Scanning and Printing Objects in 3D

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My Research Areas

• Visual navigation for mobile robots
  
  ![RoboCup](Image1)  ![Kinematic Learning](Image2)  ![Articulated Objects](Image3)  ![Quadrotors](Image4)

• Camera tracking and 3D reconstruction
  
  ![RGB-D SLAM](Image5)  ![Visual Odometry](Image6)  ![Large-Scale Reconstruction](Image7)  ![3D Printing](Image8)
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**Camera-based Navigation of a Low-Cost Quadrotor**

[IROS ’12, RSS ’13, UAV-g ‘13, RAS ’14]
TUM TeachInf Best Lecture Award 2012 and 2013
EdX Course AUTONAVx with 20k participants
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Camera-based Navigation of a Low-Cost Quadrotor

Hold Position

- autonomous flight
- only onboard sensors
- no prior knowledge about environment
- automatic mapping and scale estimation

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EdX Course „Autonomous Navigation for Flying Robots“

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  - RoboCup
  - Kinematic Learning
  - Articulated Objects
  - Quadrotors

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  - RGB-D SLAM
  - Visual Odometry
  - Large-Scale Reconstruction
  - 3D Printing
Motivation

Wouldn‘t it be cool to have a 3D photo booth?

Questions:
• How to scan a person in 3D?
• How to prepare the model for 3D printing?
Problem Description

• Setup:
  Static RGB-D camera, person sitting on a swivel chair

• Given: A sequence of color and depth images
• Wanted: Accurate, watertight 3D model
Signed Distance Function (SDF)

\[ D(x) < 0 \]
\[ D(x) = 0 \]
\[ D(x) > 0 \]

- Negative signed distance (\(=\)outside)
- Positive signed distance (\(=\)inside)

[Curless and Levoy, ’96]
Signed Distance Function (SDF)
[Curless and Levoy, ’96]

- Compute SDF from a depth image
- Measure distance of each voxel to the observed surface
- Can be done in parallel for all voxels (→ GPU)

\[ d_{\text{obs}} = z - I_Z(\pi(x, y, z)) \]
Signed Distance Function (SDF)
[Curless and Levoy, ’96]

- Calculate weighted average over all measurements
- Assume known camera poses (for now)

\[
D \leftarrow \frac{WD + wd}{W + w} \\
C \leftarrow \frac{WC + wc}{W + w} \\
W \leftarrow W + w
\]
Mesh Extraction using Marching Cubes

- Find zero-crossings in the signed distance function by interpolation
Estimating the Camera Pose

- SDF built from the first $k$ frames
Estimating the Camera Pose

- We seek the next camera pose \((k+1)\)
Estimating the Camera Pose

- KinectFusion generates a synthetic depth image from SDF and aligns it using ICP.
Estimating the Camera Pose

- Our approach: Use SDF directly during minimization
Estimating the Camera Pose

- Our approach: Use SDF directly during minimization
Estimating the Camera Pose

- Our approach: Use SDF directly during minimization

\[
\arg \min_{R,t} \sum_{ij} D(Rx_{ij} + t)^2
\]
Evaluation on Benchmark
[Bylow, Sturm, Kerl, Kahl, Cremers; RSS 2013]

- Thorough evaluation on TUM RGB-D benchmark
- Comparison with KinFu and RGB-D SLAM
- Significantly more accurate and robust than ICP

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Resolution</th>
<th>Teddy (RMSE)</th>
<th>Desk (RMSE)</th>
<th>Plant (RMSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KinFu</td>
<td>256</td>
<td>0.156 m</td>
<td>0.057 m</td>
<td>0.598 m</td>
</tr>
<tr>
<td>KinFu</td>
<td>512</td>
<td>0.337 m</td>
<td>0.068 m</td>
<td>0.281 m</td>
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<tr>
<td>Our</td>
<td>256</td>
<td>0.086 m</td>
<td>0.038 m</td>
<td>0.047 m</td>
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<tr>
<td>Our</td>
<td>512</td>
<td>0.080 m</td>
<td>0.035 m</td>
<td>0.043 m</td>
</tr>
</tbody>
</table>
Automatically Close Holes
[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

