ROBOT INTELLIGENCE LAB

Simultaneous Localization And Mapping

Vision-based SLAM

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kakaobrain

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Multi-View Geometry

Bundle Adjustment

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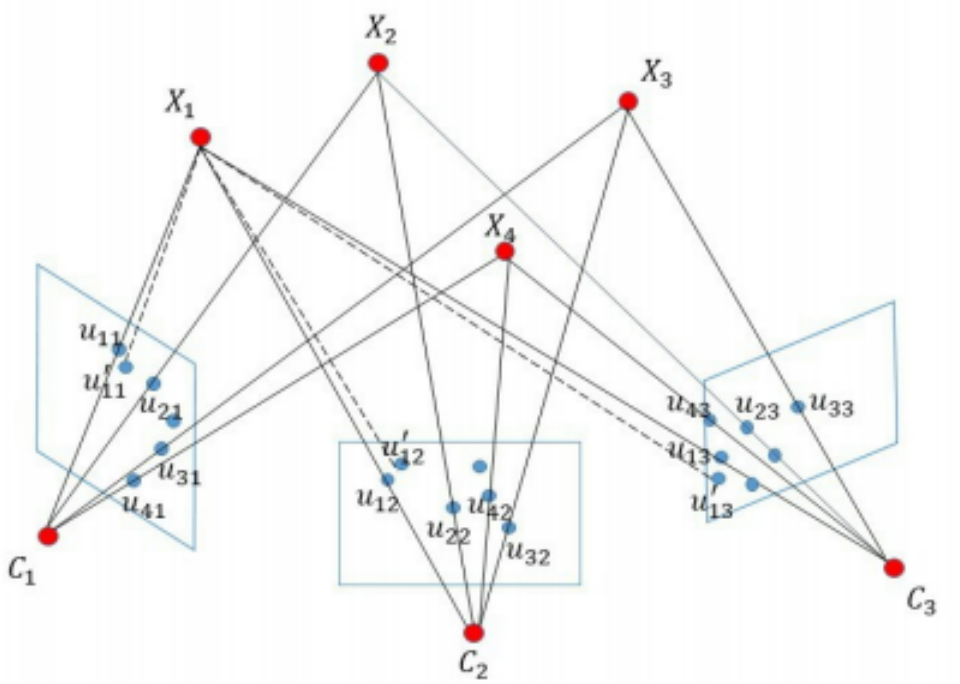
- Bundle Adjustment (BA)
  - BA estimates the 3D feature points and the position of the camera in $SE(3)$.
  - $SE(3)$: special Euclidean group consists of (x, y, z) and (r, p, y).
  - It minimizes the re-projection error using least squares.



Iterative Closest Point

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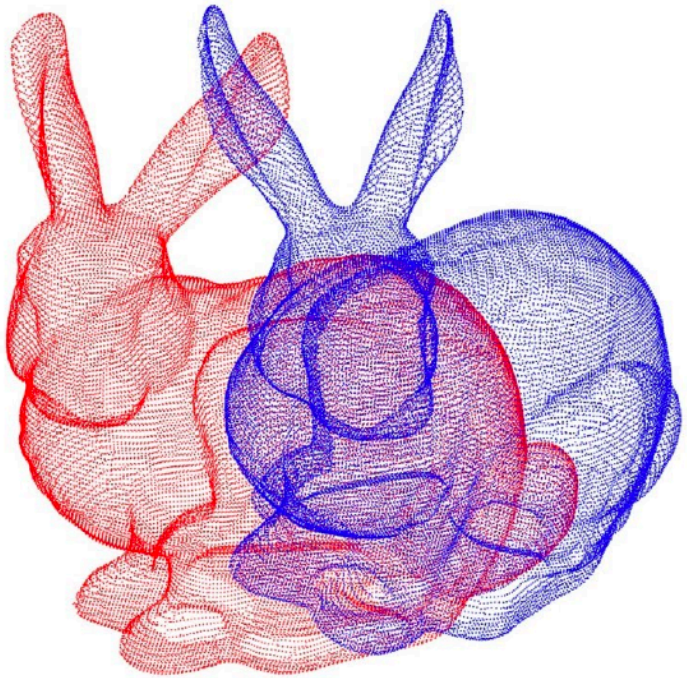
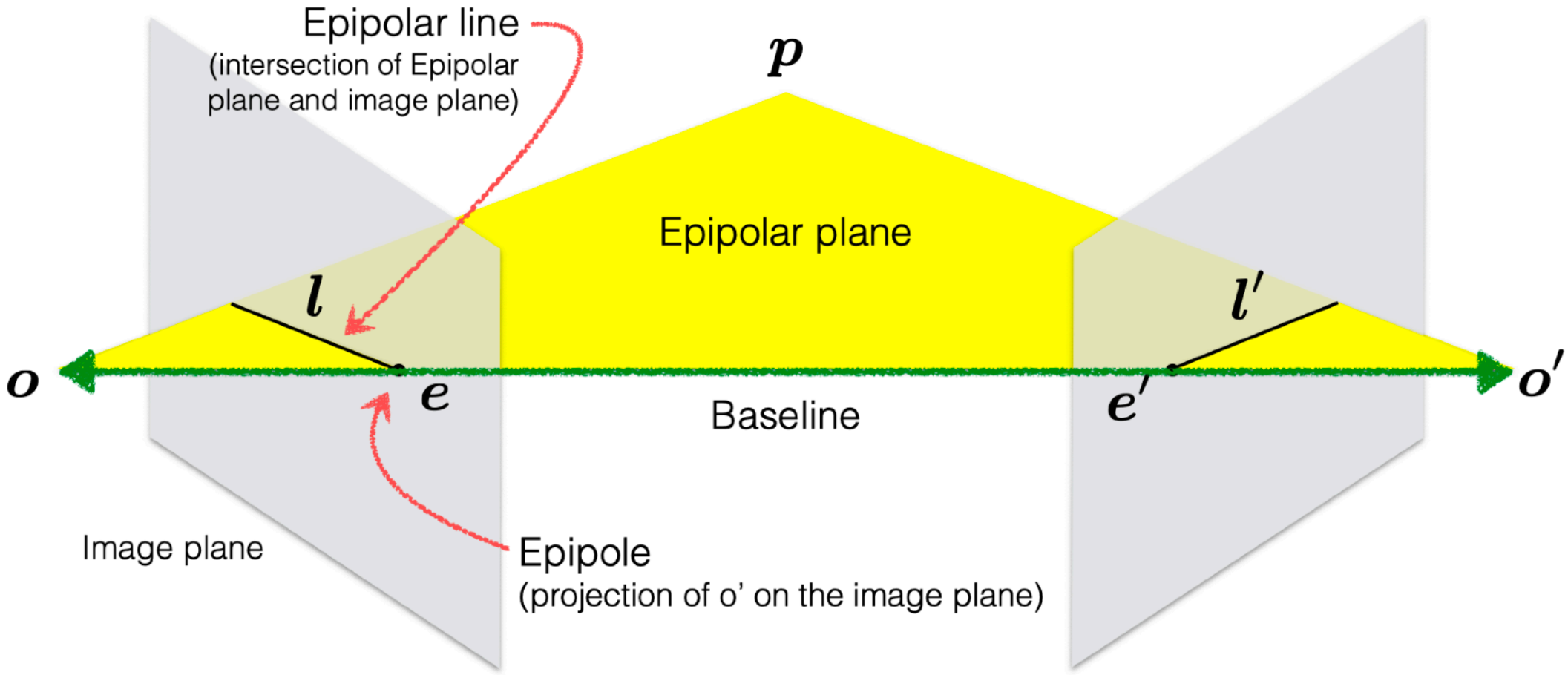
- Iterative Closest Point (ICP)
  - ICP minimizes the difference between two point clouds by estimating the translation information between two point sets.



