene fragments are registered

##### A global model is constructed based on these pairwise alignments

00-ICRA-3-D map reconstruction from range data

### Main weakness

##### Low precision of geometric registration

##### Leads to aliasing of fine geometric details and inability to disambiguate different locations based on local geometry

## ||Line process||

### Brief

##### Introduced in the context of image restoration as a means for automatically identifying discontinuities as part of a single global optimization

###### 84-PAMI-Stochastic relaxation, Gibbs distributions, and the Bayesian restoration of images

###### 92-PAMI-Constrained restoration and the recovery of discontinuities

##### Closely related to robust estimation

###### 96-IJCV-On the unification of line processes, outlier rejection, and robust statistics with applications in early vision

### Advantages

##### The optimization objective retains a least-squares form and can be optimized by a standard high-performance least-squares solver

##### Extremely effective in dealing with pairwise registration errors

# Contributions

### Provide infrastructure for rigorous evaluation of scene reconstruction accuracy

### Perform a thorough quantitative evaluation of surface registration algorithms in the context of scene reconstruction

### In addition to accuracy measurements on synthetic scenes we describe an experimental procedure for quantitative evaluation of reconstruction quality on real-world scenes in the absence of ground-truth data

# Related work

## ||Realtime dense reconstruction with a consumer depth camera||

### KinectFusion

###### 05-IJSM-Automatic correspondence for 3D modeling: an extensive review

##### Limitation

Used a flat voxel grid

Was limited to small volumes

##### Improvement

13-TOG-Scalable real-time volumetric surface reconstruction

13-ICRA-Robust real-time visual odometry for dense RGB-D mapping

13-TOG-Real-time 3D reconstruction at scale using voxel hashing

### Range image integration

###### 96-SIGGRAPH-A volumetric method for building complex models from range images

### Visual odometry

###### 03-ICCV-Real-time simultaneous localisation and mapping with a single camera

###### 04-CVPR-Visual odometry

###### 07-ISMAR-Parallel tracking and mapping for small AR workspaces

##### Use to improve the accuracy of the system

13-RSS-Realtime camera tracking and 3D reconstruction using signed distance functions

13-ICRA-Robust real-time visual odometry for dense RGB-D mapping

### Real-time 3D reconstruction

###### 02-TOG-Realtime 3D model acquisition

###### 08-IJCV-Detailed real-time urban 3D reconstruction from video

###### 10-CVPR-Live dense reconstruction with a single moving camera

## ||RGB-D reconstruction systems with integrated loop closure (online)||

### Reference

###### 12-IJRR-Using Kinect-style depth cameras for dense 3D modeling of indoor environments

###### 14-TOR-3-D mapping with an RGB-D camera

###### 13-3DV-Patch volumes: Segmentation-based consistent mapping with RGB-D cameras

###### 13-ICCV-Large-scale multi-resolution surface reconstruction from RGB-D sequences

###### 13-IROS-Deformation-based loop closure for large scale dense RGB-D SLAM

##### Detect loop closures by matching individual RGB-D images

Visual features such as SIFT or SURF keypoints

Through dense image registration

##### Delivers real-time performance

##### But assumes that different images that observe the same location in the scene are sufficiently similar

## ||High-quality off-line scene reconstruction||

### Reference

###### 09-ICCV-Reconstructing building interiors from images

###### 13-ICCV-SUN3D: A database of big spaces reconstructed using SfM and object labels

###### 14-TOG-Dense scene reconstruction with points of interest

###### 15--Fast, automated, scalable generation of textured 3D models of indoor environments

### Off-line global optimization

###### 13-TOG-Dense scene reconstruction with points of interest

###### 13-ICCV-Elastic fragments for dense scene reconstruction

###### 14-CVPR-Simultaneous localization and calibration: Self-calibration of consumer depth cameras

##### Relied on an initialization provided by an off-the-shelf loop closure detection

14-TOR-3-D mapping with an RGB-D camera

Failure when the provided loop closure set was incomplete

## ||Geometric registration||

### Extensively studied

###### 05-IJSM-Automatic correspondence for 3D modeling: an extensive review

### A typical registration pipeline

##### Steps

Samples constellations of points on one surface

Uses matching configurations on the other surface to compute candidate transformations

##### Challenge

Exhaustive sampling and matching are prohibitively expensive

### Local shape descriptors studies

##### Used for pruning and correspondence

05-SGP-Robust global registration

09-ICRA-Fast point feature histograms (FPFH) for 3D registration

11-ICRA-Point feature extraction on 3D range scans taking into account object boundaries