- Certain voxels are never observed in near range
- Regions with no data result in holes
- Idea: Truncate weights to positive values

![Graph showing distance from surface vs. visibility](image_url)
Hollowing Out
[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

- Printing cost is mostly dominated by volume
- **Idea:** Make the model hollow

![Graph showing $D'$ against $D$](image)

*before*  *after*
Video (real-time)
[Sturm, Bylow, Kahl, Cremers; GCPR 2013]
Examples of Printed Figures
[Sturm, Bylow, Kahl, Cremers; GCPR 2013]
More Examples
[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

• Need a present?
• Live Demo after the talk
FabliTec 3D Scanner

- 3D scanning software “FabliTec 3D Scanner”
- TUM spin-off, founded in 2013
- Targeting private users
- Sale and user support
- Prerequisites
  - Windows 7/8
  - Graphics card from Nvidia
  - Xbox Kinect camera
- Partners
  - German RepRap GmbH
  - Conrad Electronic
  - Volumental (formerly Kinect-at-home)
- Download free demo version from http://www.fablitec.com
3D Reconstruction from a Quadrocopter
[Bylow et al., RSS 2013; Sturm et al., UAV-g 2013]

- AscTec Pelican quadrocopter
- Real-time 3D reconstruction, position tracking and control (external processing on GPU)

external view

estimated pose
Resulting 3D Model
[Bylow et al., RSS 2013; Sturm et al., UAV-g 2013]
More Examples
[Sturm, Bylow, Kerl, Kahl, Cremers; UAV-g 2013]

- Nice 3D models, but:
  - Large memory and computational requirements are suboptimal for use on quadrocopter
  - Significant drift in larger environments
- How can we improve on this?
Can we compute the camera motion directly?

Idea

- Photo-consistency constraint

\[ I_1(x) = I_2(\pi(g_\xi(z \cdot x))) \]

- Geometry-consistency constraint

\[ Z_2(x') = p'_z \]
How to deal with noise?
[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Photo-consistency constraint will not perfectly hold
  - Sensor noise
  - Pose error
  - Reflections, specular surfaces
  - Dynamic objects (e.g., walking people)
- Residuals will be non-zero

\[ r = I_1(x) - I_2(\pi(g_\xi(z \cdot x))) \]

\[ \left( r = \begin{pmatrix} I_2(x') - I_1(x) \\ Z_2(x') - p'_z \end{pmatrix} \right) \]

- How does the residual distribution \( p(r) \) look like?
How to deal with noise?

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Zero-mean, peaked distribution
- Example: Correct camera pose
How to deal with noise?
[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

• Zero-mean, peaked distribution
• Example: Wrong camera pose
• Our goal: Find the camera pose that maximizes the observation likelihood
**Our goal:** Find the camera pose that maximizes the observation likelihood

\[
\xi^* = \arg \max_{\xi} \prod_i p(r_i(\xi))
\]

compute over all pixels

- Assume pixel-wise residuals are conditionally independent
- How can we solve this optimization problem?
Dense Alignment
[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

• Take negative logarithm

\[ \xi^* = \arg \min_\xi \sum_i - \log p(r_i(\xi)) \]

• Set derivative to zero

\[ \sum_i \frac{\partial \log p(r_i(\xi))}{\partial \xi} = \sum_i \frac{\partial \log p(r_i)}{\partial r_i} \frac{\partial r_i(\xi)}{\partial \xi} \equiv 0 \]

• \( r_i(\xi) \) is non-linear in \( \xi \)
• Solve using Gauss-Newton method (linearize, solve, repeat)
Example
[Kerl, Sturm, Cremers; ICRA 2013]
Example
[Kerl, Sturm, Cremers; ICRA 2013]

Residuals before registration

\[(I_2(x') - I_1(x))^2 \quad \xi = 0\]

Residuals after registration

\[(I_2(x') - I_1(x))^2 \quad \xi = \xi^*\]
Coarse-to-Fine
[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

• Linearization only holds for small motions
• Coarse-to-fine scheme
• Image pyramids
Dense Visual Odometry: Results

[Steinbrücker, Sturm, Cremers, ICCV LDRMC 2011; Kerl, Sturm, Cremers, ICRA 2013]

- Runs in real-time on single CPU core (SSE optimized)
- Available as open-source
- Average drift: ~3cm/s
Dense Visual Odometry: Results
[Kerl, Sturm, Cremers; IROS 2013]

- **Problem**: Considerable drift accumulation (1.8m/min)
- How can we further reduce this drift?