Epipolar Geometry



Essential Matrix

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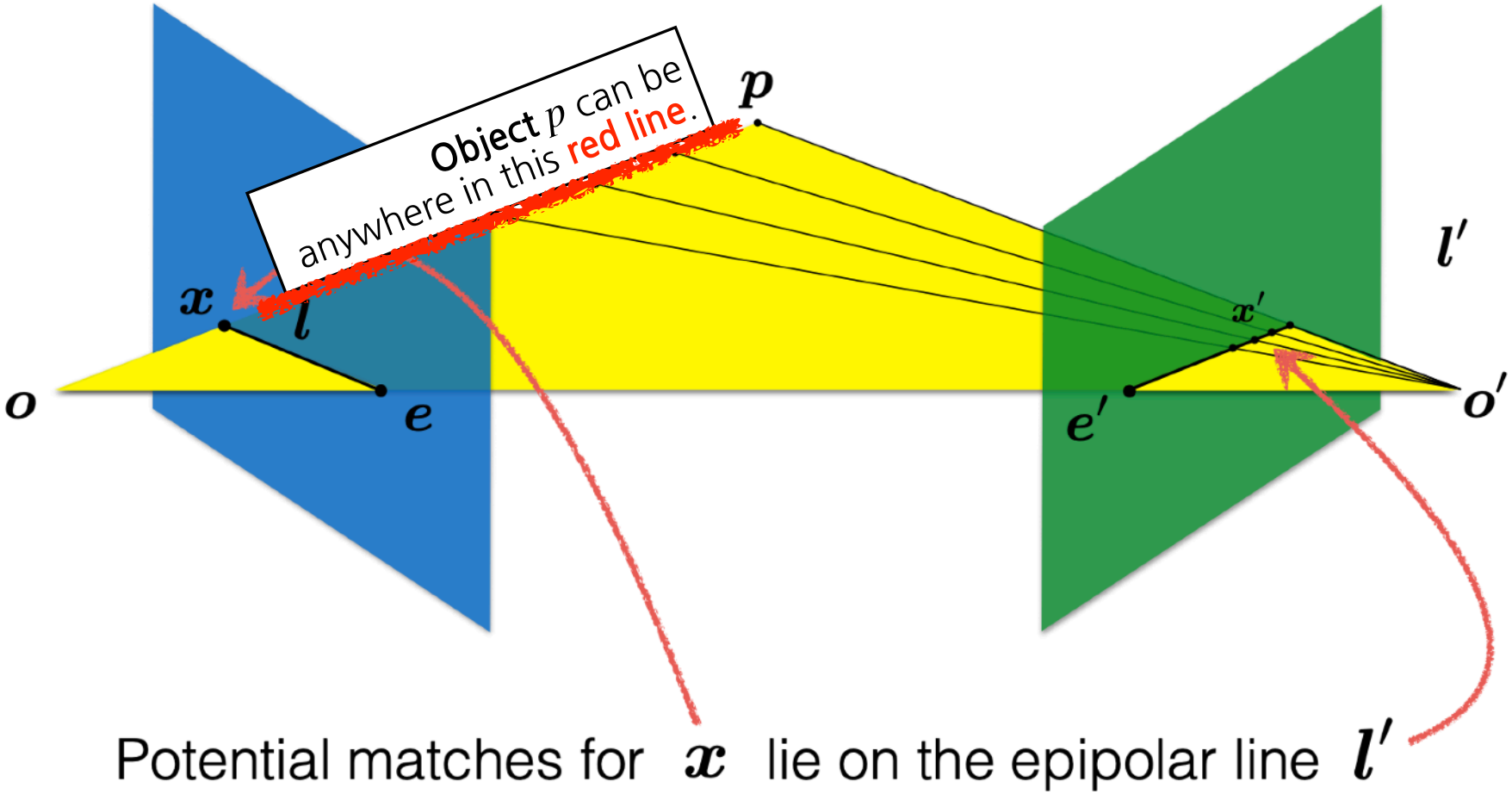
- Epipolar constraint



Essential Matrix

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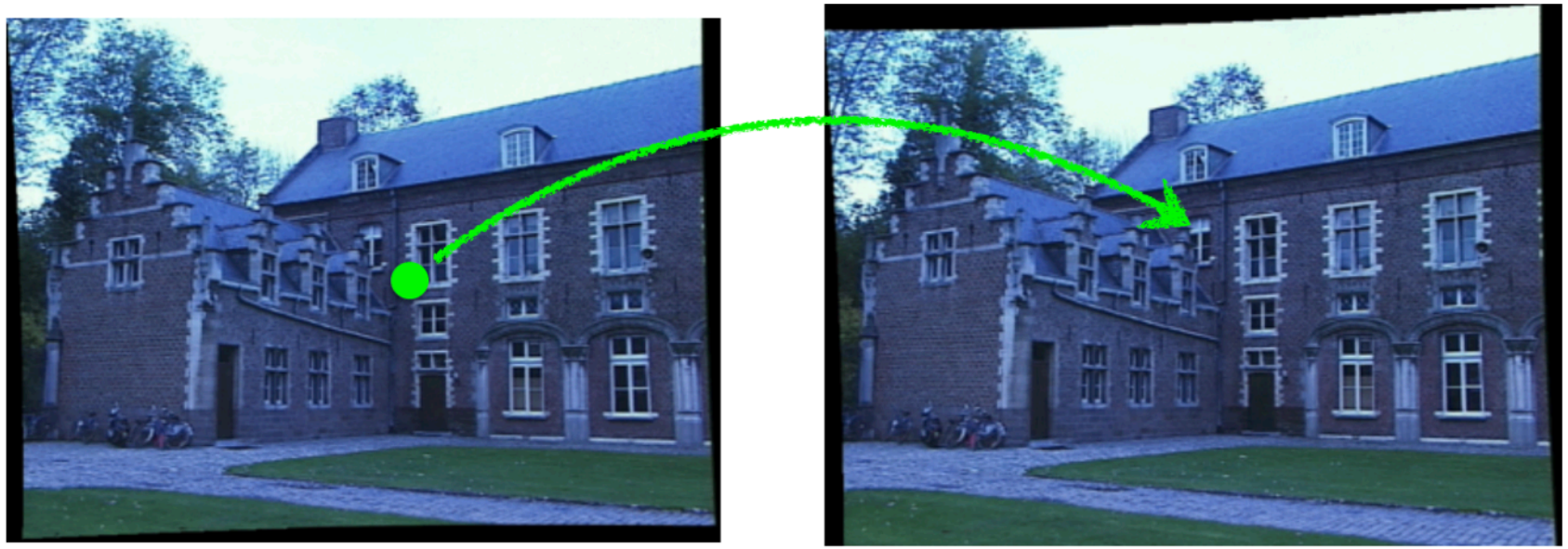
- **Task**: Match a point in the left image to the point in the right image.



Left image

Right image

- How would you do it?
- Epipolar constraints (line) reduces the search to a single line!
- How do you compute the epipolar line?

Essential Matrix

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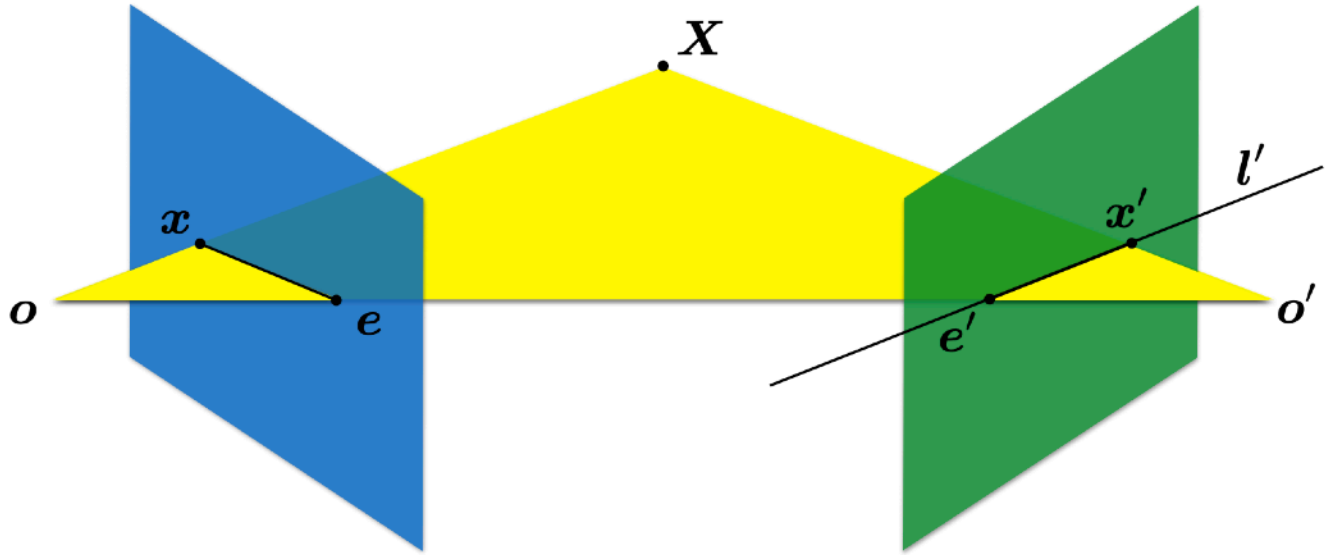
- Essential matrix E is a 3×3 matrix that encodes epipolar geometry.

Given a point in one image,
multiplying by the **essential matrix** will tell us
the **epipolar line** in the second view.

$$\mathbf{E}x = l'$$



Essential Matrix

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Longuet-Higgins equation $\boldsymbol{x}'^{\top}\mathbf{E}\boldsymbol{x} = 0$

Epipolar lines $\boldsymbol{x}^{\top}\boldsymbol{l} = 0$ $\quad \boldsymbol{x}'^{\top}\boldsymbol{l}' = 0$

$\boldsymbol{l}' = \mathbf{E}\boldsymbol{x}$ $\quad \boldsymbol{l} = \mathbf{E}^{T}\boldsymbol{x}'$