13-IJCV-Rotational projection statistics for 3D local surface description and object recognition

##### Proposed different types of constellations

08-TOG-4-points congruent sets for robust pairwise surface registration

10-CVPR-Model globally, match locally: Efficient and robust 3D object recognition

14--Super 4PCS: Fast global pointcloud registration via smart indexing

### Nevertheless, misregistrations are still common in practice

## ||Global optimization||

### Based on hypothesized pairwise relations

##### Introduce by

97--Globally consistent range scan alignment for environment mapping

##### Used in robotics

08-IJRR-FAB-MAP: probabilistic localization and mapping in the space of appearance

08-TOR-iSAM: Incremental smoothing and mapping

10--tutorial on graph-based SLAM

## ||Line process||

### Introduced by

###### 96-IJCV-On the unification of line processes, outlier rejection, and robust statistics with applications in early vision

##### This formulation enables effective outlier rejection using a high performance least-squares solver

### Related formulations in robot localization

###### 12-IROS-Switchable constraints for robust pose graph SLAM

###### 13-ICRA-Switchable constraints vs. max-mixture models vs. RRR – a comparison of three approaches to robust pose graph SLAM

###### 13-IROS-Robust pose-graph loop-closures with expectation-maximization

###### 14-ICRA-Experimental analysis of dynamic covariance scaling for robust map optimization under bad initial estimates

### In bundle adjustments

###### 14-ECCV-Robust bundle adjustment revisited

### In structure from motion, robustness can be increased by appropriate penalty functions

###### 13-PAMI-SfM with MRFs: Discrete-continuous optimization for large-scale structure from motion

###### 11-CVPR-L1 rotation averaging using the Weiszfeld algorithm

###### 13-ICCV-Efficient and robust largescale rotation averaging

### By identifying inconsistent substructures among pairwise relations between poses

###### 08-CVPR-What can missing correspondences tell us about 3D structure and motion?

###### 10-CVPR-Disambiguating visual relations using loop constraints

###### 11-CVPR-Structure from motion for scenes with large duplicate structures

###### 13-ICCV-Network principles for SfM: Disambiguating repeated structures with local context

### The proposed method

##### Present a formulation for dense surface reconstruction that identifies outliers

Directly optimizing for surface alignment

Using an objective that efficiently incorporates dense correspondence constraints

# Overview

## ||Fragment construction||

### Steps

##### Partition the input RGB-D video into k-frame segments (k=50 in all experiments)

##### Use RGB-D odometry to estimate the camera trajectory

13-ICRA-Robust odometry estimation for RGB-D cameras

##### Fuse the range images to obtain a surface mesh for each segment

96-SIGGRAPH-A volumetric method for building complex models from range images

##### Let be the vertex set of fragment and Let be a rigid transformation that aligns to computed by RGB-D odeometry

### Related

##### These scene fragments integrate out some of the noise in the range data and yield more reliable normal information

13-ToG-Dense scene reconstruction with points of interest

13-ICCV-Elastic fragments for dense scene reconstruction

##### Fragments are analogous to submaps, which are used in a number of robotic mapping systems

99-CIRA-Incremental mapping of large cyclic environments

04-IJRR-Simultaneous localization and map building in large-scale cyclic environments using the Atlas framework

05-TOR-Vision-based global localization and mapping for mobile robots

07-RSS-Mapping large loops with a single hand-held camera

## ||Geometric registration||

### Motivation

##### Yields broken reconstructions in which non-consecutive fragments that cover overlapping parts of the scene are misaligned

##### Test each pair of fragments to find overlapping pairs

### Steps

##### A geometric registration algorithm is run on each pair

##### If the algorithm succeeds in aligning the fragments with sufficient overlap, a candidate loop closure is established between fragments andwith an associated transformation

## ||Robust optimization||

### Motivation

##### Many of the putative loop closures found by pairwise registration are false positives

### Steps

##### We identify these spurious loop closures by optimizing a dense surface registration objective augmented by a line process over the loop closure constraints

##### A single least-squares objective jointly estimates the global configuration of the scene and the validity of each constraint

##### This formulation enables reliable pruning of erroneous constraints even when they substantially outnumber genuine loop closures

## ||Final model||

### Steps

##### After the final set of loop closures is identified, the odometry and loop closure transformations are refined using ICP

