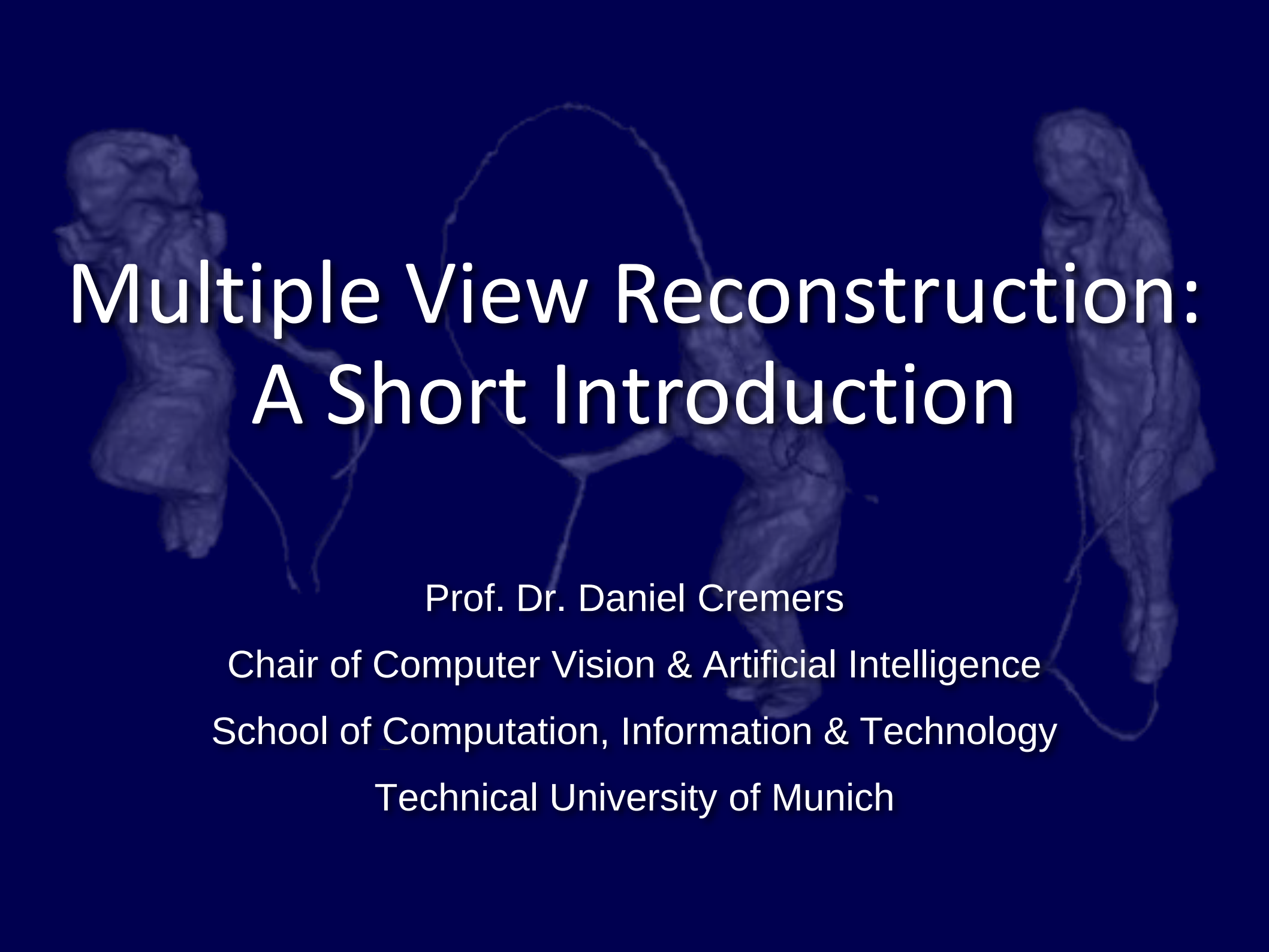


Multiple View Reconstruction: A Short Introduction

Prof. Dr. Daniel Cremers

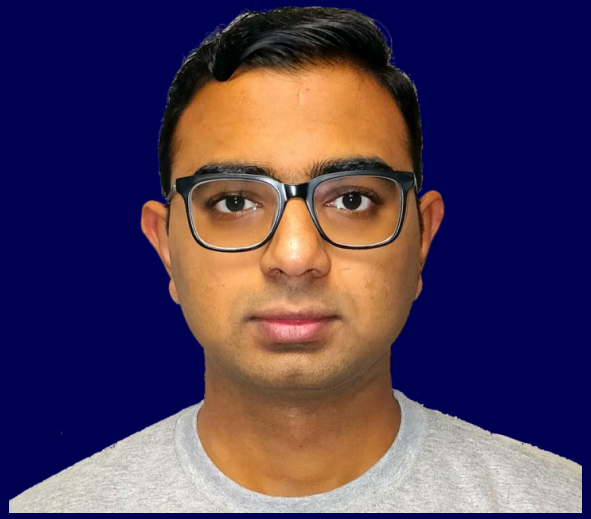
Chair of Computer Vision & Artificial Intelligence