Homography Matrix

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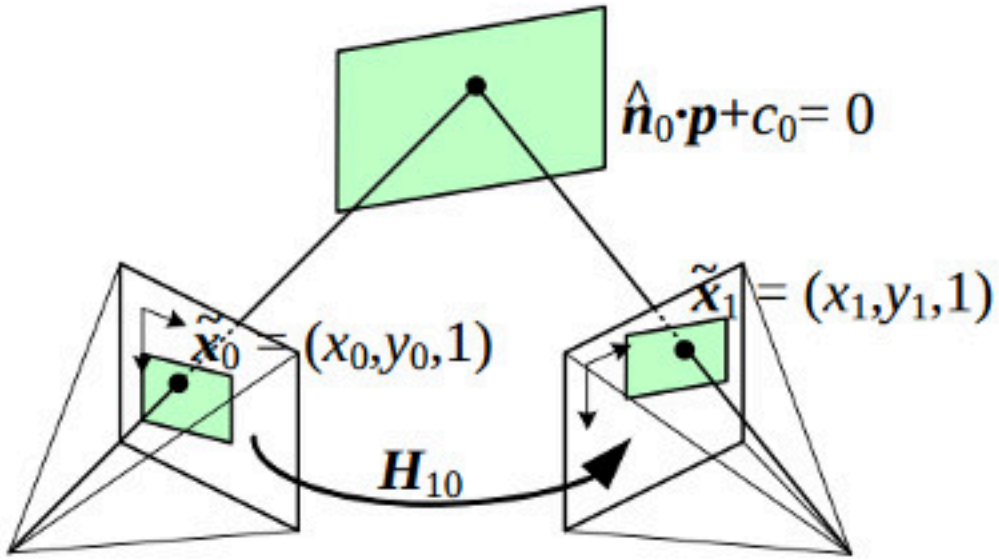
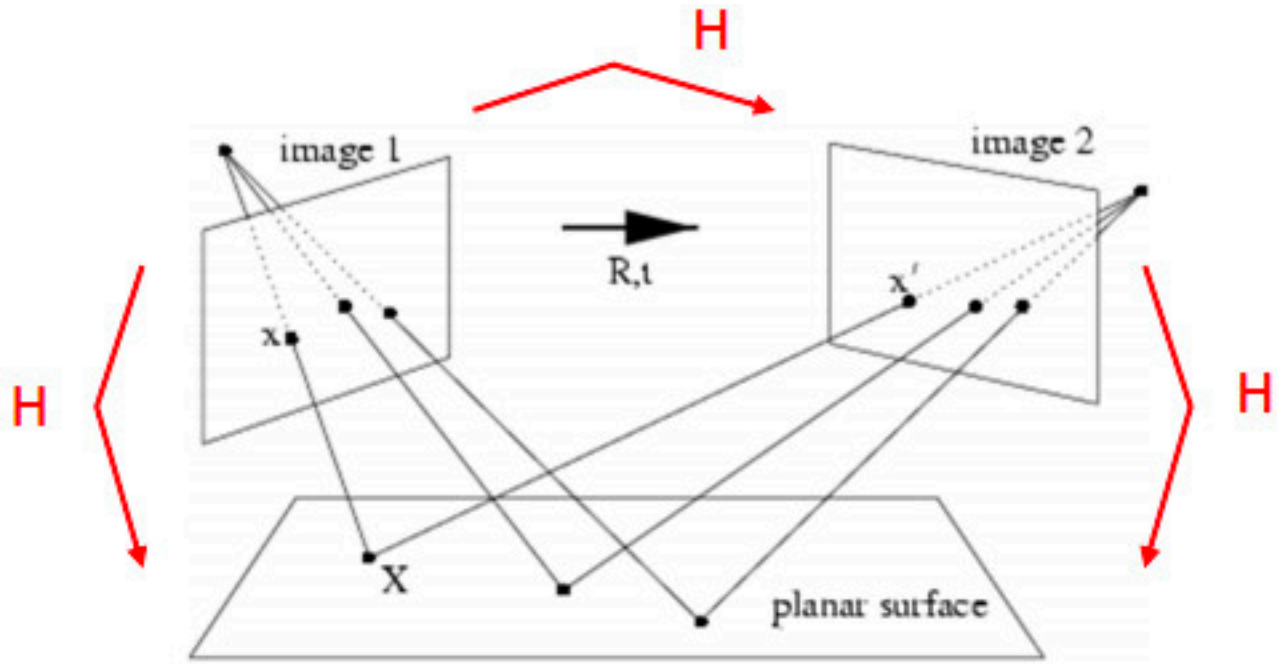
- The homography matrix is a 3×3 matrix which relates the transformation between two planes (up to a scale factor).





Homography Matrix

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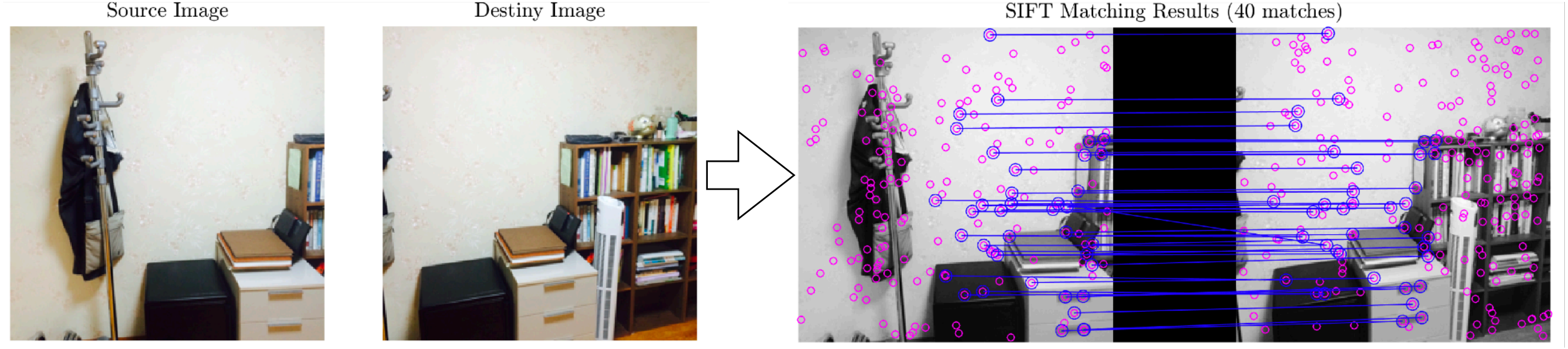
- Given two images, a feature matching is performed (e.g., SIFT matching).



Homography Matrix

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- Then, we compute the homography matrix using RANSAC.

