Dense 3D Reconstruction from Autonomous Quadrocopters

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Autonomous Quadrocopters

Quadrocopters juggling
Mueller, Lupashin, D’Andrea IROS ‘11

Swarms of quadcopters
Kushleyev, Mellinger, Kumar RSS ‘12

Drawbacks:
- Controlled environment
- Marker points
- External sensors / mocap systems
Realworld Environments
Can we use visual SLAM for autonomous quadrocopter navigation?

Can we reconstruction the world from autonomous quadcopters?
Some Related Work

Autonomous quadrocopters:

Grzonka et al. ‘09, Mellinger et al. ‘11, Müller et al. ‘11, Achtelik et al. ‘11, Grabe et al. ‘12, Fraundorfer et al. ‘12, Schauwecker et al. ‘12, Huang et al. ‘11,…

Multiple view reconstruction:


RGB-D based reconstruction:

Rusinkiewicz et al. ‘02, Curless & Levoy ‘96, Newcombe et al. ‘11, Whelan et al. ‘12, Comport et al. ‘12, Izadi et al. ‘13, …
Overview

Autonomous quadrocopters

Dense reconstruction

Realtime 3D scanning

Reconstruction on the fly
Overview

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Reconstruction on the fly
The Parrot AR.Drone

available online @ $300

no hardware / onboard software modifications

connected to ground station via WLAN

Onboard sensors:

- front camera (320 x 240 @ 18fps)
- inertial measurement unit
- ultrasound altimeter
- onboard, optical-flow-based velocity estimation

Realtime structure and motion / visual SLAM:

Chiuso et al., ECCV ’00, Favaro, Jin, Soatto, ICCV ’01,
Nister, ICCV ’03, Davison, ICCV ’03, Klein, Murray, ISMAR ’07,…
Open source mono-SLAM system PTAM (*Klein & Murray '07*)

**Drawbacks:** Unreliable, no scale

**Our contributions:**
- Camera-based autonomous navigation
- Enhanced reliability by incorporating IMU data
- ML scale estimate using ultrasound & velocity

*Engel, Sturm, Cremers, IROS 2012*
Start and Initialize Map

Engel, Sturm, Cremers, IROS 2012
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Multiple View Reconstruction

Kolev, Klodt, Brox, Cremers, Int. J. of Computer Vision '09:
Theorem: Globally optimal surfaces can be computed by convex optimization.
Evolution to Global Optimum

*Kolev, Klodt, Brox, Cremers, IJCV 2009*
Kolev, Cremers, ECCV ‘08, PAMI ‘09:
Theorem: Provably silhouette-consistent reconstructions can be computed by convex optimization over convex domains.
Action Reconstruction

Oswald, Cremers, ICCV ‘13 4DMoD Workshop

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Action Reconstruction

Oswald, Cremers, ICCV ‘13 4DMoD Workshop
Action Reconstruction
Action Reconstruction
Can we do realtime dense reconstruction from a handheld camera?
Realtime Dense Reconstruction

Much related work on structure and motion, stereo, and optic flow:

- Fitzgibbon, Zisserman, ECCV '98
- Jin, Favaro, Soatto, CVPR ’00
- Nister, ICCV ’03
- Davison, ICCV ’03
- Pollefeys et al., IJCV ’04
- Wang et al., 3DPVT ’06
- Zach et al., DAGM ’07
- Gallup et al. CVPR ’07
- Klein, Murray, ISMAR ’07
- Wedel et al., ICCV ’09
- Newcombe, Davison, CVPR ‘10

Real-time calibration

Compute optic flow between consecutive images and use it to update a depth map.
Realtime Dense Reconstruction

Brightness constancy:

\[ I_0(x) = I_i \left( \pi \left( g_i(ux) \right) \right) \]

\[
\min_{u,v} \sum_i \int_\Omega \left| I_0(x) - I_i \left( \pi \left( g_i(u \cdot x) \right) \right) \right| dx + \int_\Omega |\nabla u(x)| dx
\]

\[ + \frac{1}{\theta} \int_\Omega (u - v)^2 dx + \int_\Omega |\nabla v(x)| dx \]

Stuehmer, Gumhold, Cremers, DAGM '10
Realtime Dense Reconstruction

Stuehmer, Gumhold, Cremers, DAGM '10
Realtime Dense Reconstruction

Stuehmer, Gumhold, Cremers, DAGM ’10
Realtime Dense Reconstruction

1.8 fps  11.3 fps  24 fps

Stuehmer, Gumhold, Cremers, DAGM '10
Realtime Dense Reconstruction

Newcombe et al., ICCV ’11

Wendel et al., CVPR ’12
Dense versus Semi-Dense?
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Pose Estimation for Known Structure