School of Computation, Information & Technology

Technical University of Munich

Tutorials

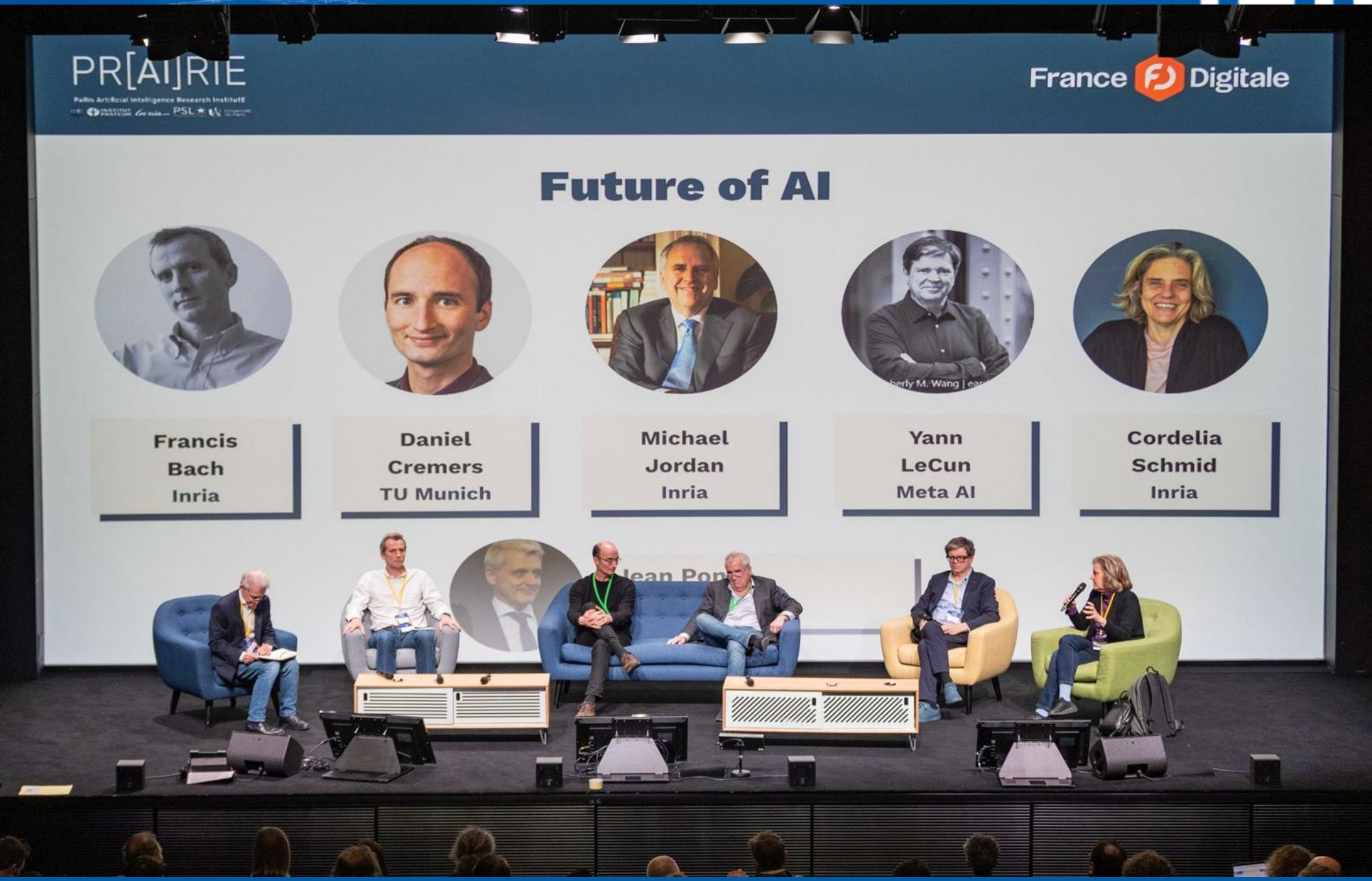
Shenhan Qian



Tarun Yenamandra

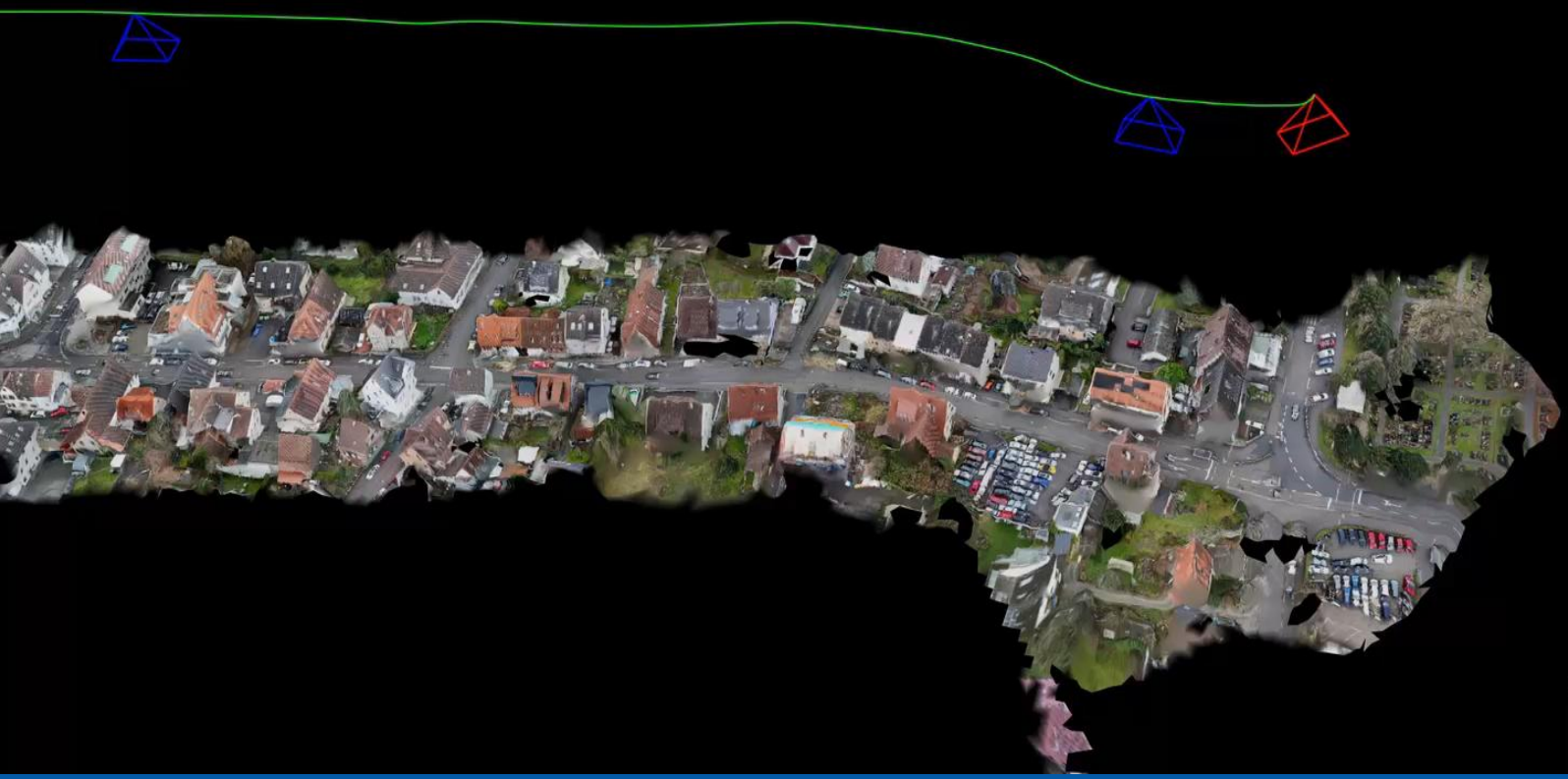
Simon Weber

AI Panel, Paris, April, 2024



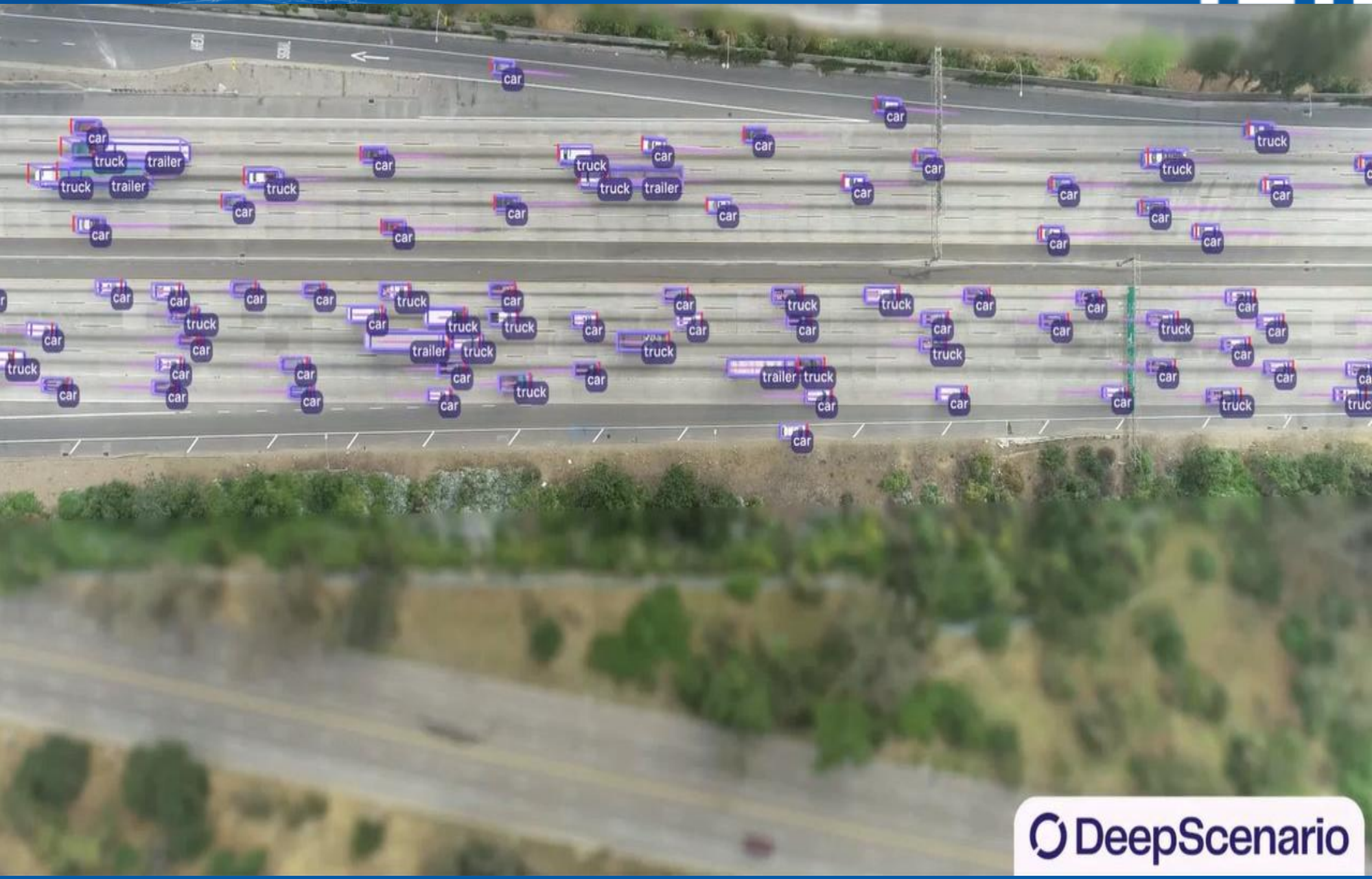
How do Humans behave in Traffic?

3D Reconstruction from Drones



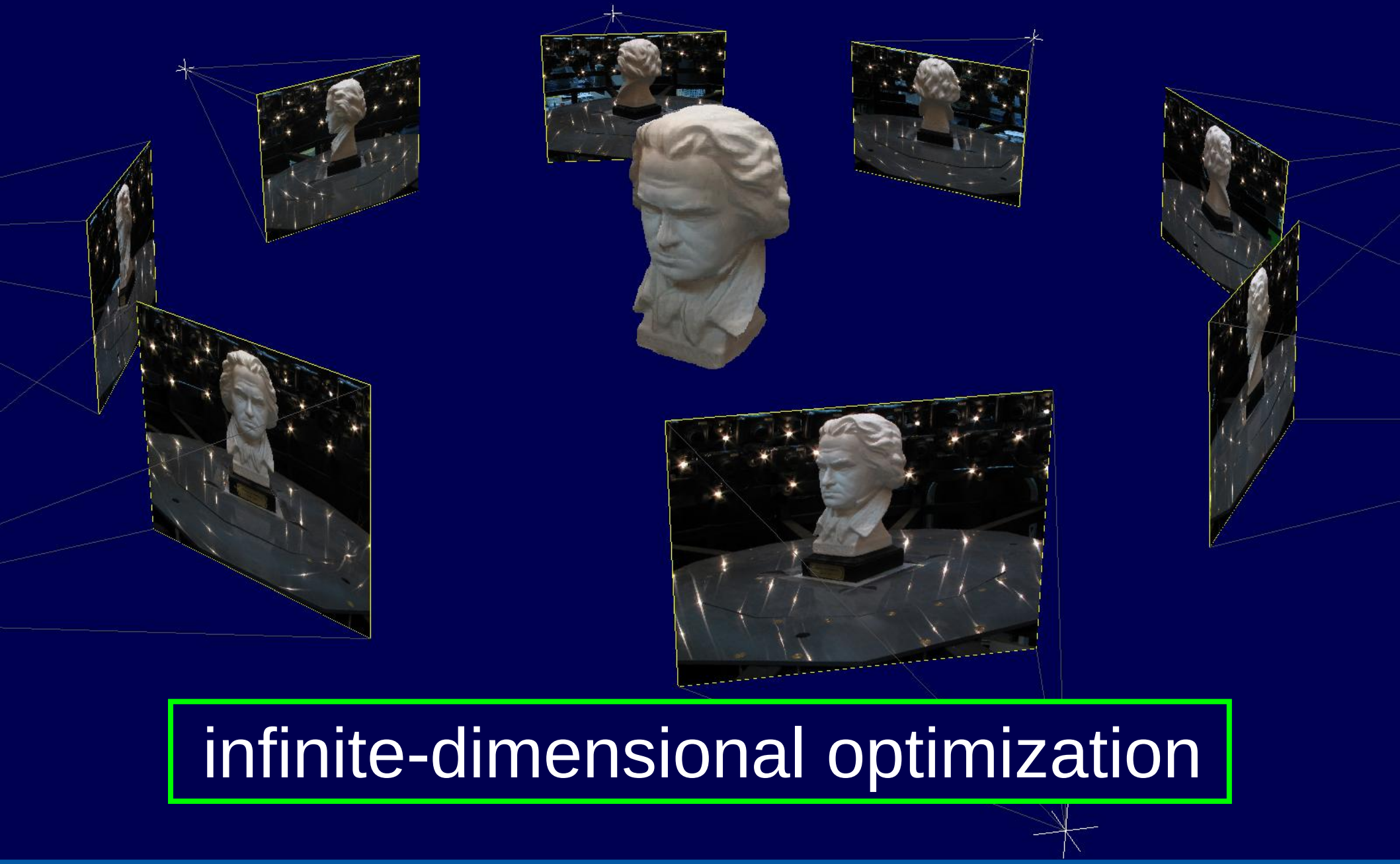
DeepScenario

3D Traffic Monitoring from Drones



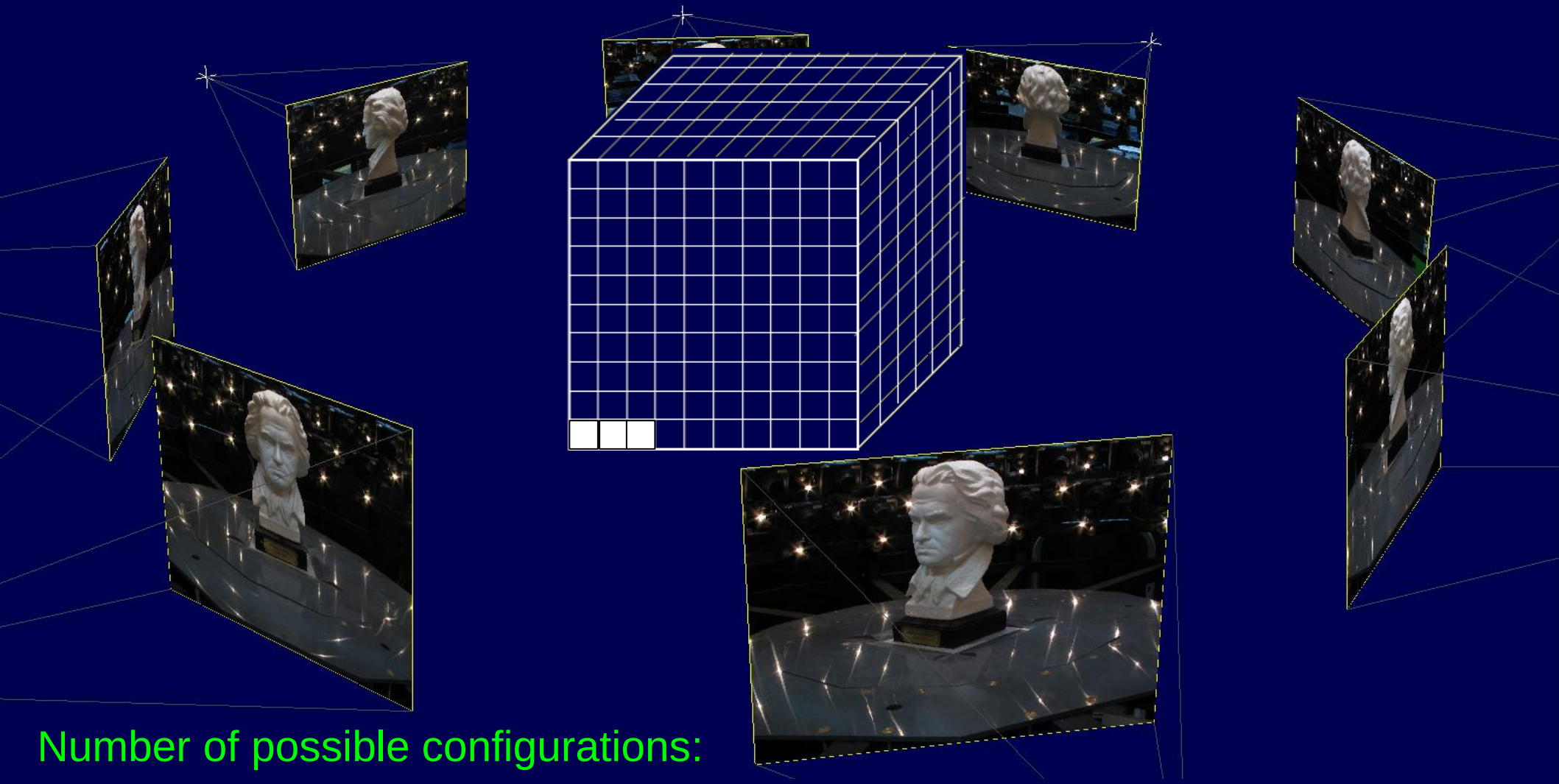
Generative Models of Human Driving

3D Reconstruction from Images



infinite-dimensional optimization