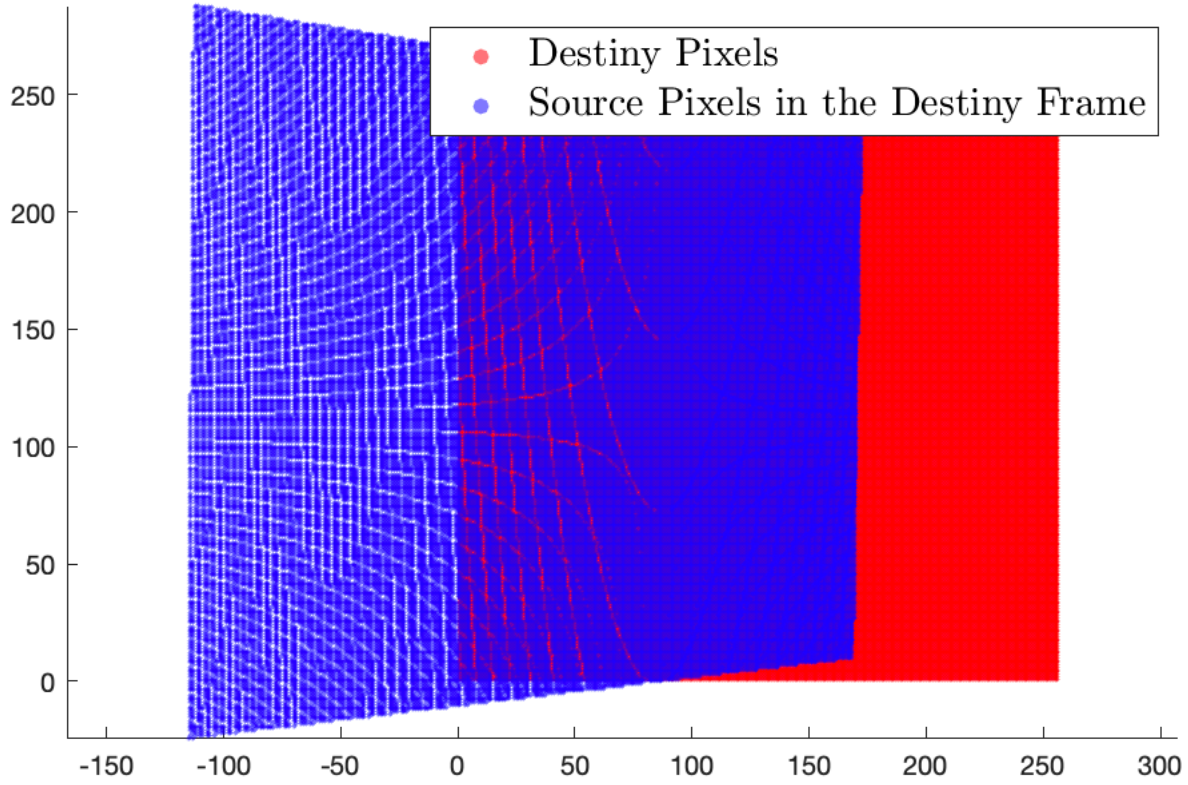

Image Stitching

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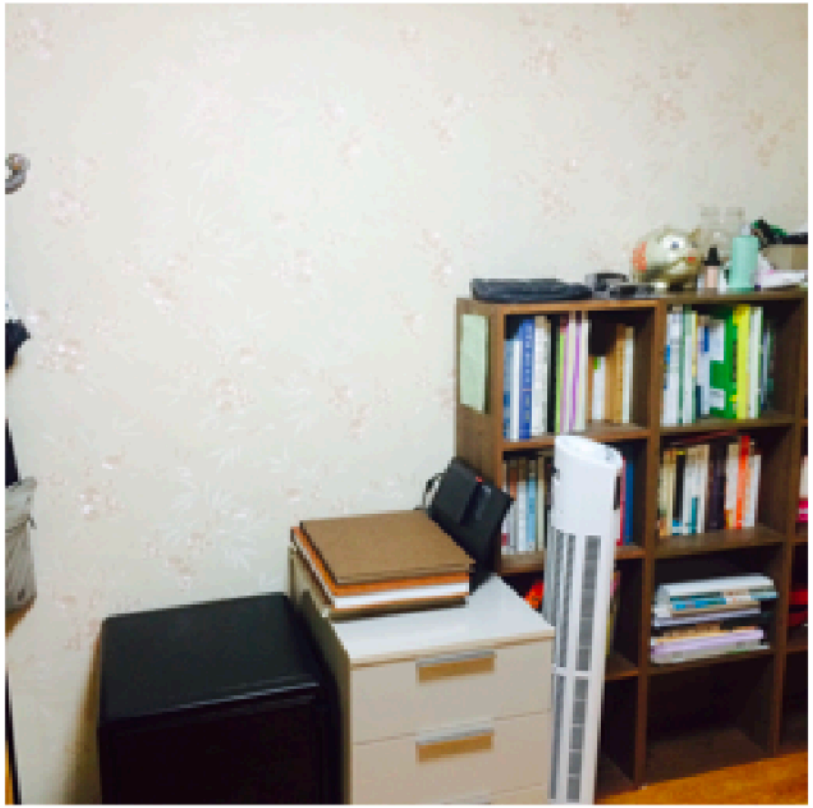
Source Image

Destiny Image



Mosaiced Image

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MonoSLAM

"MonoSLAM: Real-Time Single Camera SLAM," 2007 (Oxford, ICL, AIST)

MonoSLAM

ROBOT INTELLIGENCE LAB

- "MonoSLAM: Real-Time Single Camera SLAM," 2007 (Oxford, ICL, AIST)
  - The first successful application of SLAM from mobile robotics to the "pure vision" domain of a single uncontrolled camera, achieving real time but drift-free performance.
  - The core is the online creation of a sparse but persistent map of **natural landmarks** within a probabilisitic framework.
  - It combines visual feature template matching and EKF.

MonoSLAM

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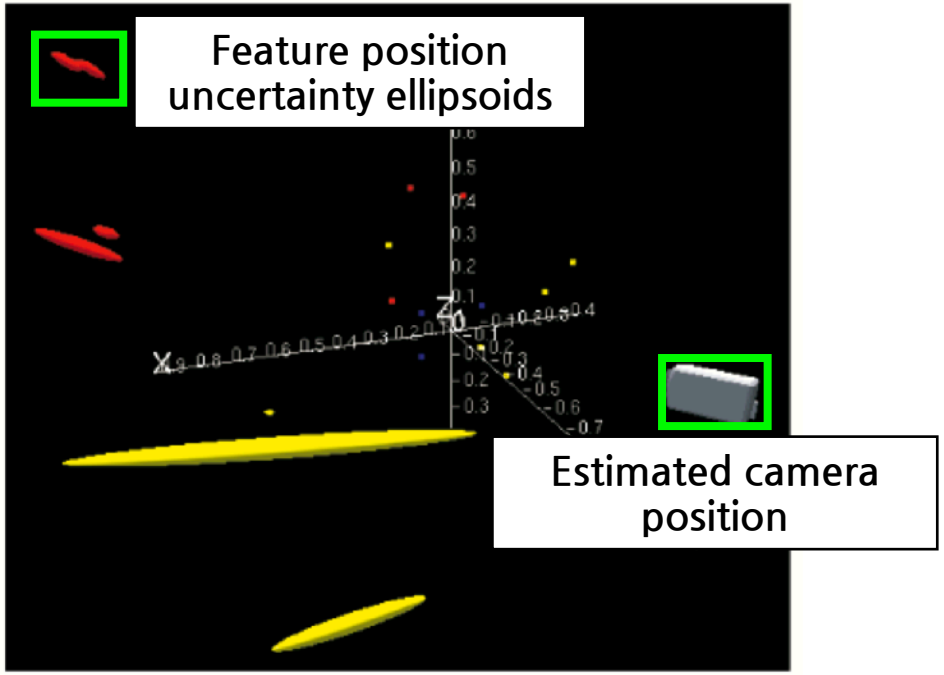
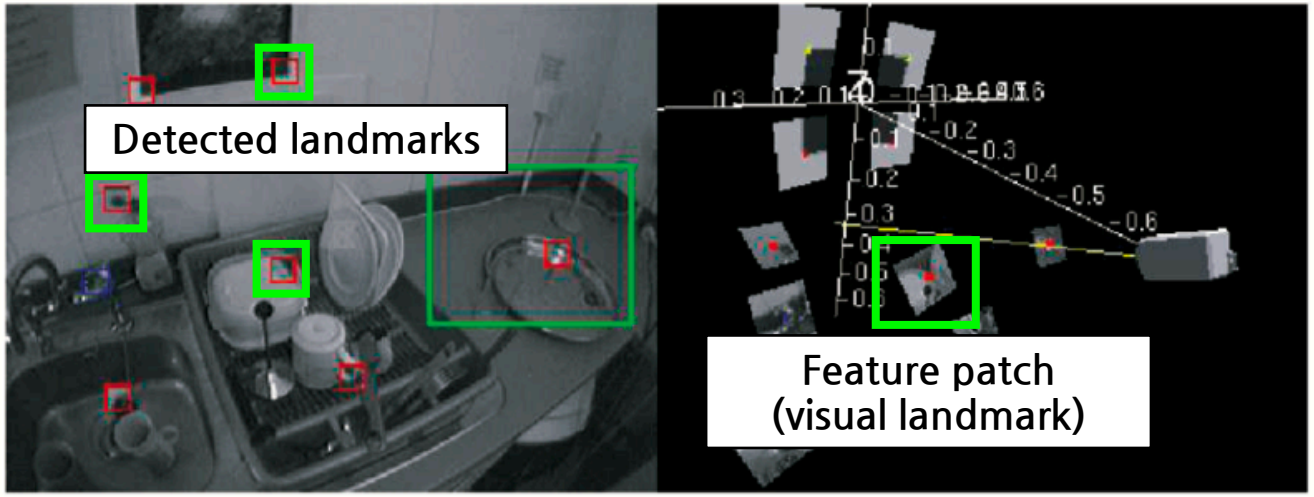
- Probabilistic 3D Map
  - MonoSLAM incorporates a probabilistic **feature-based** map, representing a snapshot of the current estimates of the state of the camera and the uncertainty in these estimates.
  - The map is updated by the extended Kalman filter (EKF).



MonoSLAM

ROBOT INTELLIGENCE LAB

- Natural Visual Landmarks
  - The role of the map is to permit real-time localization rather than serve as a complete scene description, and therefore aim to capture a sparse set of high-quality **landmarks**.
  - Relatively large (11x11 pixels) image patches work as **long-term landmark** features.



MonoSLAM

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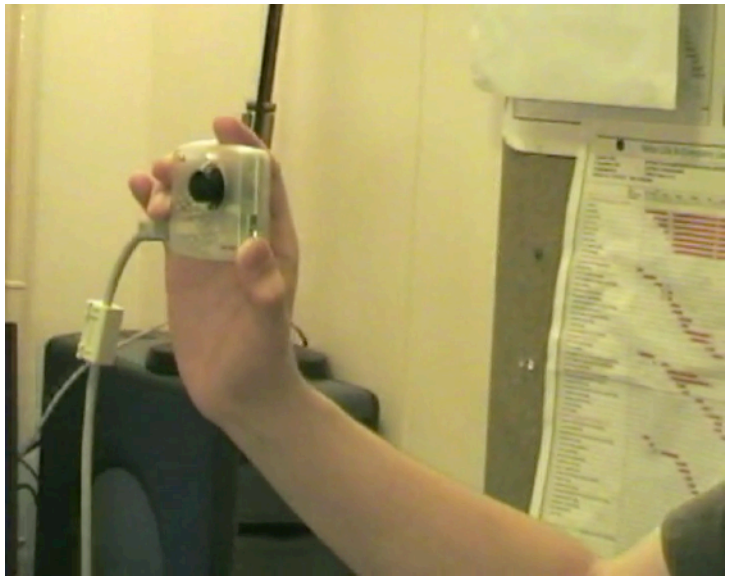