Existing approaches to camera calibration:

- Visual odometry from **sparse** feature matching (**color only**)
  (feature detection, descriptor computation, matching & optimization)

- Point cloud registration (ICP) (**depth only**)
  (iteratively compute point correspondences and align)

Proposed method:

- exploits both color and depth information

- directly optimizes dense color consistency

- pose estimated in realtime by coarse-to-fine warping

*Steinbruecker, Sturm, Cremers ‘11*
Realtime dense camera calibration

Lie algebra representation of rigid body motion:

\[ g_\xi = \exp \left( \xi \right), \quad \xi \in \mathbb{R}^6 \]

Photo-consistency:

\[
\min_{\xi \in \mathbb{R}^6} \int_{\Omega} \left| I_0(x) - I_i \left( \pi \left( g_\xi (u \cdot x) \right) \right) \right|^2 \, dx
\]

Steinbruecker, Sturm, Cremers ‘11
Realtime dense camera calibration

Photo-consistency:

$$E(\xi) = \int_{\Omega} \left| I_0(x) - I_i(\pi(g_\xi(u \cdot x))) \right|^2 dx$$

Taylor expansion:

$$E(\xi) \approx \int_{\Omega} \left| I_0(x) - I_i - \nabla I^\top \left( \frac{d\pi}{dg_\xi} \right) \left( \frac{dg_\xi}{d\xi} \right) \xi \right|^2 dx$$

Optimal solution:

$$\frac{dE(\xi)}{d\xi} = A\xi + b = 0 \quad \Rightarrow \quad \xi = -A^{-1}b$$

Solve in coarse-to-fine manner.

Steinbruecker, Sturm, Cremers ‘11
Realtime dense camera calibration

http://cvpr.in.tum.de/datasets/rgbd-dataset
Calibration for increasing baseline

Steinbruecker, Sturm, Cremers ‘11
Third Person Perspective
Quantitative comparison

Pose accuracy for increasing baseline

Steinbruecker, Sturm, Cremers '11
RGB-D Benchmark

- 39 sequences (19 with ground truth)
- one zip-archive per sequence containing:
  - color & depth images (png),
  - accelerometer data,
  - trajectory file

http://vision.in.tum.de/datasets/rgbd-dataset

Sturm, Engelhard, Burgard, Cremers IROS '12
**RGB-D SLAM benchmark**

http://vision.in.tum.de/datasets/rgbd-dataset

Sturm, Engelhard, Burgard, Cremers  IROS ‘12
RGB-D Based 3D Modeling

Color input

Depth input

Fuse geometry: Curless, Levoy ’96, Newcombe et al. ‘11
RGB-D Based 3D Modeling
CopyMe3D: Scanning and Printing Persons in 3D

Jürgen Sturm, Erik Bylow, Fredrik Kahl, Daniel Cremers

German Conference on Pattern Recognition (GCPR)
September 2013

Download demo @ http://www.fablitec.com
Realtime 3D Modeling

Download free demo @ http://www.fablitec.com
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Reconstruction on the Fly

Bylow, Sturm, Kerl, Kahl, Cremers  RSS ‘13
Reconstruction on the Fly

Bylow, Sturm, Kerl, Kahl, Cremers  RSS ‘13
Reconstruction on the Fly

Bylow, Sturm, Kerl, Kahl, Cremers  RSS ‘13
Reconstruction on the Fly

Bylow, Sturm, Kerl, Kahl, Cremers  RSS ‘13
Limitations for large-scale reconstruction:

- Camera tracking accumulates drift
- Volumetric fusion requires much memory:
  - $512^3$ voxels @ 24 byte/voxel $\rightarrow$ 3.2 GB
  - $1024^3$ voxels @ 24 byte/voxel $\rightarrow$ 24 GB
Large Scale: Octrees

Steinbrücker, Kerl, Sturm, Cremers  ICCV ‘13
Realtime Large-Scale Fusion...
Volumetric 3D Mapping in Real-Time on a CPU

Frank Steinbrücker, Jürgen Sturm, Daniel Cremers

ICRA 2014 Submission 636

Computer Vision and Pattern Recognition Group
Department of Computer Science
Technical University of Munich

Steinbrücker, Sturm, Cremers, ICRA 2014
Summary

- autonomous quadcopters
- dense reconstruction
- action reconstruction

- RGB-D modeling
- reconstruction on the fly
- large scale