3D Reconstruction from Images

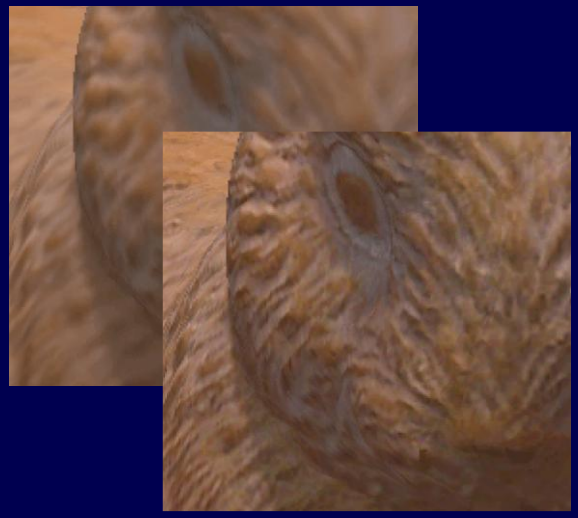


Number of possible configurations:

$$2^N = 2^{512 \times 512 \times 512} \approx 10^{40Mio}$$

Overview

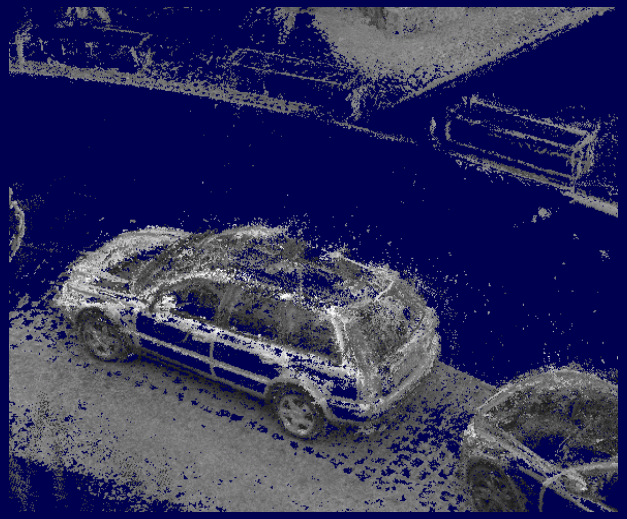
Multiview reconstruction



Super-res. textures

Free-viewpoint TV

Realtime dense scanning



Visual SLAM

Deep Networks for SLAM

Overview

Multiview reconstruction

Super-res. textures

Free-viewpoint TV

Realtime dense scanning

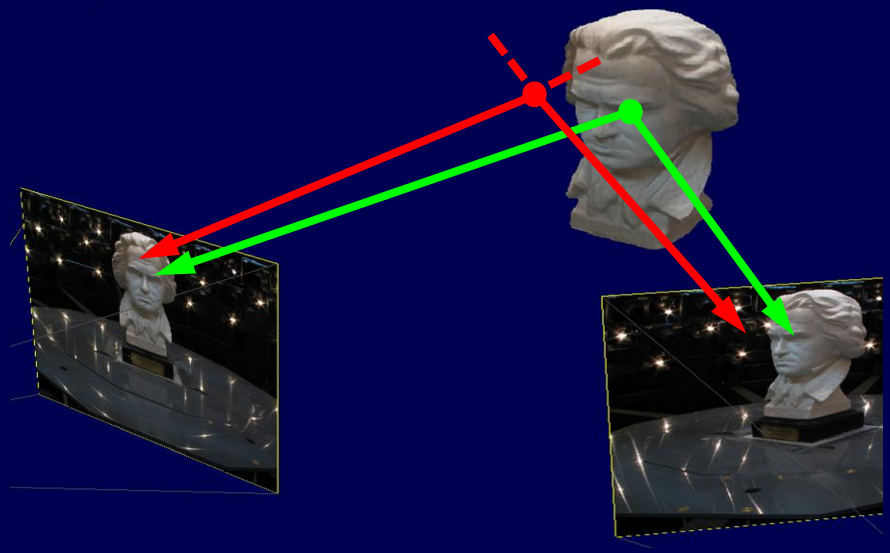
Visual SLAM

Deep Networks for SLAM

Solutions via Energy Minimization

Photoconsistency function:

$$\rho : \mathbb{R}^3 \rightarrow [0, 1]$$



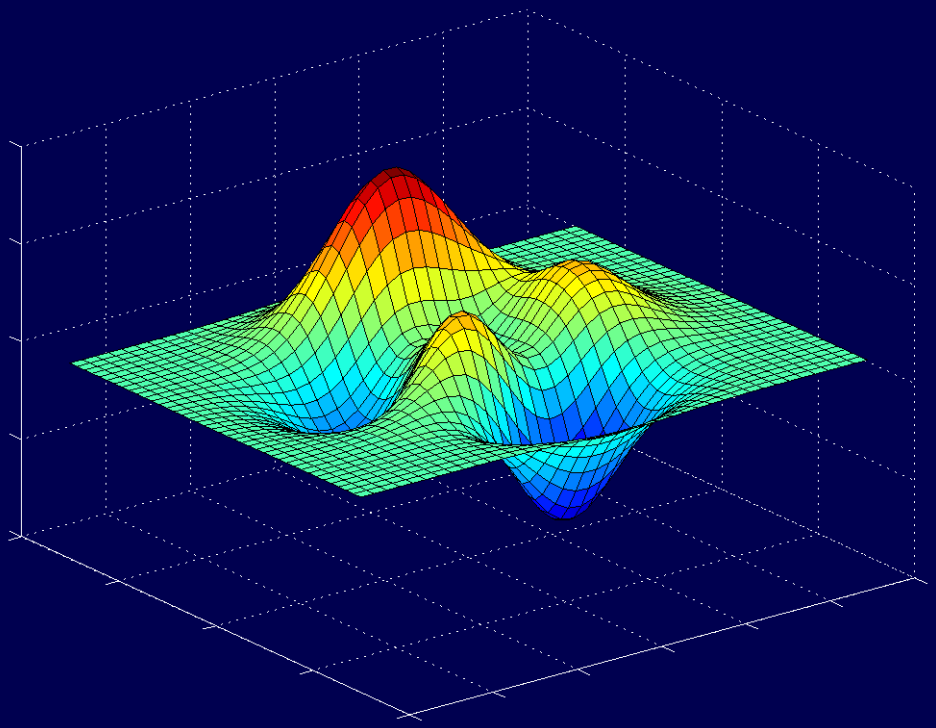
Determine a surface S of optimal photoconsistency by minimizing

$$E(S) = \int_S \rho \, dA$$

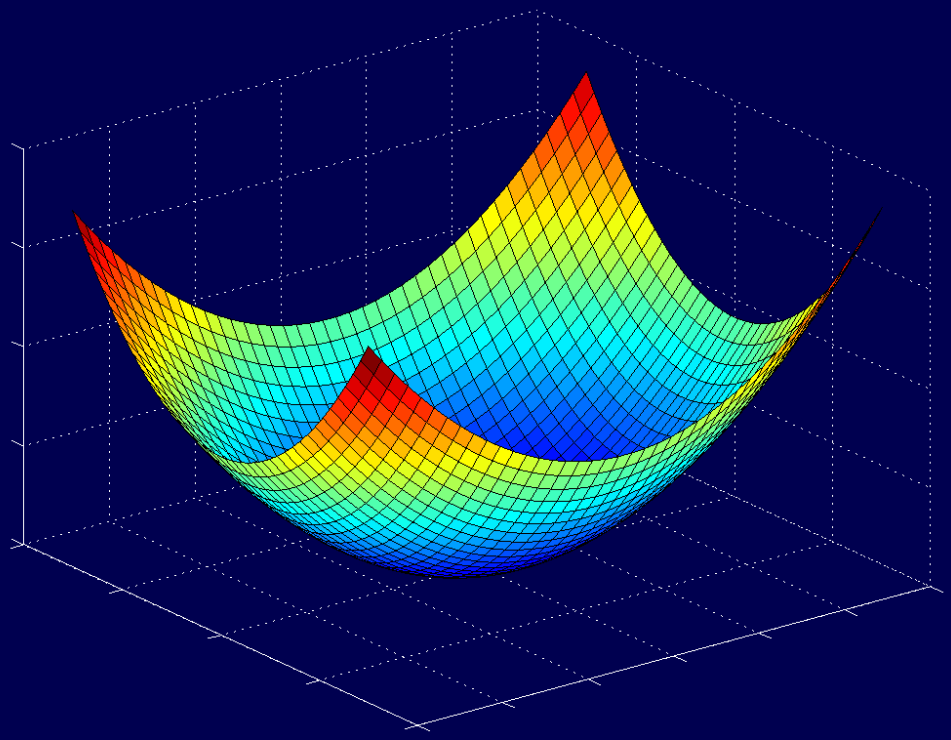
Kolev, Klodt, Brox, Cremers, Int. J. of Computer Vision '09:

Theorem: Globally optimal surfaces can be computed via convex relaxation.

Optimization and Convexity

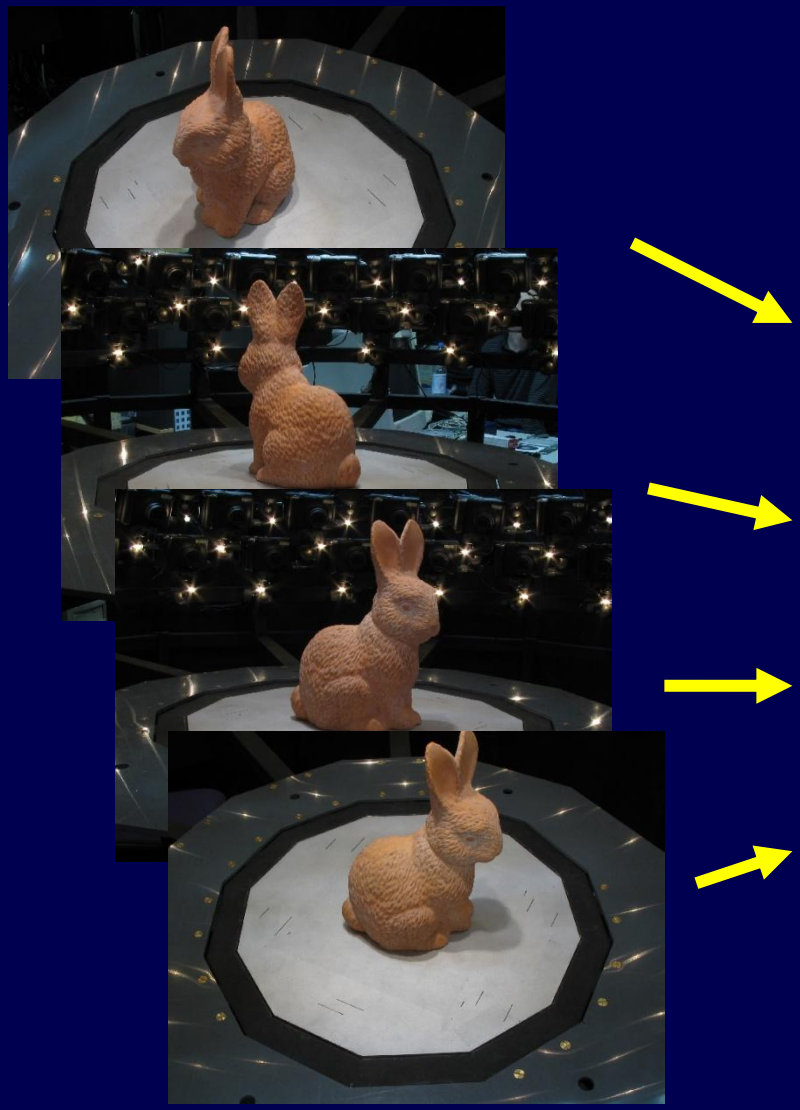


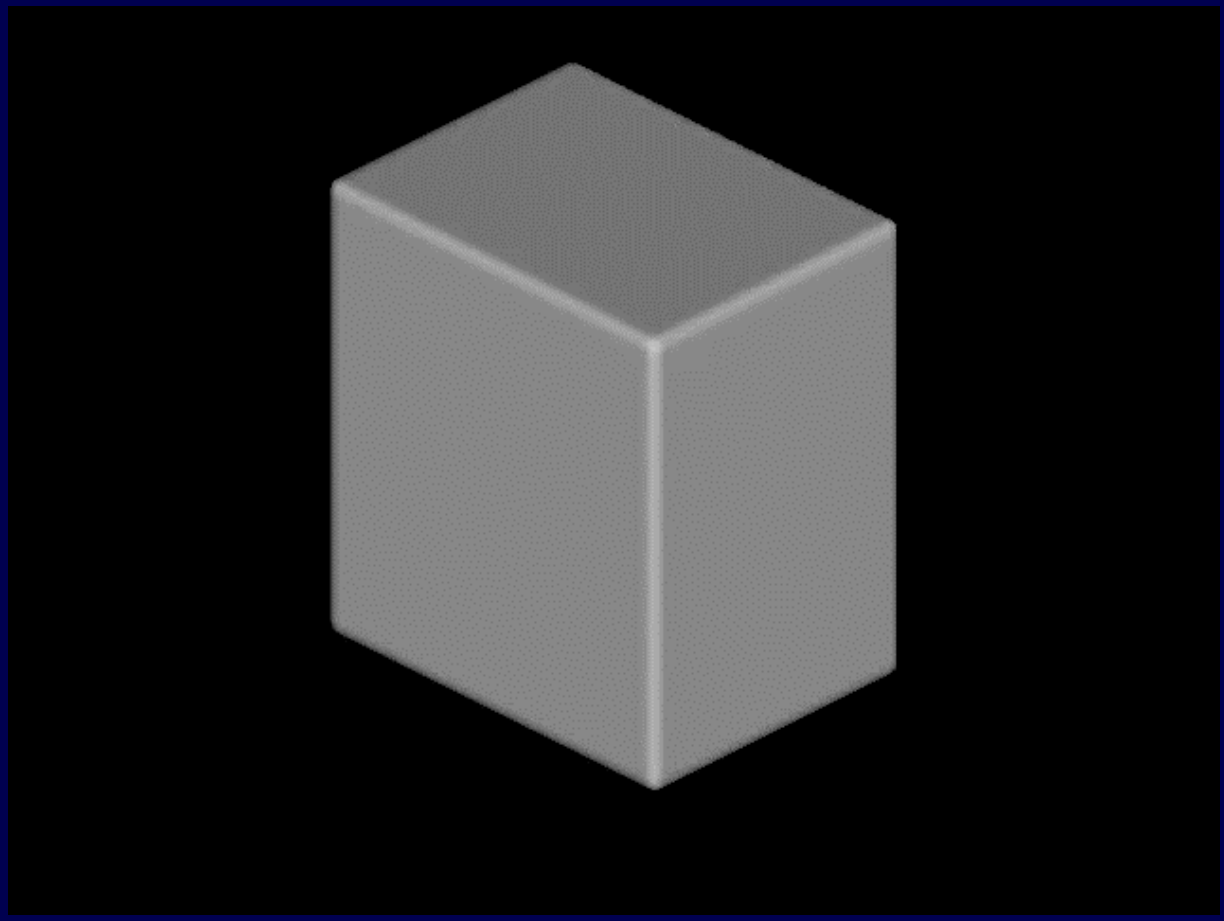
Non-convex energy



Convex energy

Evolution to Global Optimum

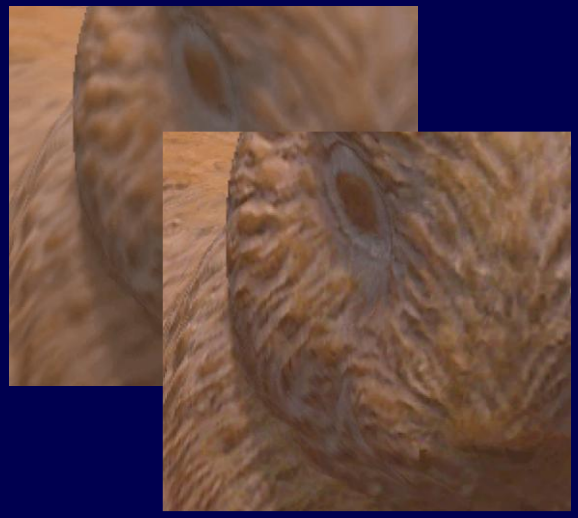




Kolev, Klodt, Brox, Cremers, IJCV 2009

Overview

Multiview reconstruction



Super-res. textures

Free-viewpoint TV

Realtime dense scanning

Visual SLAM

Deep Networks for SLAM

Super-Resolution Texture Map

Given all images $\mathcal{I}_i : \Omega_i \rightarrow \mathbb{R}^3$, determine the surface color $T : S \rightarrow \mathbb{R}^3$

$$\min_T \sum_{i=1}^{n} \int_{\Omega_i} \left(b * (T \circ \pi_i^{-1}) - \mathcal{I}_i \right)^2 dx + \lambda \int_S \|\nabla_S T\| ds$$