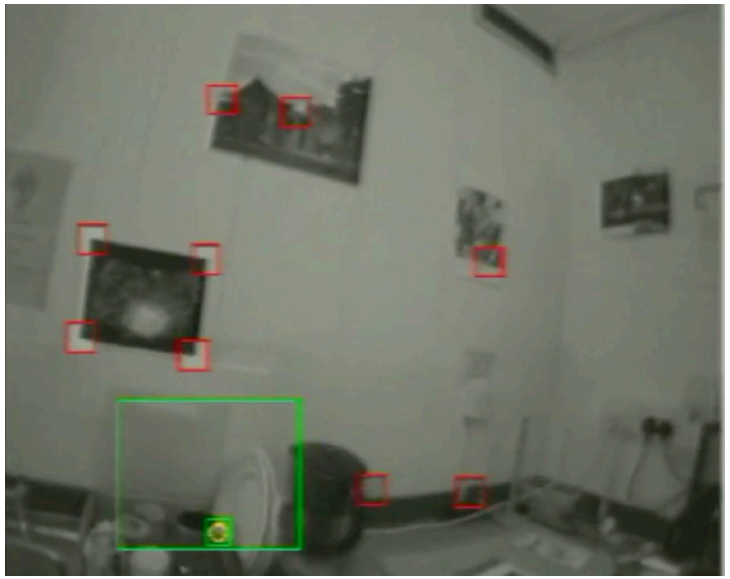

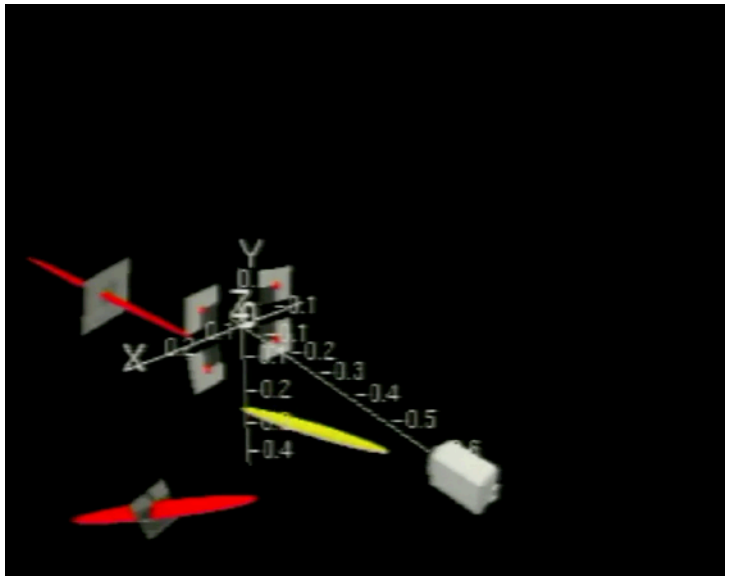

https://youtu.be/mimAWVm-0qA

PTAM

"Parallel Tracking and Mapping for Small AR Workspaces," 2007 (Oxford)

PTAM

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- "Parallel Tracking and Mapping for Small AR Workspaces," 2007 (Oxford)
  - It is specifically designed to track a hand-held camera in a small AR workspace named PTAM (parallel tracking and mapping).
  - The core is to **split tracking and mapping** into two separate tasks which allows the use of (computationally-expensive) batch optimization for mapping.
    - No more SLAM wiggle (i.e., no additional smoothing for incremental update)
  - But, it has a clear limitation in terms of general performances.

PTAM

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- Overview of PTAM
  - Tracking and Mapping are separated.
    - Tracking (of camera positions) is no longer probabilistically slaved to the map-making procedure.
  - Mapping is based on **keyframes**, which are processed using Bundle Adjustments.
  - The map is densely initialized from a stereo pair (5-point algorithm).
  - New points are initialized with an epipolar search.

PTAM

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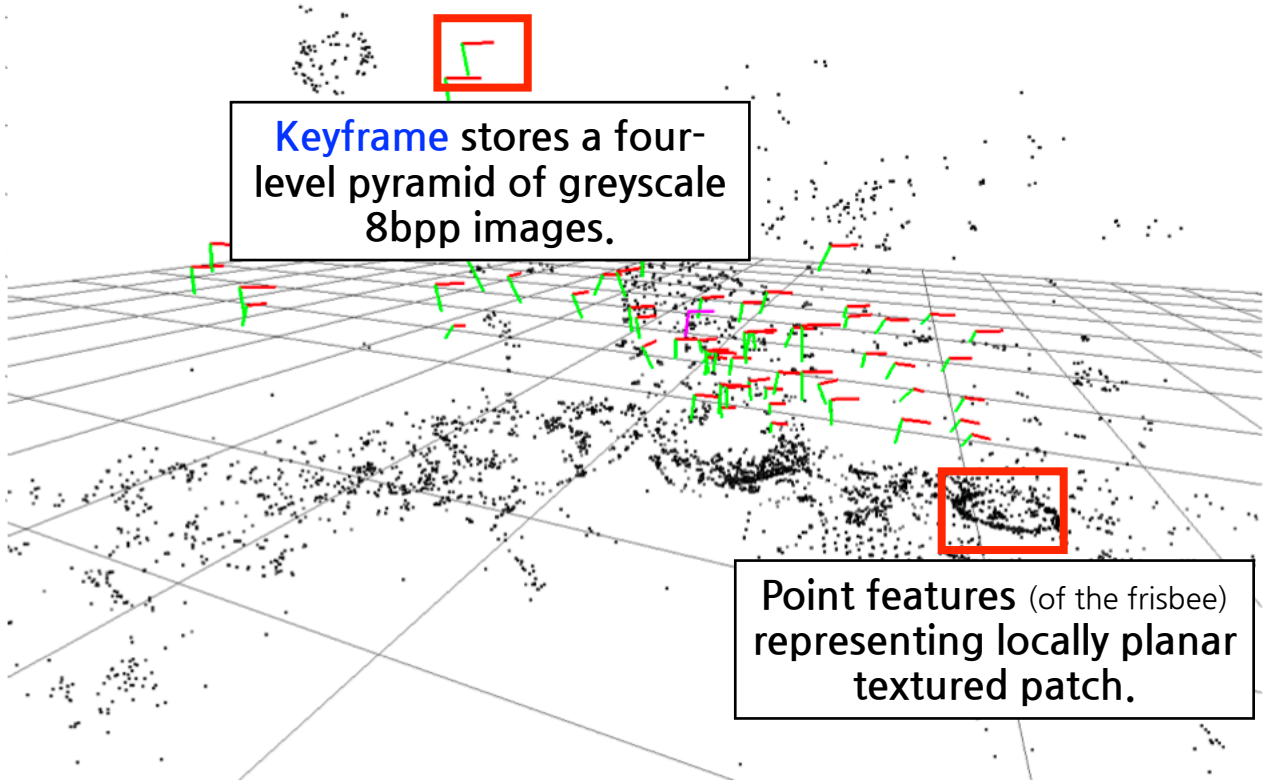

PTAM

https://youtu.be/Y9HMn6bd-v8

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Graph-based SLAM

"A Tutorial on Graph-Based SLAM," 2010

Graph-based SLAM

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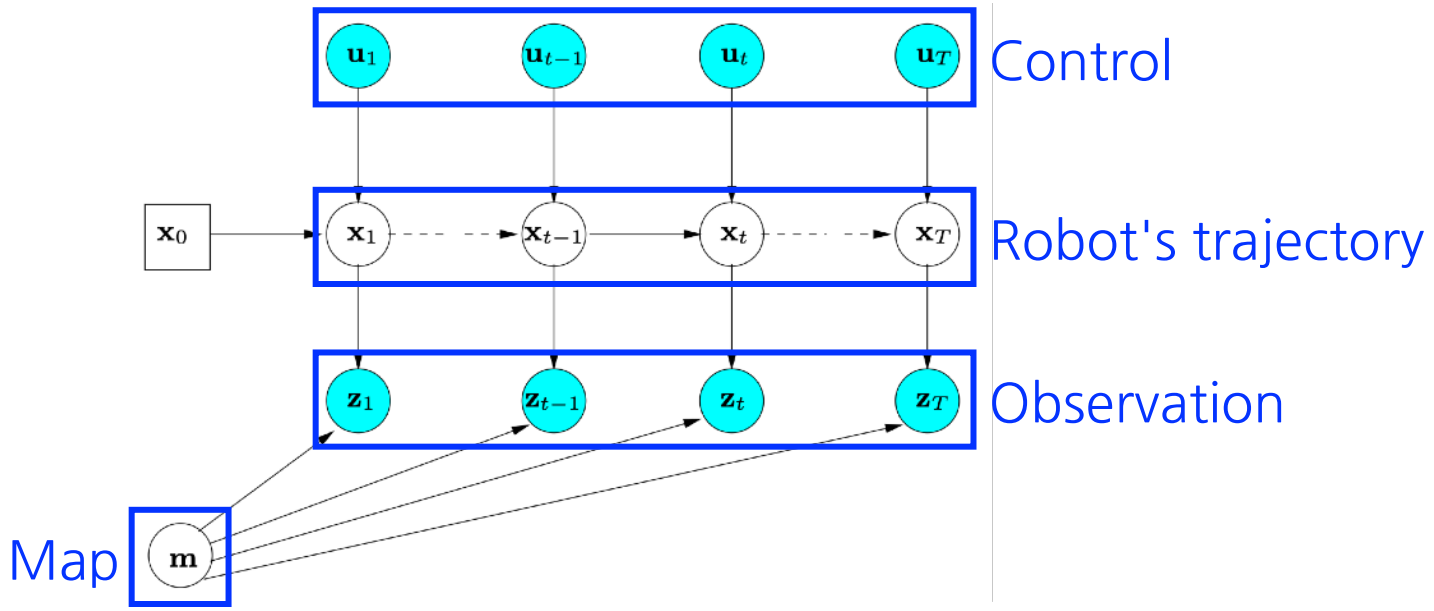
- "A Tutorial on Graph-Based SLAM," 2010
  - It uses a graph whose nodes correspond to the poses of the robot at different points in time and whose edges represent constraints between the poses (obtained from observations and control inputs).