- Local drift: Track w.r.t. key frames

- Global drift: Detect loop closures and optimize pose graph
Dense Visual Odometry: Results
[Kerl, Sturm, Cremers; IROS 2013]

- Keyframes are added dynamically (based on entropy evaluation)
- Localize w.r.t to current keyframe (first CPU core/thread)
- Detect loop closures and optimize pose graph (second CPU core/thread)
Large-Scale 3D Reconstruction
[Steinbrücker, Kerl, Sturm, Cremers; ICCV 2013]

- We have: Optimized pose graph
- We want: High-resolution 3D map

- Problem: High-resolution voxel grids consume much memory (grows cubically)
  - $512^3$ voxels, 24 byte per voxel $\rightarrow$ 3.2 GB
  - $1024^3$ voxels, 24 byte per voxel $\rightarrow$ 24 GB
  - ...

- Idea:
  - Save data in oct-tree data structure
  - Only allocate cells that are close to the surface
  - Store geometry at multiple resolutions
  - Tree can grow dynamically (no fixed size)
Large-Scale 3D Reconstruction
[Steinbrücker, Kerl, Sturm, Cremers; ICCV 2013]

- Runs at 200 fps on a GPU (assuming camera poses are known)
3D Mapping in Real-Time on a CPU
[Steinbrücker, Sturm, Cremers; ICRA 2014]

- Runs at 45 fps on CPU, available as open-source!
Same with a Monocular Camera?
[Engel, Sturm, Cremers; ICCV 2013]

• Soon available as open-source!
Summary

• (Scientific) Take home messages:
  – Dense methods make better use of available data
  – Supersede sparse/feature-based approaches
  – Real-time visual SLAM and 3D reconstruction is there

• Dense visual odometry: simple, fast, efficient
• Dense visual SLAM: eliminates drift
• Dense 3D reconstruction: nice models

• Nice, but..
  But what do we need this for??
What do we need this for?

- **Robotics**
  - Laser scanners will eventually get replaced by (depth) cameras
  - Localization, mapping/SLAM, exploration, navigation

- **Augmented reality (AR)**
  - Games that play in your home
  - Virtual shopping: place furniture
  - User manuals: teach interactively how to repair/maintain a device

**Key capabilities:**
- Know how the camera is moving (odometry)
- Know where the camera is (absolute position)
- Know how the environment looks like (occlusion modeling, scene understanding)
The 2014 IKEA Catalog App (powered by metaio SDK)

Utilizes next-generation SLAM tracking to place furniture in home, easily and conveniently

Influences and educates purchasing decision while driving massive brand awareness

http://www.youtube.com/watch?v=vDNzTasuYEw
Volkswagen XL1 MARTA (powered by metaio SDK)

First-ever integrated AR support system for service technicians

Visualizes and overlays animated step-by-step service instructions

Utilizes Metaio’s most robust 2D and 3D AR tracking technology.

Copyright ©Volkswagen AG

http://www.youtube.com/watch?v=h2l3VzrkmRY
Some of the AR apps based on metaio SDK
metaio – A Brief introduction

✓ ONLY dedicated company to serve the entire AR value chain
✓ 10+ years of professional experience in AR development
✓ 130+ people working in Germany (HQ) and the USA
✓ 1000+ B2B customers worldwide
✓ 100,000+ active developers across the world
✓ 5million+ downloads of metaio´s AR browser (junaio)
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<td>(AREngine)</td>
<td>AR Applications</td>
<td>AR Usage</td>
<td>AR Content Access</td>
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</tbody>
</table>

**hardware**
- intel
- ARM
- NVIDIA

**software**
- metaio SDK
- metaio Creator
- metaio Cloud
- metaio Engineer

**content**
- LUCHIDA
- CYBERNET
- ONX

**users**
- junaio
- certified developer
- JUNAIO

**miscellaneous**
- Texas Instruments

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