blur & downsample

back-projection

Goldlücke, Cremers, ICCV '09, DAGM '09, IJCV '13*

** Best Paper Award*

Super-Resolution Texture Map

Goldlücke, Cremers, ICCV '09, DAGM '09, IJCV '13*

** Best Paper Award*

Super-Resolution Texture Map

Closeup of input image

Super-resolution texture

Goldlücke, Cremers, ICCV '09, DAGM '09, IJCV '13*

** Best Paper Award*

Overview

Multiview reconstruction

Super-res. textures

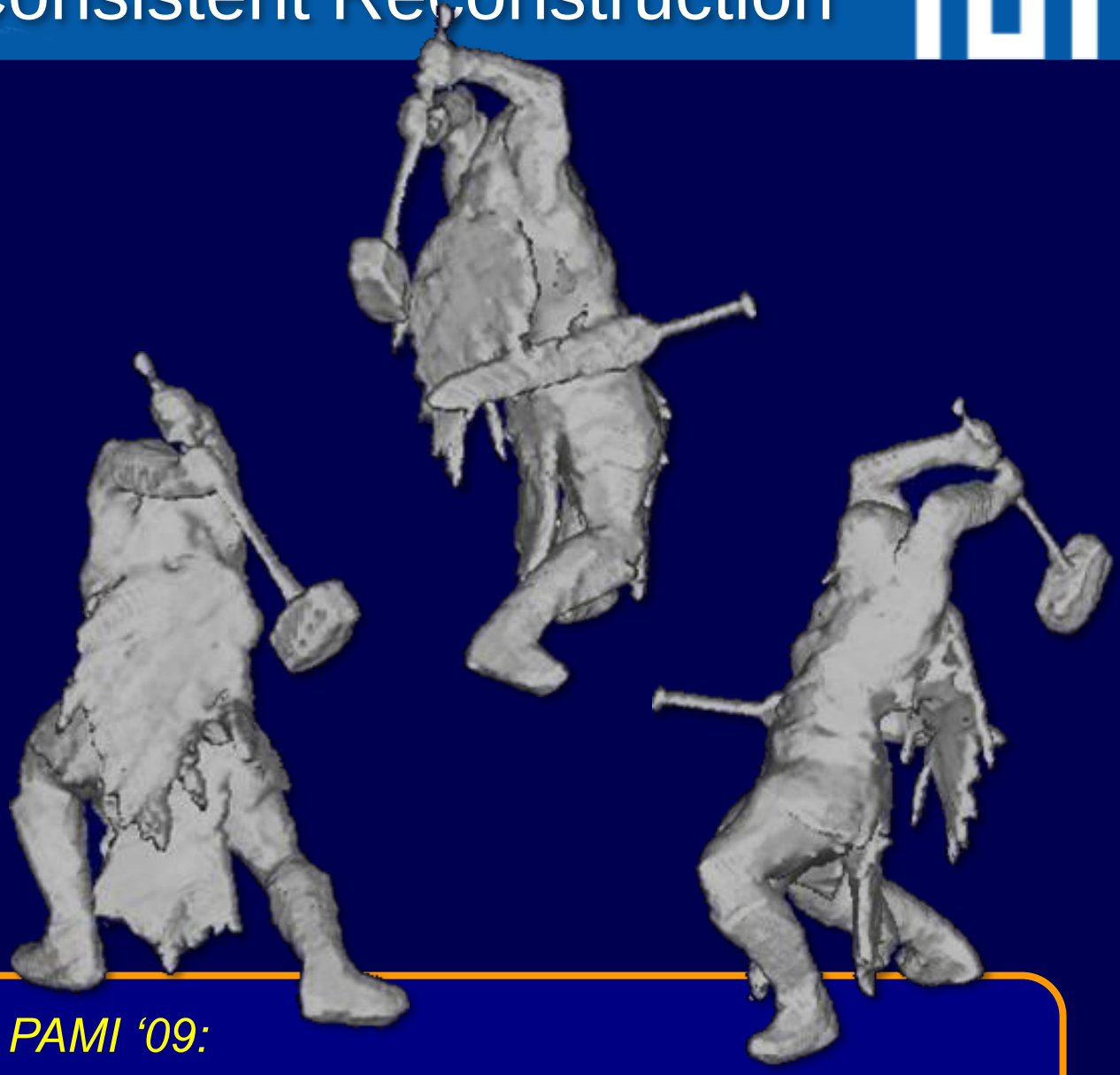
Free-viewpoint TV

Realtime dense scanning

Visual SLAM

Deep Networks for SLAM

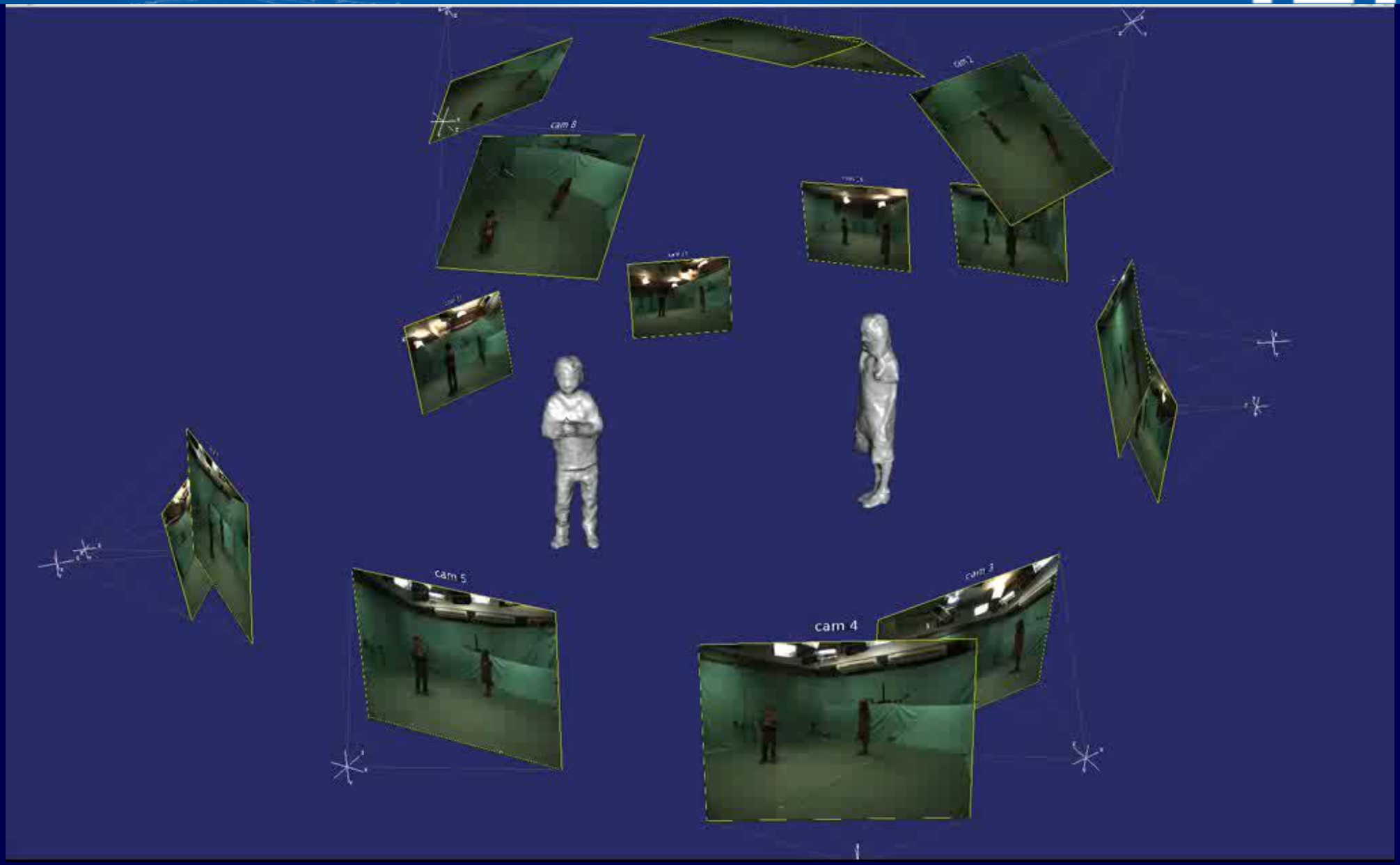
Silhouette-Consistent Reconstruction



Kolev, Cremers, ECCV '08, PAMI '09:

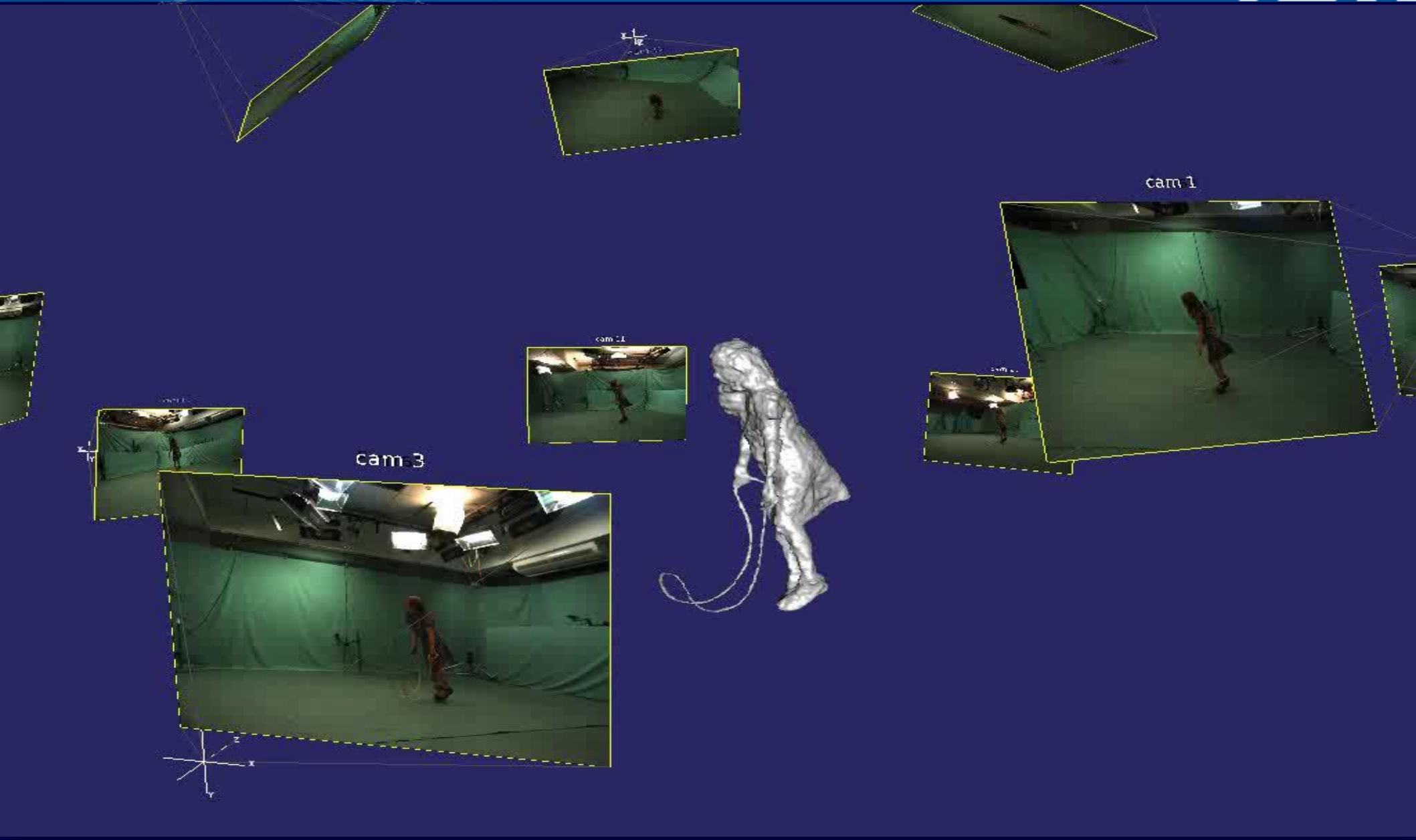
Theorem: Provably silhouette-consistent reconstructions can be computed by convex optimization over convex domains.

Action Reconstruction



Oswald, Cremers, ICCV '13 4DMoD Workshop

Reconstructing Dynamic Scenes



Oswald, Stühmer, Cremers, ECCV '14

Multiview Reconstruction

Can we do realtime dense reconstruction from a handheld camera?