Graph-based SLAM

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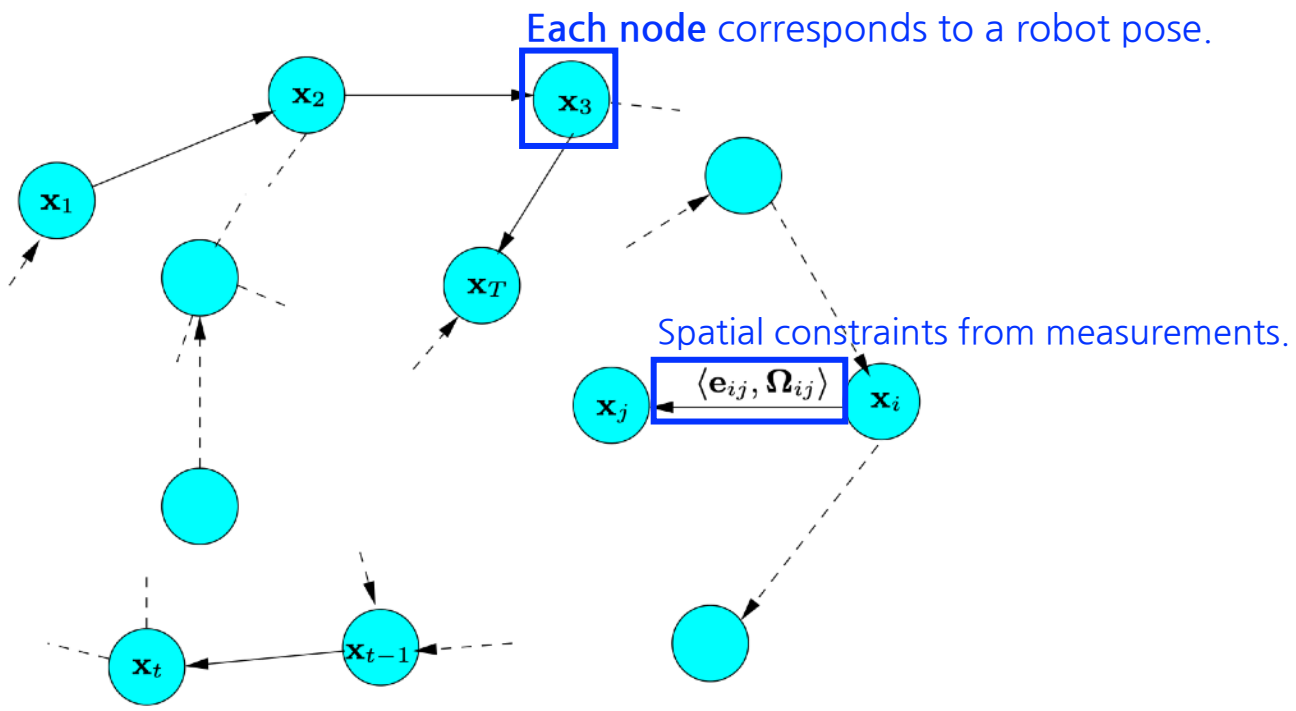
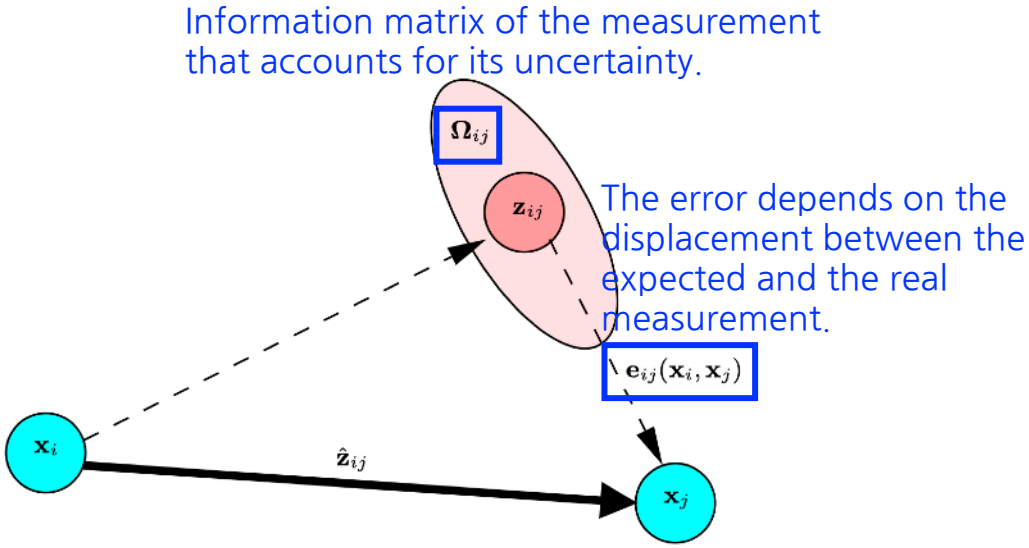


A pose-graph representation of SLAM



Aspects of an edge in SLAM

Graph-based SLAM

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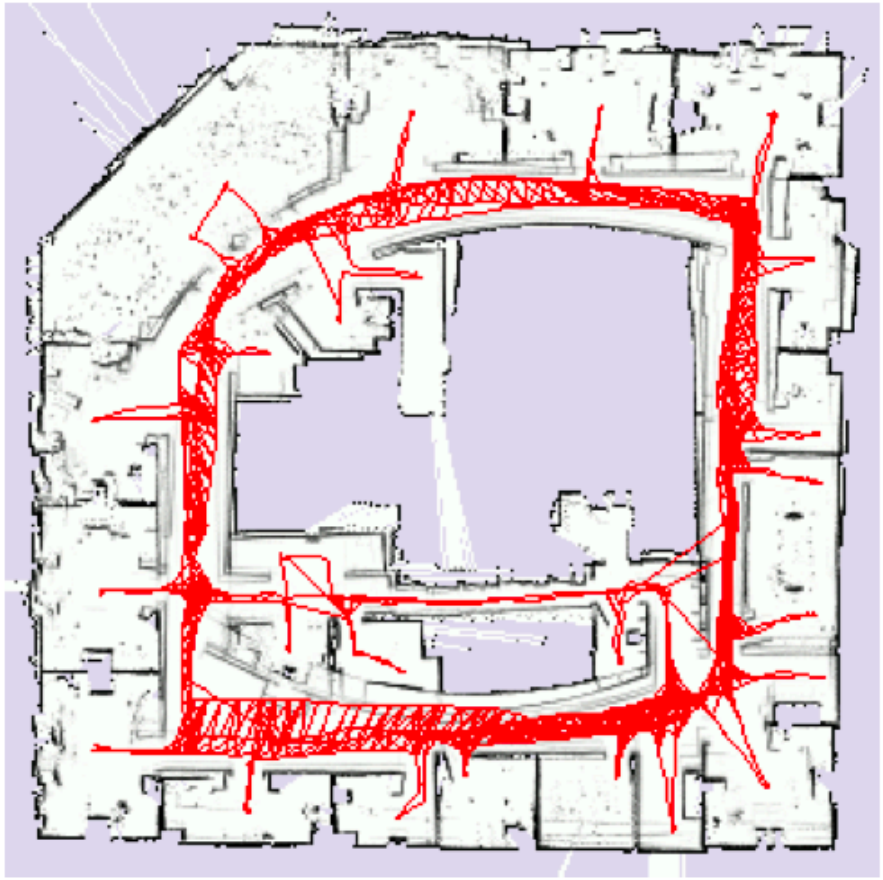
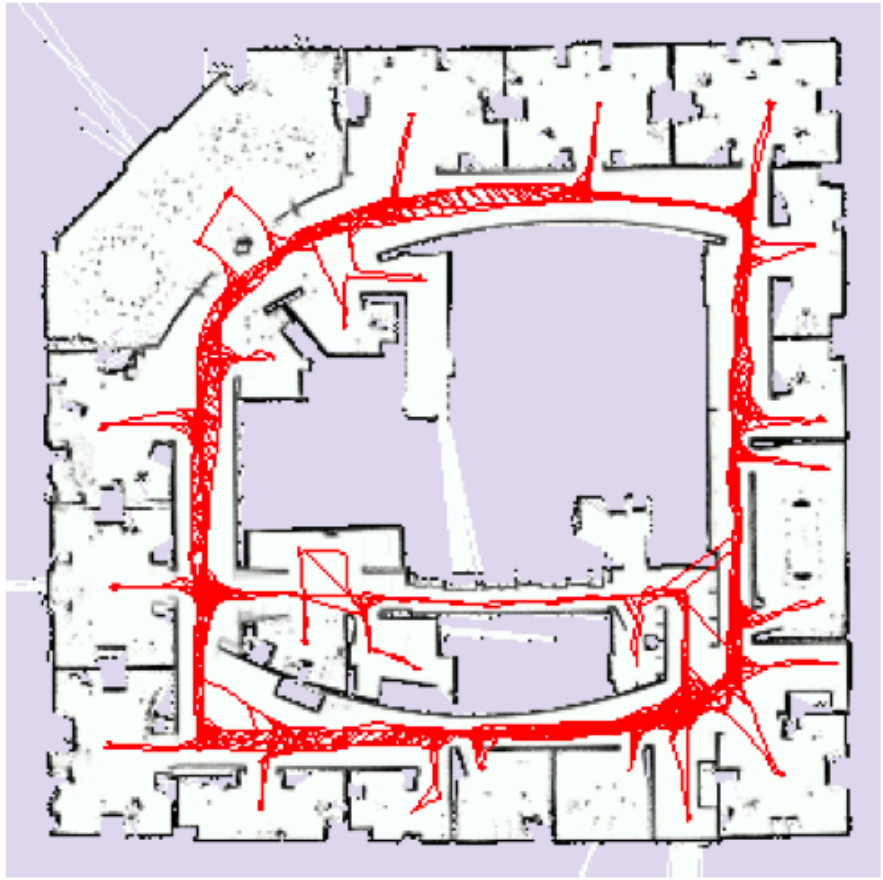