##### Pose graph optimization is used to obtain the final fragment poses in the global frame

11-ICRA-G2o: A general framework for graph optimization

##### Optional nonridged refinement can be used to further improve the registration

14-CVPR-Simultaneous localization and calibration: Self-calibration of consumer depth cameras

##### The registered fragments are fused into a global mesh model by volumetric integration

96-SIGGRAPH-A volumetric method for building complex models from range images

# Geometric Registration

### Construct dataset

##### Augments the synthetic scenes of ICL-NUIM with complex camera trajectories and a realistic noise model

14-ICRA-A benchmark for RGB-D visual odometry, 3D reconstruction and SLAM

### Pairwise matching

##### Consider a fragment pair (with being the smaller one)

##### This pair was identified as a ground-truth loop closure if their overlap in the ground-truth scene covers more than 30% of

##### A ground-truth transformation and a set of point-to-point correspondences were associated with this pair

### Transformation pruning

##### An algorithm may have correctly determined that there is a loop closure between and but produced an erroneous transformation

##### Accept If RMSE of the correspondences is below

### Evaluation

##### OpenCV implementation of the surface registration algorithm

10-CVPR-Model globally, match locally: Efficient and robust 3D object recognition

All look-up tables were precomputed for accelerated performance

##### 4PCS

08-TOG-4-points congruent sets for robust pairwise surface registration

##### Super 4PCS

14-CGF-Super 4PCS: Fast global pointcloud registration via smart indexing

##### PPF Integral

10-CVPR-Model globally, match locally: Efficient and robust 3D object recognition

06-PAMI-Integral invariants for shape matching

05--Robust global registration

##### PCL

09-ICRA-ast point feature histograms (FPFH) for 3D registration

12—Point cloud library: Three-dimensional object recognition and 6 DoF pose estimation

##### Conclusion

The precision of even the highest-performing geometric registration algorithms is below 20%

We attribute this primarily to the limited discriminative power of surface geometry that was sampled at limited range, resolution, and field of view, and corrupted by noise and distortion

# Global Optimization

### Pose graph

###### 10--A tutorial on graph-based SLAM

##### Consider a pose graph with

Vertices

Edges

### Objective function 1

##### Compute a set of poses that localizes the fragments in the global coordinate frame

### Objective function 2

##### The challenge is that most of the transformations are incorrect and will corrupt the optimized configuration

##### Add a line process ,

##### and are optimized jointly

### Alignment term

##### Measures the inconsistency between poses and and relative pose

##### Let be the set of correspondence pairs between and that are within distance (based on typical sensor noise magnitudes)

12--Accuracy and resolution of Kinect depth data for indoor mapping applications

##### Formulation

##### Use a standard local parameterization

Represent as a 6-vertor

Euler Angles

Transition

When

Euler angle to matrix

Taylor expansion

Thus

can be locally approximated as

is the symmetric matrix form of the cross product of

Define

Define

need to be computed once for each alignment term

### Final optimization

##### is defined to be proportional to the average cardinality of

is s the average cardinality of

is the distance threshold

##### Optimization is used g2o

11-ICRA- G2o: A general framework for graph optimization

Loop closures with <0.25 are pruned

### Comparison

##### Related

Line process

96-IJCV-On the unification of line processes, outlier rejection, and robust statistics with applications in early vision

Pose graph optimization

12-IROS-Switchable constraints for robust pose graph SLAM

##### Comparison

12-IROS-Switchable constraints for robust pose graph SLAM (SC)

13-IROS-Robust pose-graph loop-closures with expectation-maximization (EM)

# Evaluation

## ||Dataset||

### Augmented ICL-NUIM

###### 14-ICRA-A benchmark for RGB-D visual odometry, 3D reconstruction and SLAM

### SUN3D dataset

###### 13-ICCV-SUN3D: A database of big spaces reconstructed using SfM and object labels

## ||Synthetic scenes||

### Use error measure proposed by **Handa** et al

### Four reconstruction pipelines

##### Kinitinuous

13-IROS-Deformation-based loop closure for large scale dense RGB-D SLAM

##### DVO SLAM

13-IROS-Dense visual SLAM for RGB-D cameras

##### Automatic bundle adjustment

13-ICCV-SUN3D: A database of big spaces reconstructed using SfM and object labels

##### The proposed method

### Loop closure

##### The state-of-the-art image-based pipeline of Kerl et al

13-IROS-Dense visual SLAM for RGB-D cameras

##### SC

##### EM

## ||Real-world scenes||

### Supplements

### Balanced Rank Estimation

###### 13-ICML-Efficient ranking from pairwise comparisons

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