Overview

Multiview reconstruction

Super-res. textures

Free-viewpoint TV

Realtime dense scanning

Visual SLAM

Deep Networks for SLAM

From Realtime Optical Flow…

Input video

Optical flow field

Wedel, Pock, Bischof, Cremers, ICCV '09

From Realtime Optical Flow…

Input video

Optical flow field*

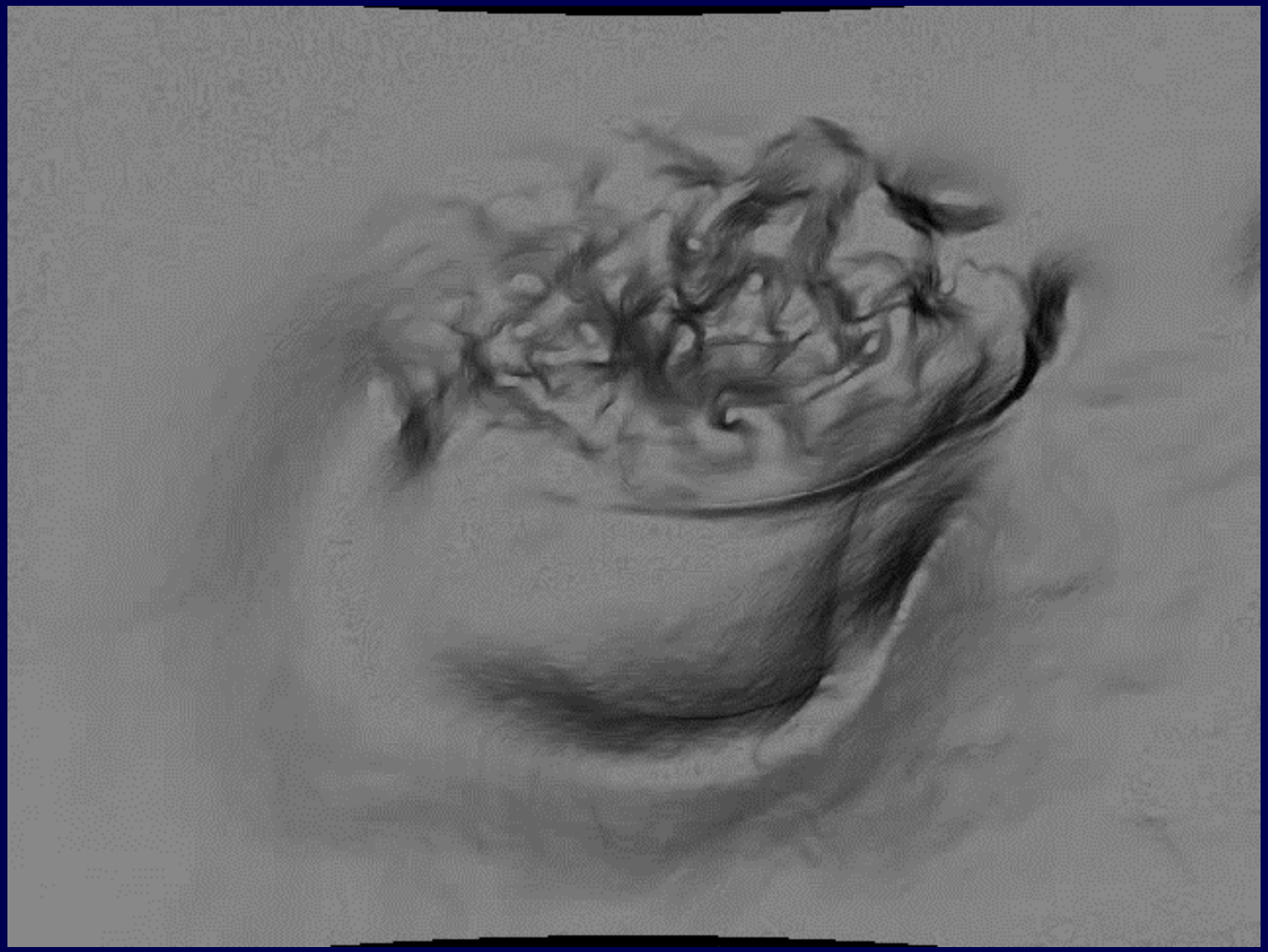
* 60 fps at 640 x 480 resolution

Wedel, Pock, Bischof, Cremers, ICCV '09

Realtime Dense Reconstruction

Stuehmer, Gumhold, Cremers, DAGM '10

Realtime Dense Reconstruction

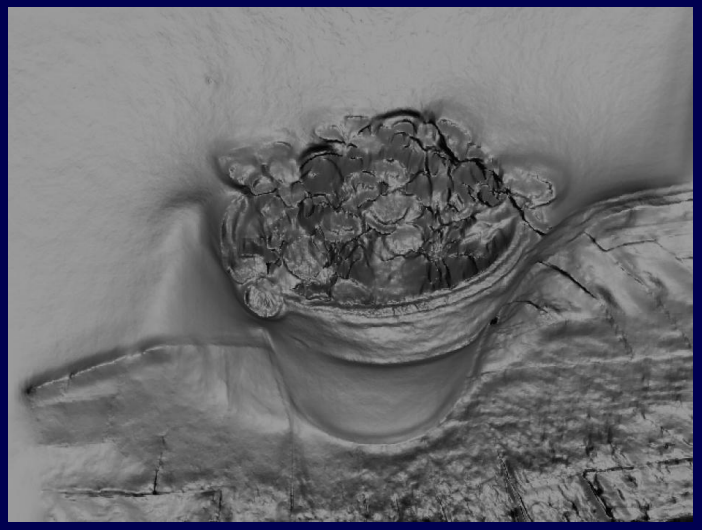


Stuehmer, Gumhold, Cremers, DAGM '10

Realtime Dense Reconstruction

16.0 fps

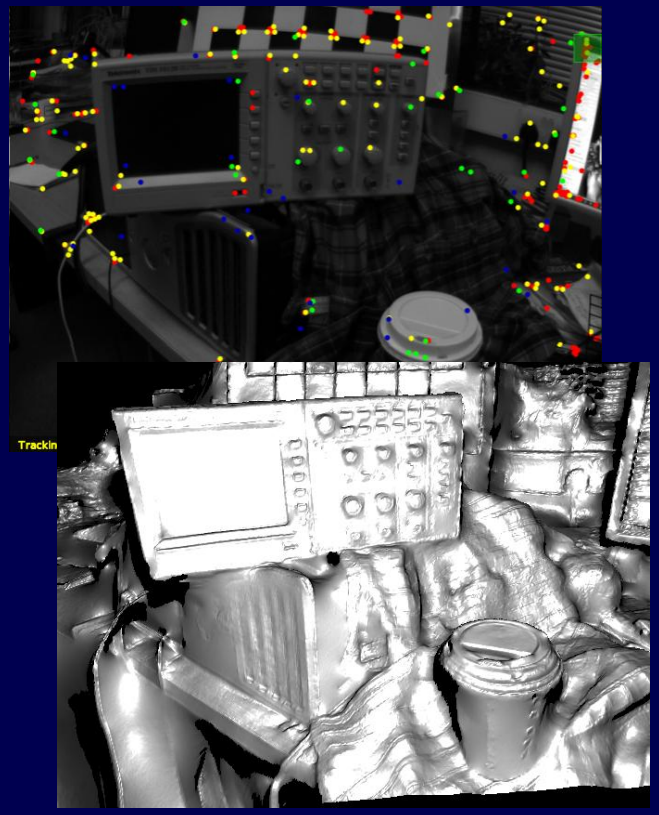
22.0 fps



41.1 fps

Stuehmer, Gumhold, Cremers, DAGM '10

Realtime Dense Reconstruction



Newcombe et al. ICCV ’11

Wendel et al. CVPR ’12

Pizzoli et al. ICRA ’14

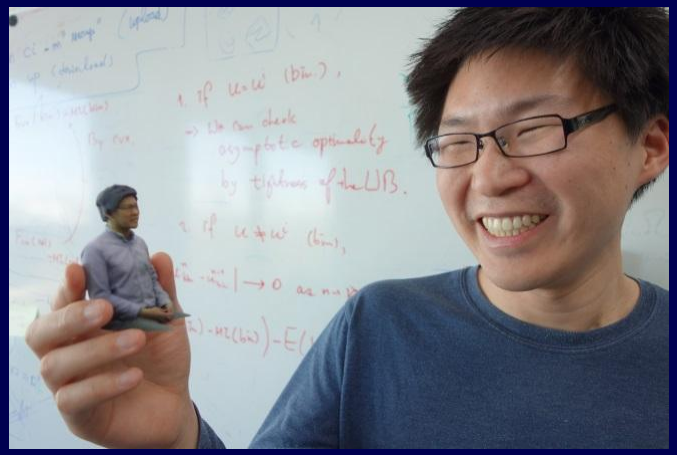
Realtime 3D Modeling

Sturm, Bylow, Kahl, Cremers, GCPR '13

Realtime 3D Modeling

Realtime 3D Modeling

Realtime 3D Modeling



Sturm, Bylow, Kahl, Cremers, GCPR '13

Realtime 3D Modeling

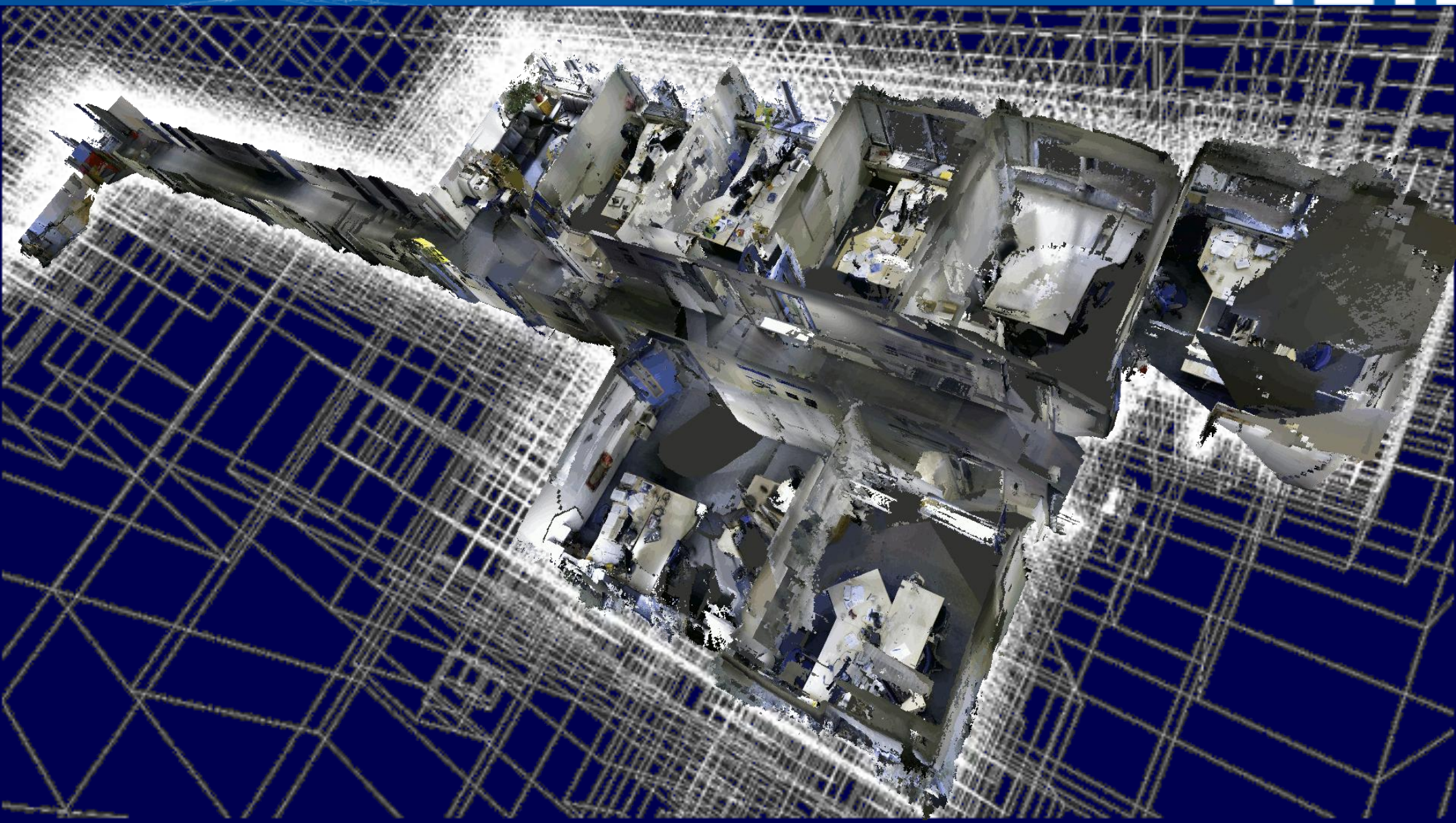
Realtime 3D Modeling

Realtime 3D Modeling

Reconstruction on the Fly

Bylow, Sturm, Kerl, Kahl, Cremers RSS '13

Large Scale: Octrees



Steinbrücker, Kerl, Sturm, Cremers ICCV '13

Realtime Large-Scale Reconstruction

Steinbrücker, Kerl, Sturm, Cremers ICCV '13, ICRA '14

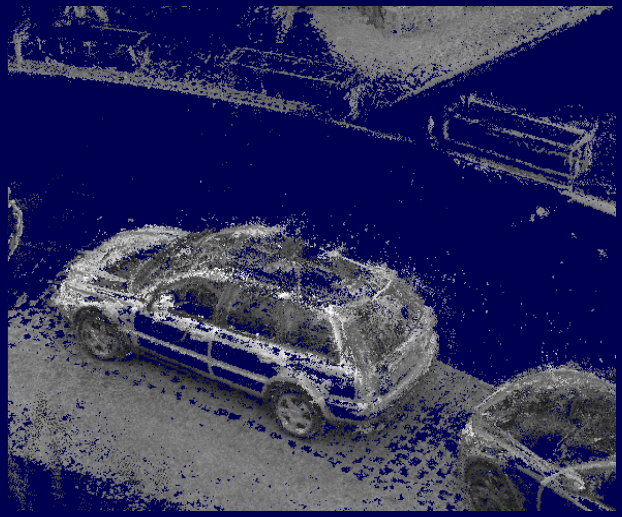
Overview

Multiview reconstruction

Super-res. textures

Free-viewpoint TV

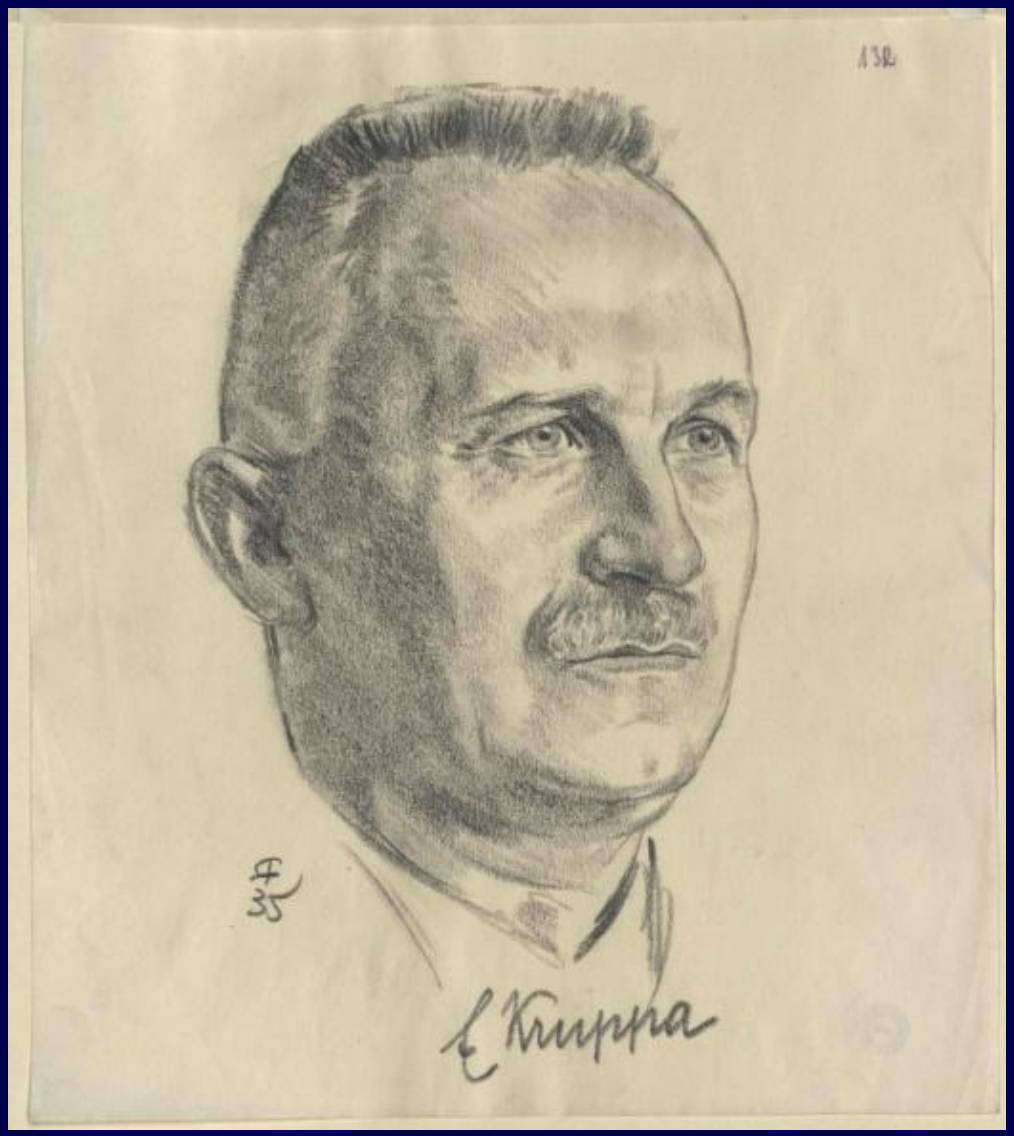
Realtime dense scanning



Visual SLAM

Deep Networks for SLAM

Simultaneous Localization & Mapping

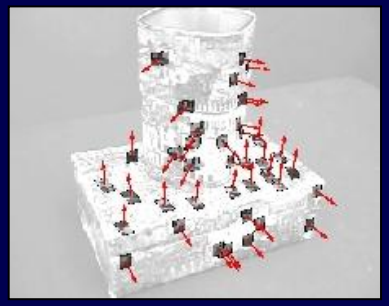


Erwin Wilhelm Kruppa (1885 - 1967)

Kruppa 1913:

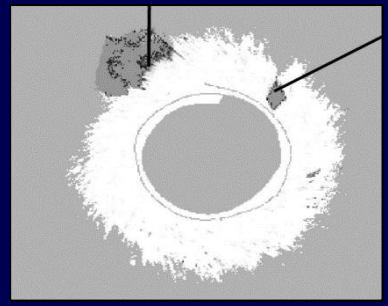
Two views of five points are sufficient to determine both the camera motion and the 3D location of these points up to finitely many solutions.

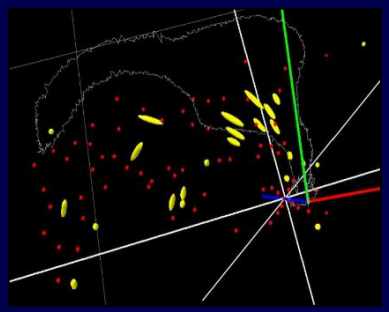
Real-time Visual SLAM



Structure from Motion Causally Integrated Over Time.
Chiuso, Favaro, Jin, Soatto; PAMI ’02.

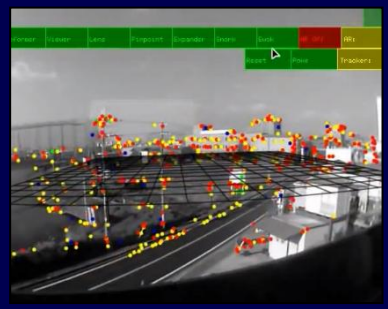
Visual Odometry.
Nistér, Naroditsky, Bergen; CVPR ’04.

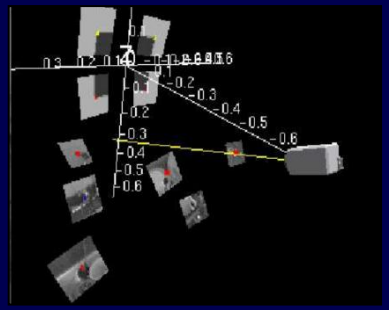




Scalable monocular SLAM.
Eade, Drummond; CVPR ’06.

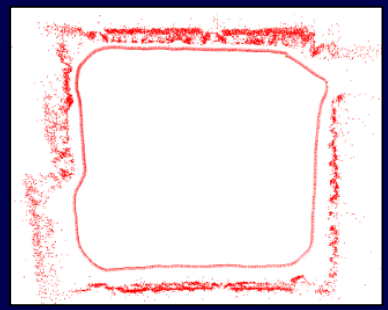
Parallel Tracking and Mapping for Small AR Workspaces. *Klein, Murray*; ISMAR ’07.





MonoSLAM: Real-time single camera SLAM.
Davison, Reid, Molton, Stasse; PAMI ’07.

Scale Drift-Aware Large Scale Monocular SLAM.
Strasdat, Montiel, Davison; RSS ’10.



DTAM: Dense Tracking and Mapping in Real-Time.
Newcombe, Lovegrove, Davison; ICCV ’11.

REMODE: Probabilistic, Monocular Dense Reconstruction in Real Time. *Pizzoli, Forster, Scaramuzza*; ICRA ’14.

Real-time Visual SLAM

Keypoint-Based

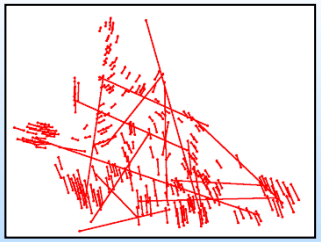
Input Images

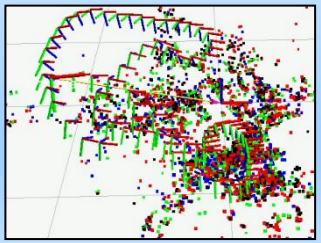
Extract & Match Features (SIFT / SURF / BRIEF /...)

abstract images to feature observations

Track: min. reprojection error (point distances)

Map: est. feature-parameters (3D points / normals)





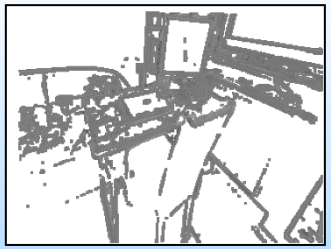
Direct (LSD-SLAM)

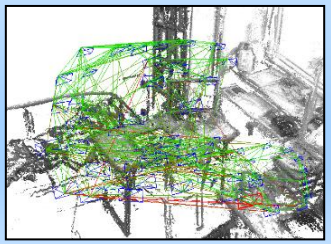
Input Images

keep full image

Track: min. photometric error (intensity difference)

Map: est. per-pixel depth (semi-dense depth map)