Unoptimized pose graph



Optimized pose graph

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LSD-SLAM

"LSD-SLAM: Large-Scale Direct Monocular SLAM," 2014 (TUM)

LSD-SLAM

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- "LSD-SLAM: Large-Scale Direct Monocular SLAM," 2014 (TUM)
  - It proposes a **direct** feature-less monocular SLAM algorithm to build large-scale, consistent maps of the environment.
  - There are two different approaches in Monocular SLAM
    1. **Feature**-based methods: Extract features from images and compute scene geometry from these features only.
    2. **Direct** methods: direct visual odometry (VO) optimizes the geometry directly on the image intensities.
  - LSD-SLAM uses **direct image alignment** with filtering-based estimation of semi-dense maps where the global map is represented as a pose graph.

Feature-Based (Indirect) vs. Direct

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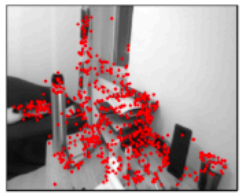
Feature-Based

Input Images

Feature descriptions and matching is required!

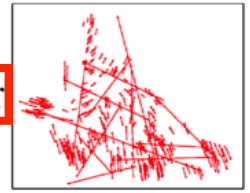
Extract & Match Features
(SIFT / SURF / ...)



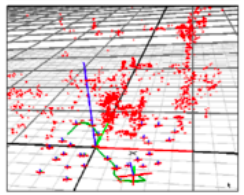
abstract image to feature observations

Bundle adjustment

Track:
min. **reprojection** error
(point distances)



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



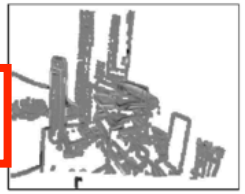
Direct

Input Images

keep full images (no abstraction)

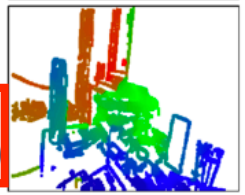
Intensities of pixels matter

Track:
min. **photometric** error
(intensity differences)



Depth per each pixel!

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



Photometric Error

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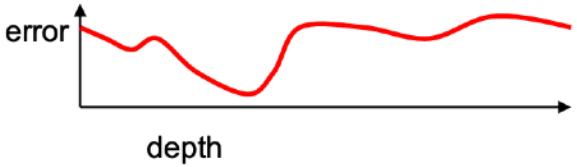
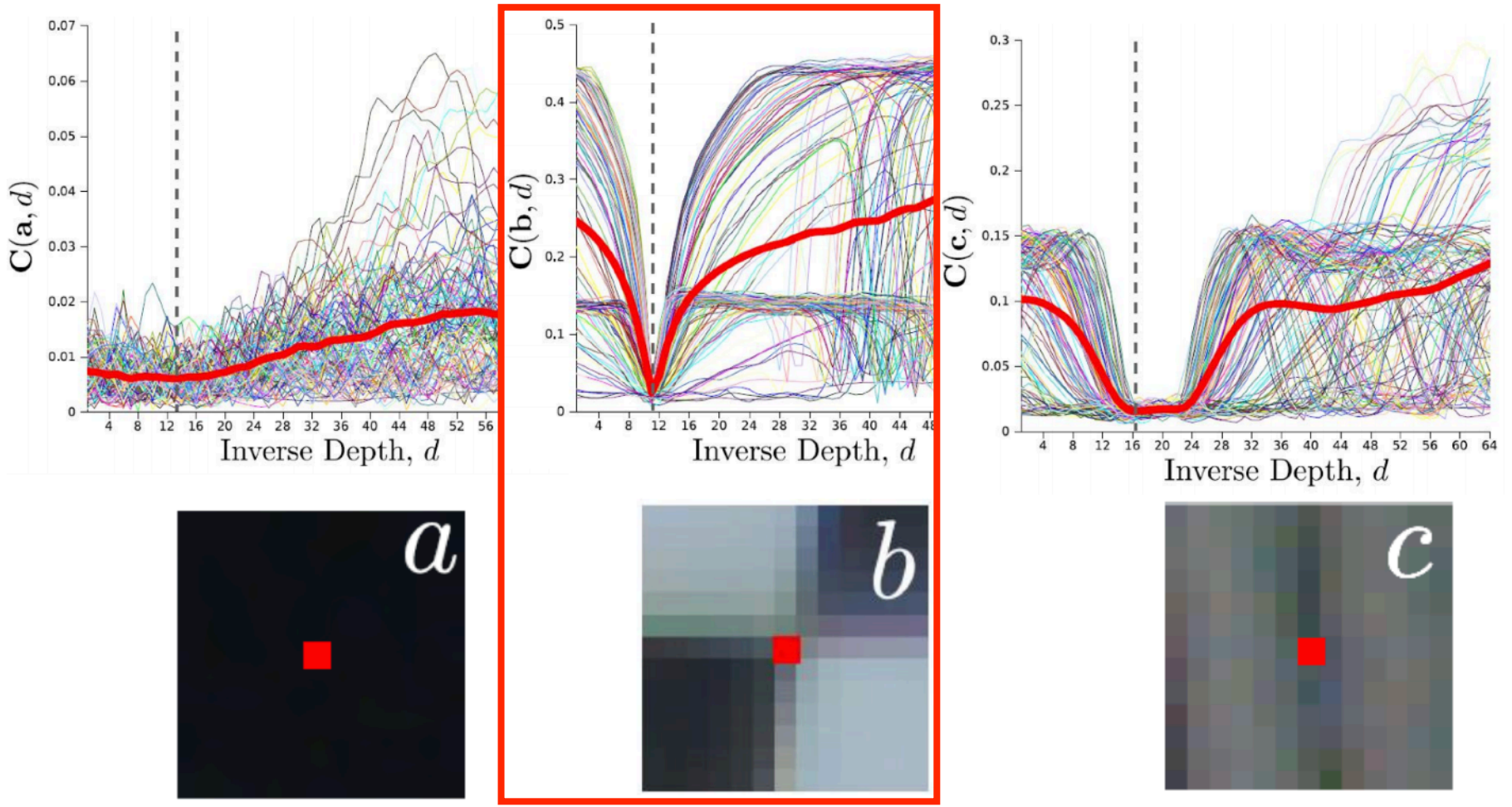


This error plot is derived for every combination of the reference image and any further image

We assume that the **relative positions** and **orientations between cameras** are **known**.

IDEA: the optimal depth minimizes the photometric error in all the images as a function of the depth in the first image

Photometric Error



For distinctive pixels, the aggregated photometric error has typically one clear minimum.

LSD-SLAM

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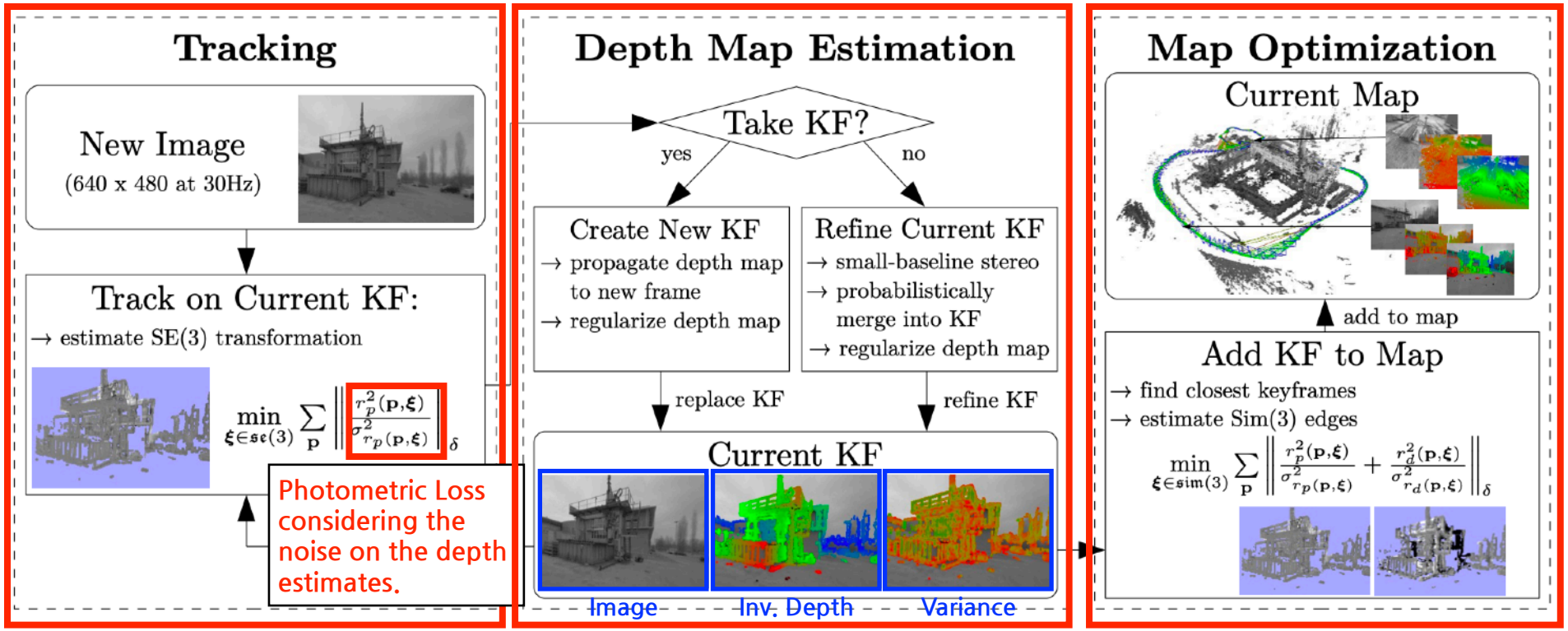


Tracking component continuously tracks new camera images by estimating the rigid body pose (p and R) w.r.t the current keyframe.