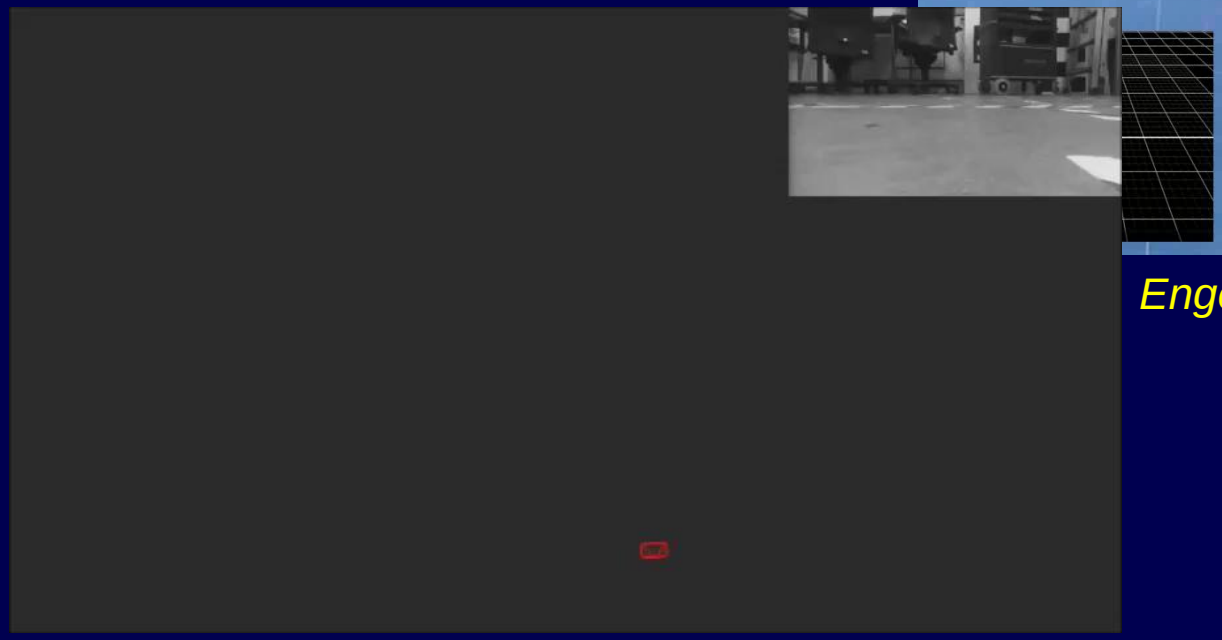
LSD SLAM: Large-Scale Direct SLAM

Engel, Sturm, Cremers, ICCV '13, Engel, Schöps, Cremers, ECCV '14

Visual SLAM for Autonomous Systems

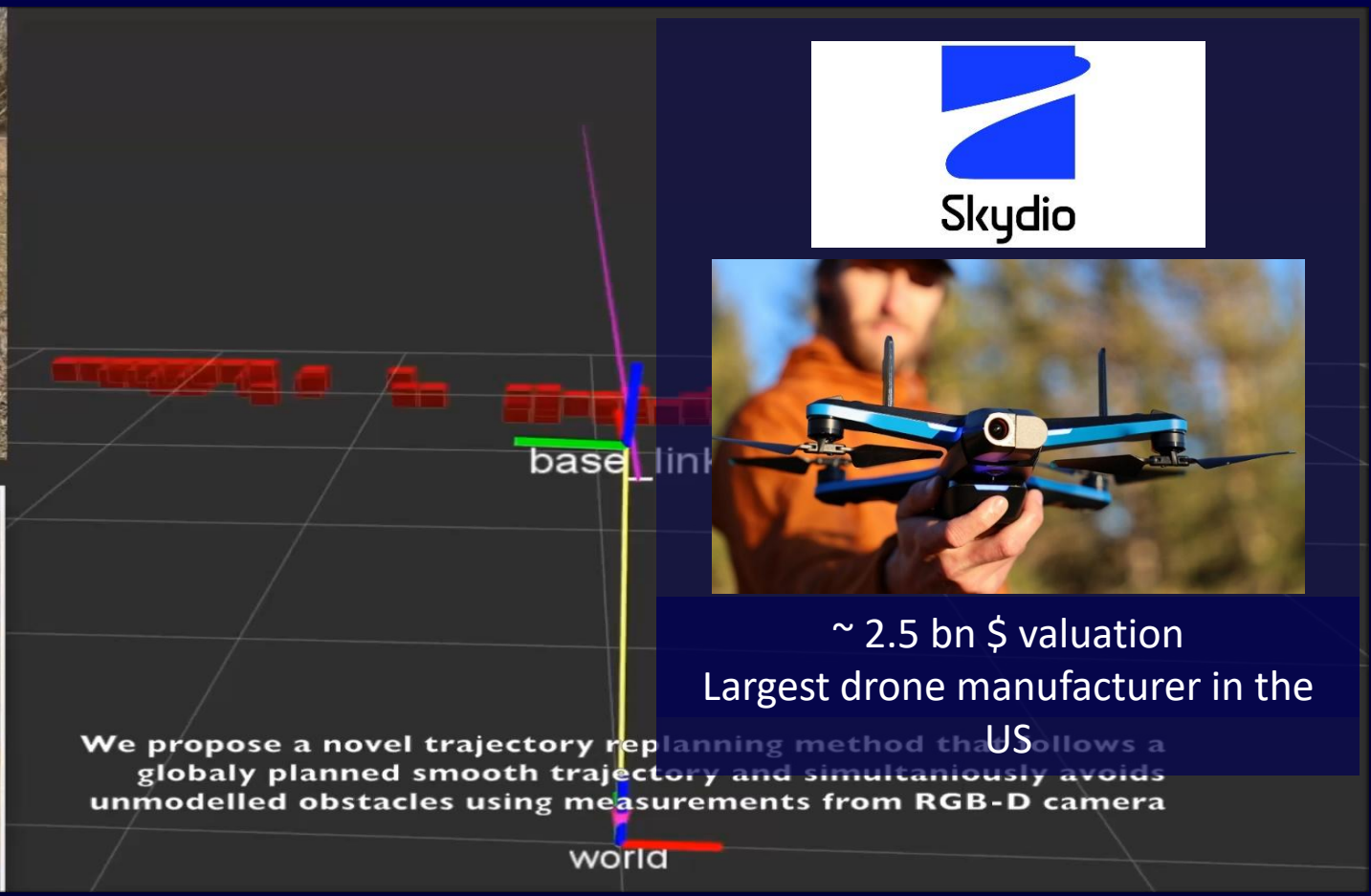
Bonn 2007

Engel, Sturm, Cremers, IROS 2012



Von Stumberg, Usenko, Engel, Cremers, ECMR '17

3D Computer Vision for Autonomous Systems

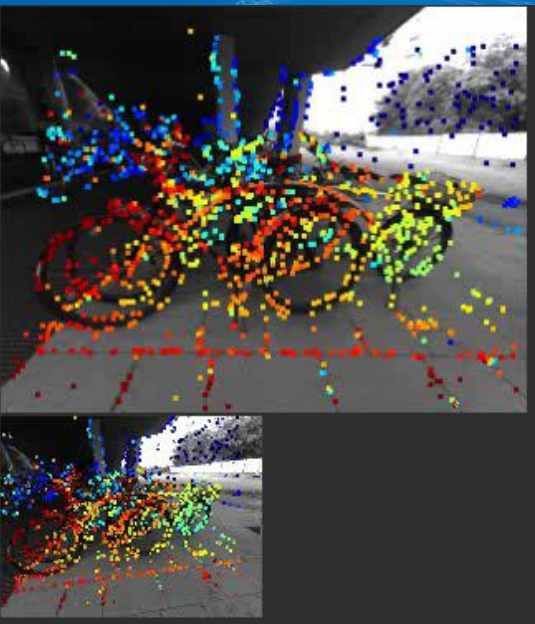


Skydio

~ 2.5 bn $ valuation
Largest drone manufacturer in the US

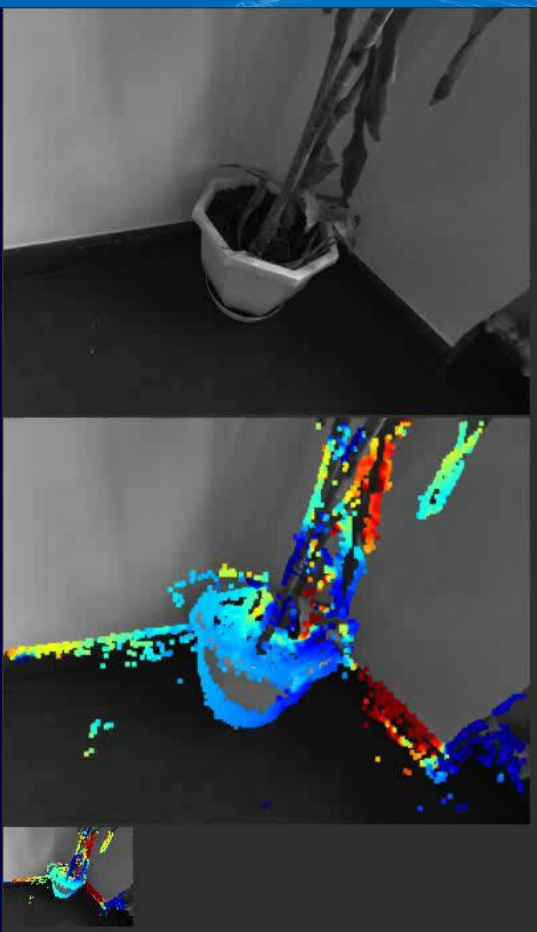
Usenko, Von Stumberg, Pangercic, Cremers, IROS '17 (Best Paper Finalist)

Direct Sparse Odometry



Engel, Koltun, Cremers, "Direct Sparse Odometry", PAMI '18

Direct Sparse Odometry

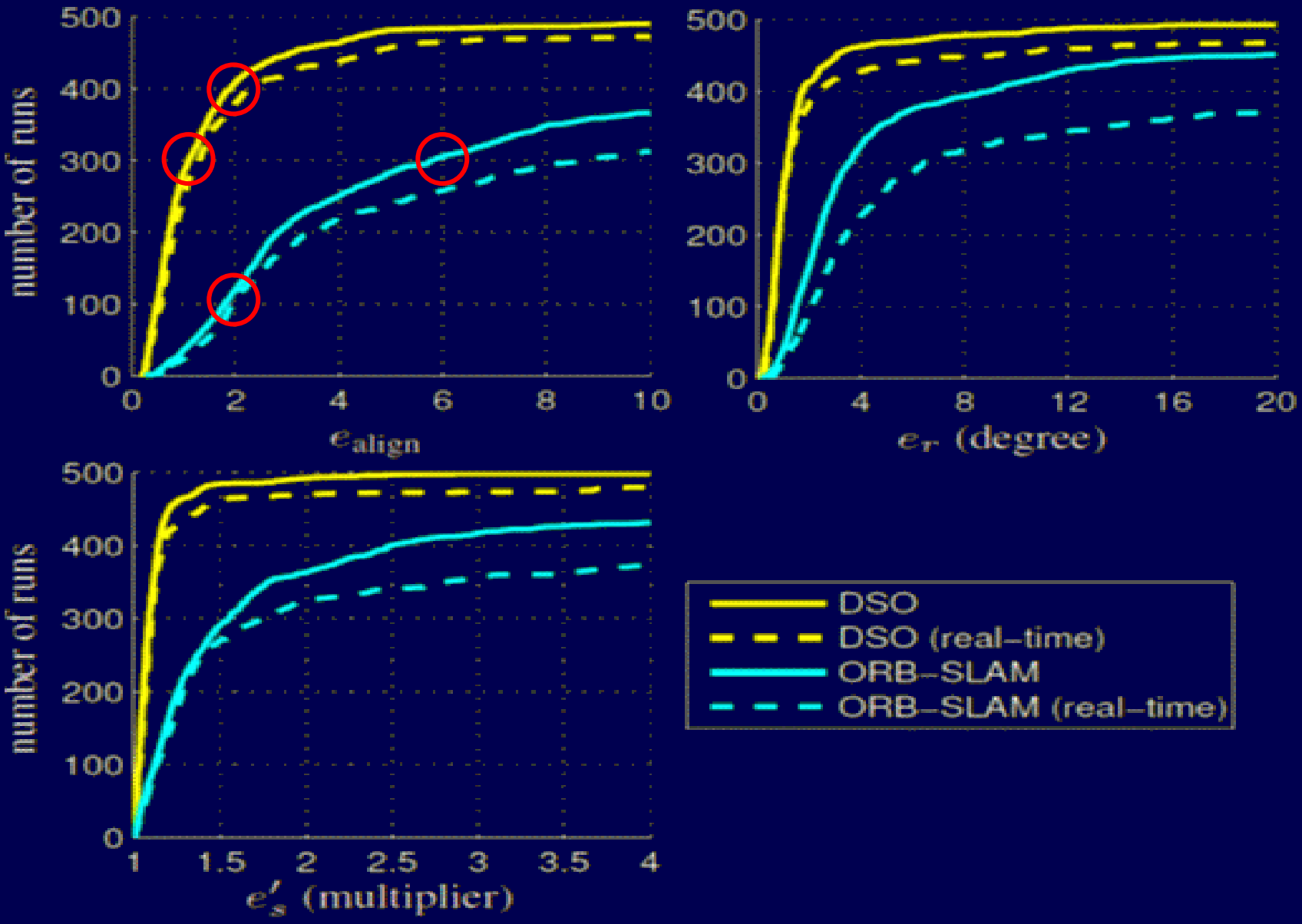


Engel, Koltun, Cremers, "Direct Sparse Odometry", PAMI '18

Quantitative Evaluation

50 sequences
105 minutes
190k frames

Quantitative Evaluation

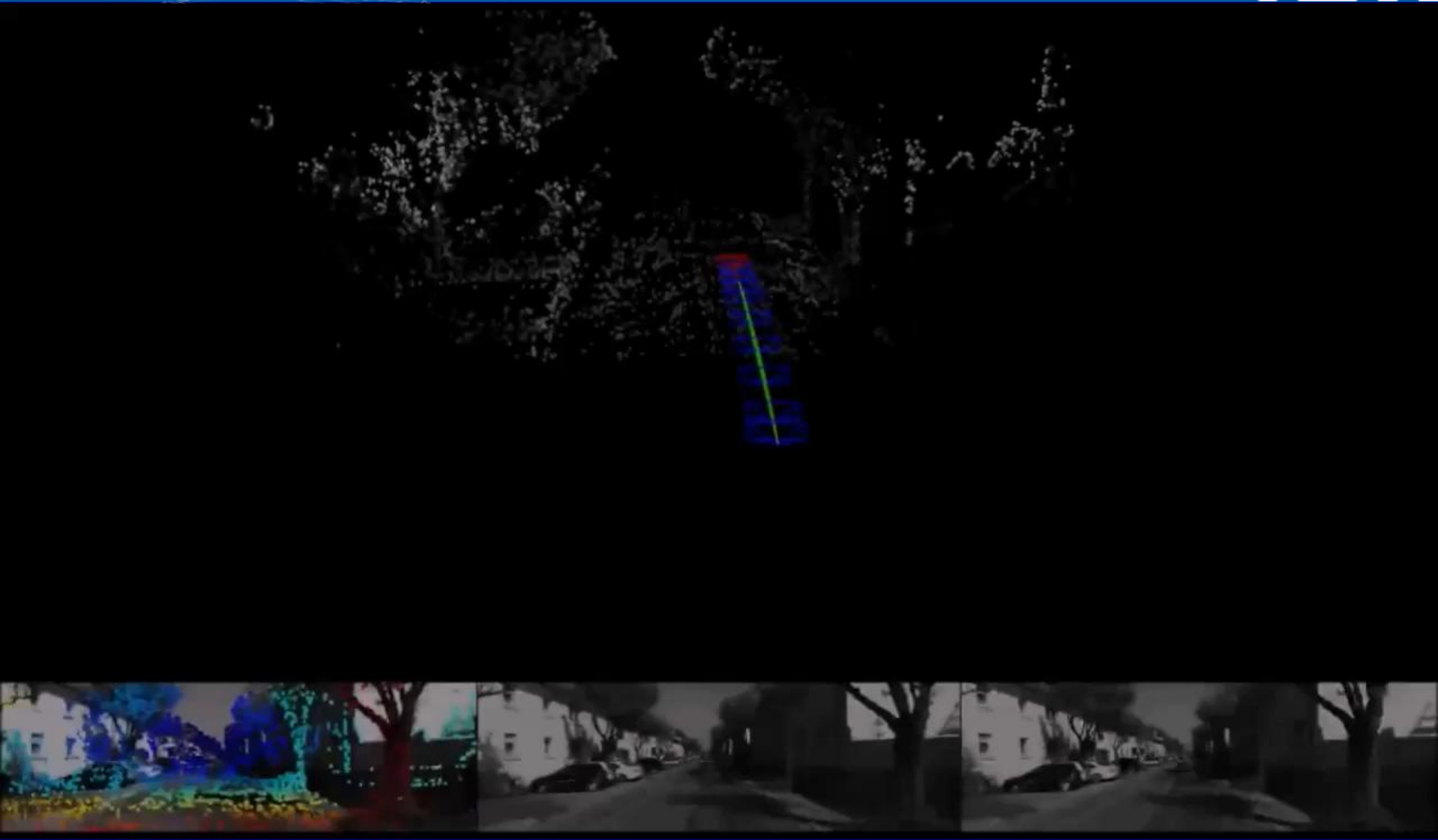


Engel, Koltun, Cremers, IEEE PAMI '18

Meta: Project ARIA

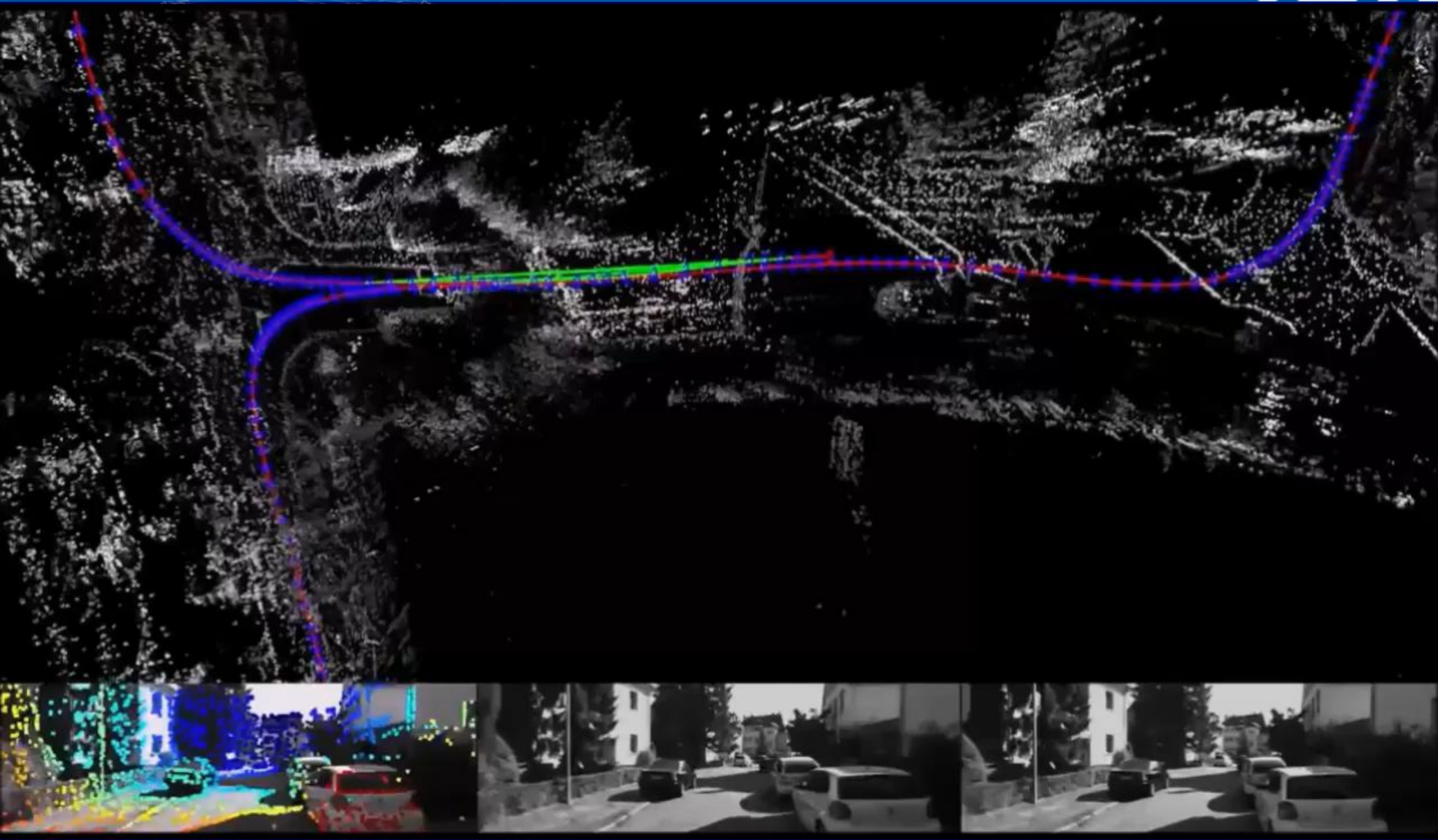
Engel et al. 2023:
Project Aria: A New Tool for Egocentric Multi-Modal AI Research

Stereo Direct Sparse Odometry



Wang, Schwörer, Cremers, "Stereo DSO", ICCV '17

Stereo Direct Sparse Odometry



Wang, Schwörer, Cremers, "Stereo DSO", ICCV '17

Visual-inertial Odometry

Von Stumberg, Cremers, "DM-VIO", ICRA '22

Overview

Multiview reconstruction

Super-res. textures

Free-viewpoint TV

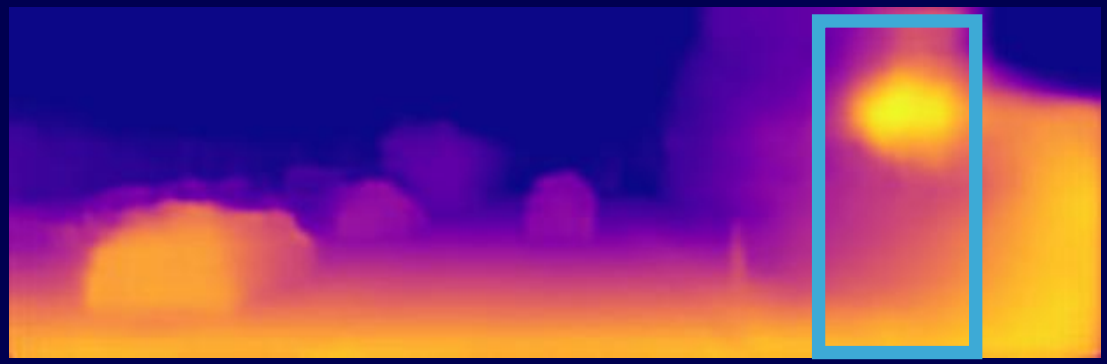
Realtime dense scanning

Visual SLAM

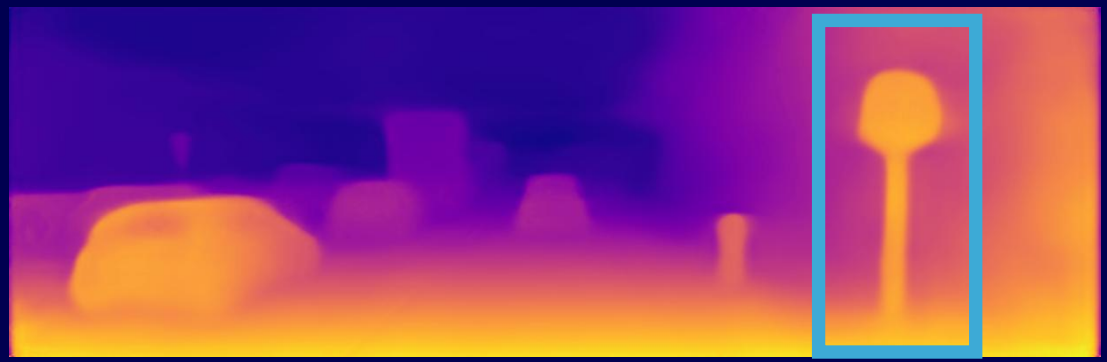
Deep Networks for SLAM

Depth Prediction from a Single Image

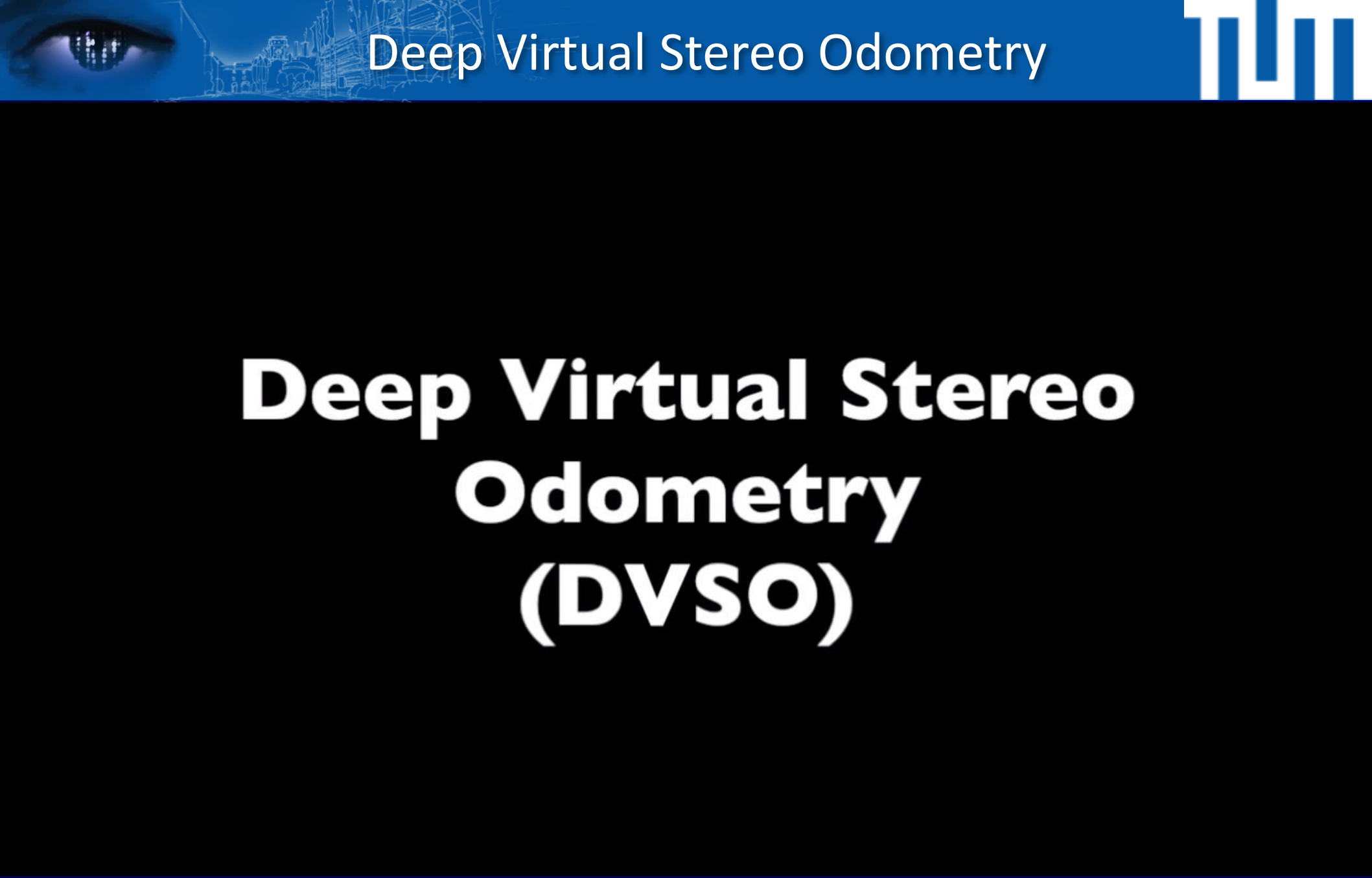
Deep Neural Network



Kuznietsov et al. CVPR 2017

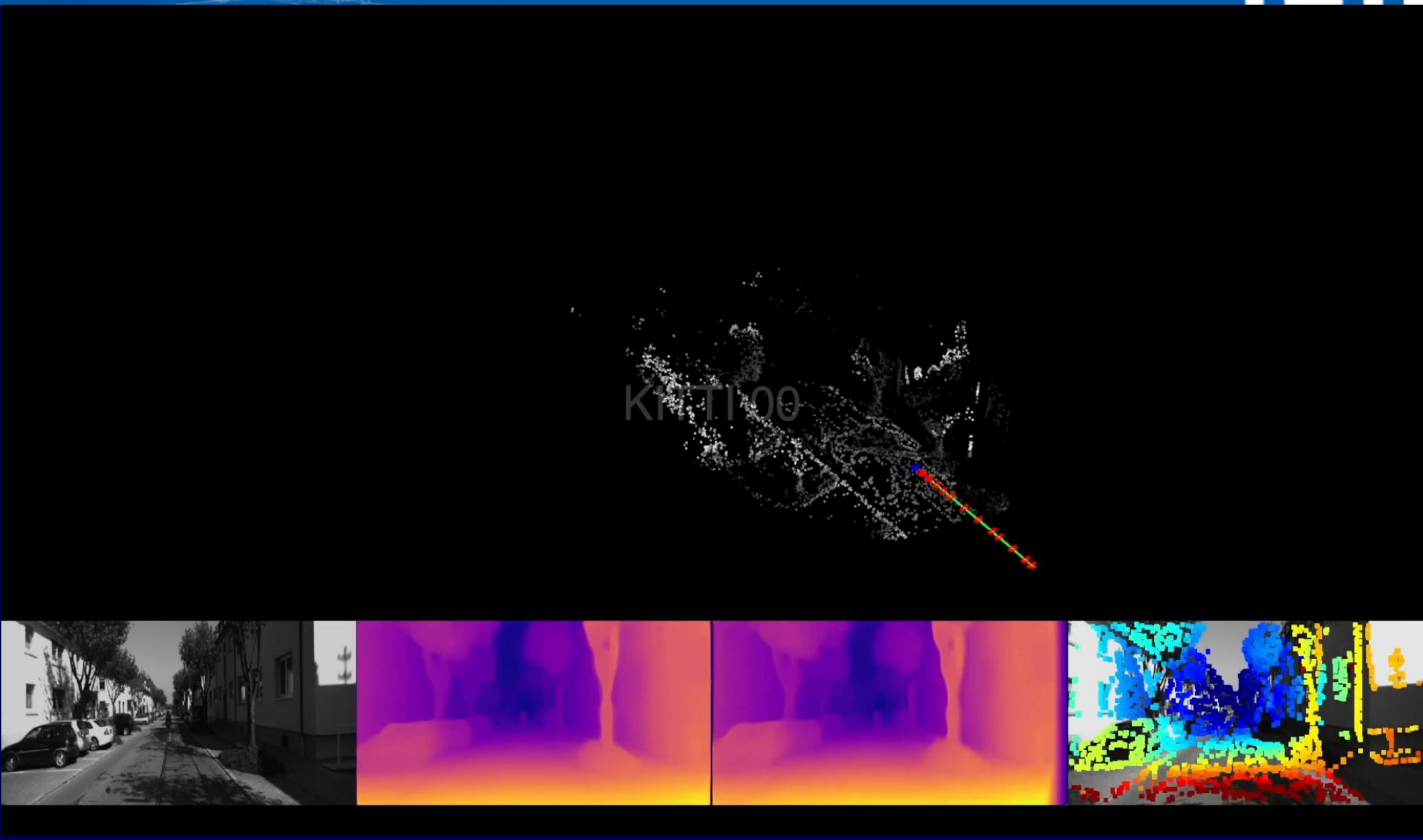


Yang, Wang, Stueckler, Cremers, ECCV 2018



Yang et al., "Deep Virtual Stereo Odometry", ECCV 2018

Deep Virtual Stereo Odometry



Yang et al., ECCV 2018, CVPR 2020

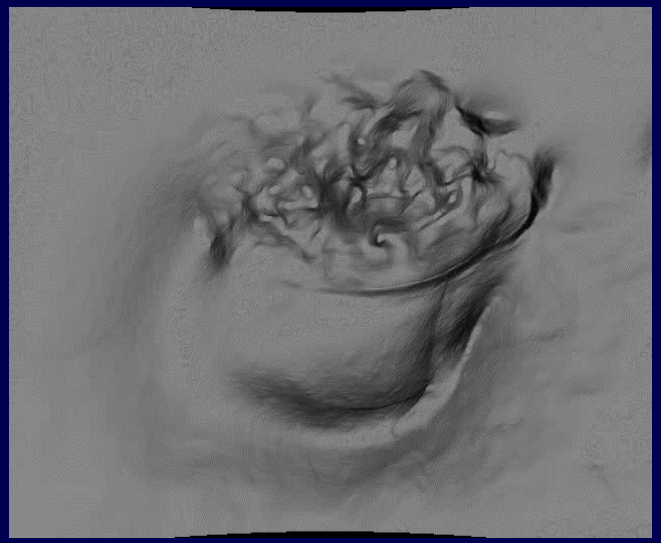
Virtual Worlds from a Single Camera

Wimbauer et al., "MonoRec: Monocular Dense Reconstruction", CVPR '21

Summary

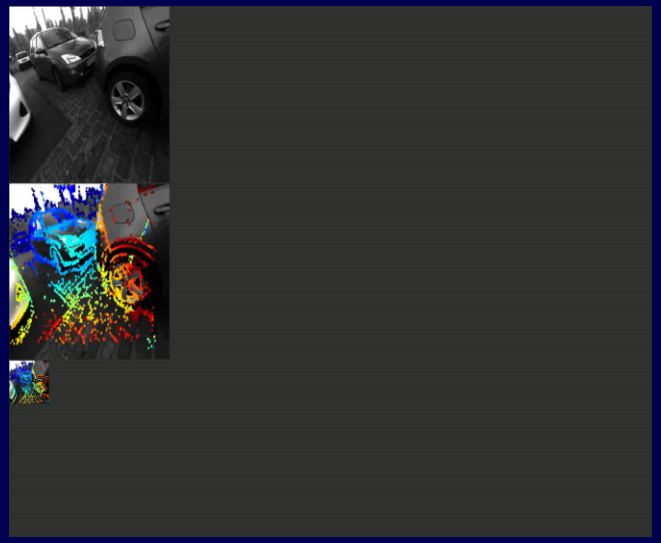
3D reconstruction

Super-res. textures



Realtime dense geometry

RGB-D Scanning



Direct Sparse Odometry

Mono dense reconstruction