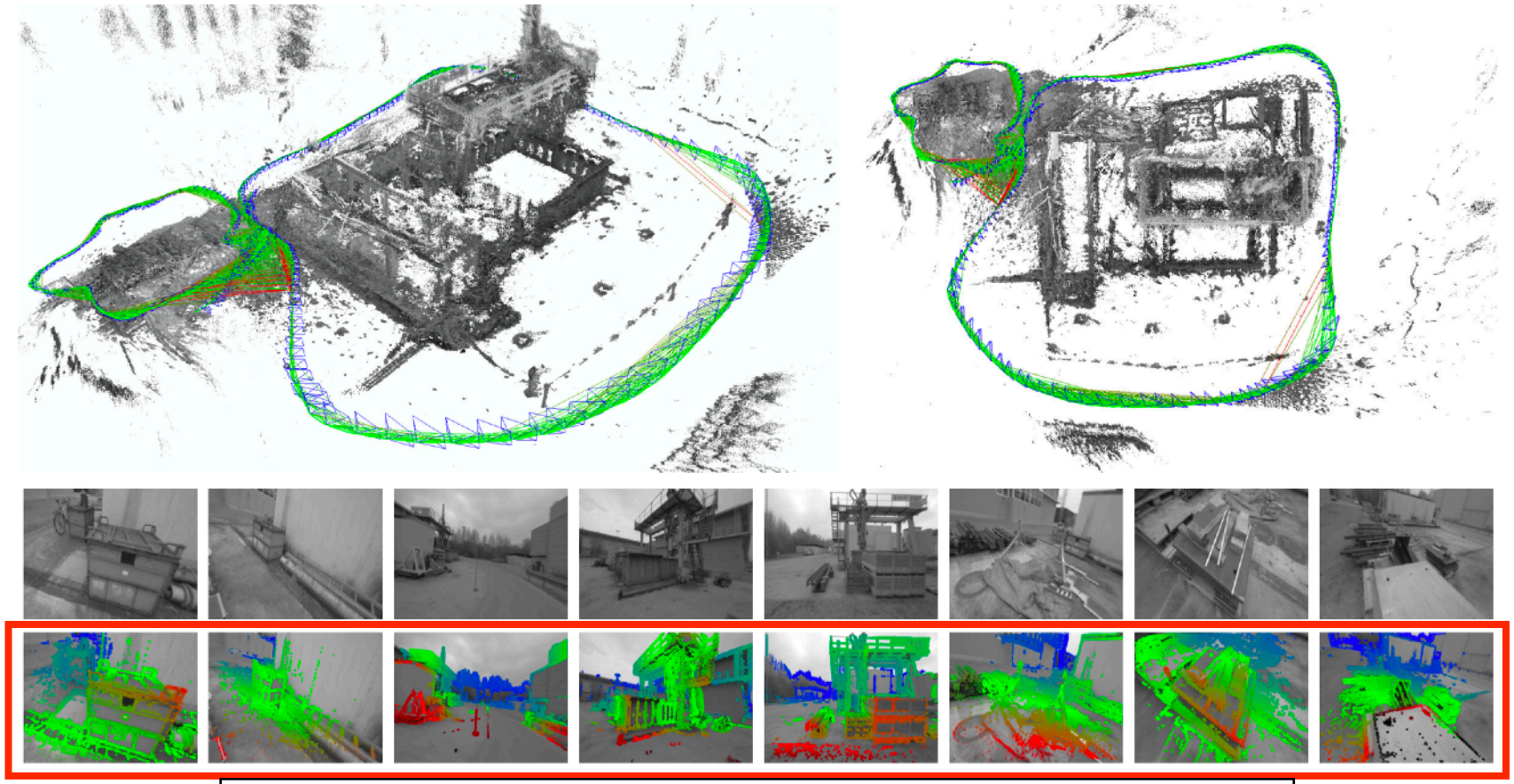
Depth map is estimated by projecting points from the previous keyframe into the new keyframe.

To handle the scale ambiguity, the mean of the inverse depth is scaled to be one.

Finally, graph optimization is used to estimate the global map.

LSD-SLAM

ROBOT INTELLIGENCE LAB



Keyframes with color-coded semi-dense inverse depth map

LSD-SLAM

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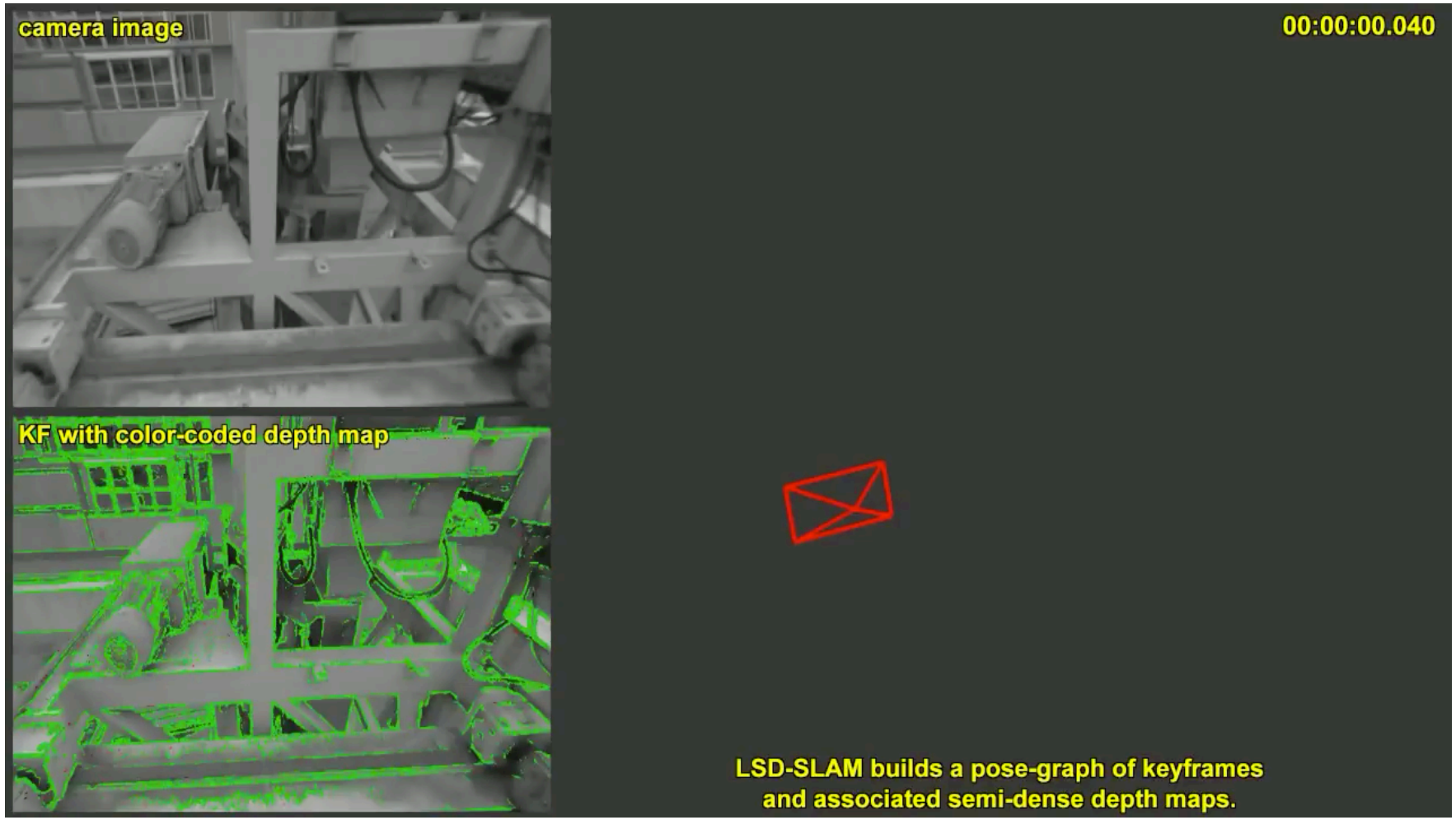
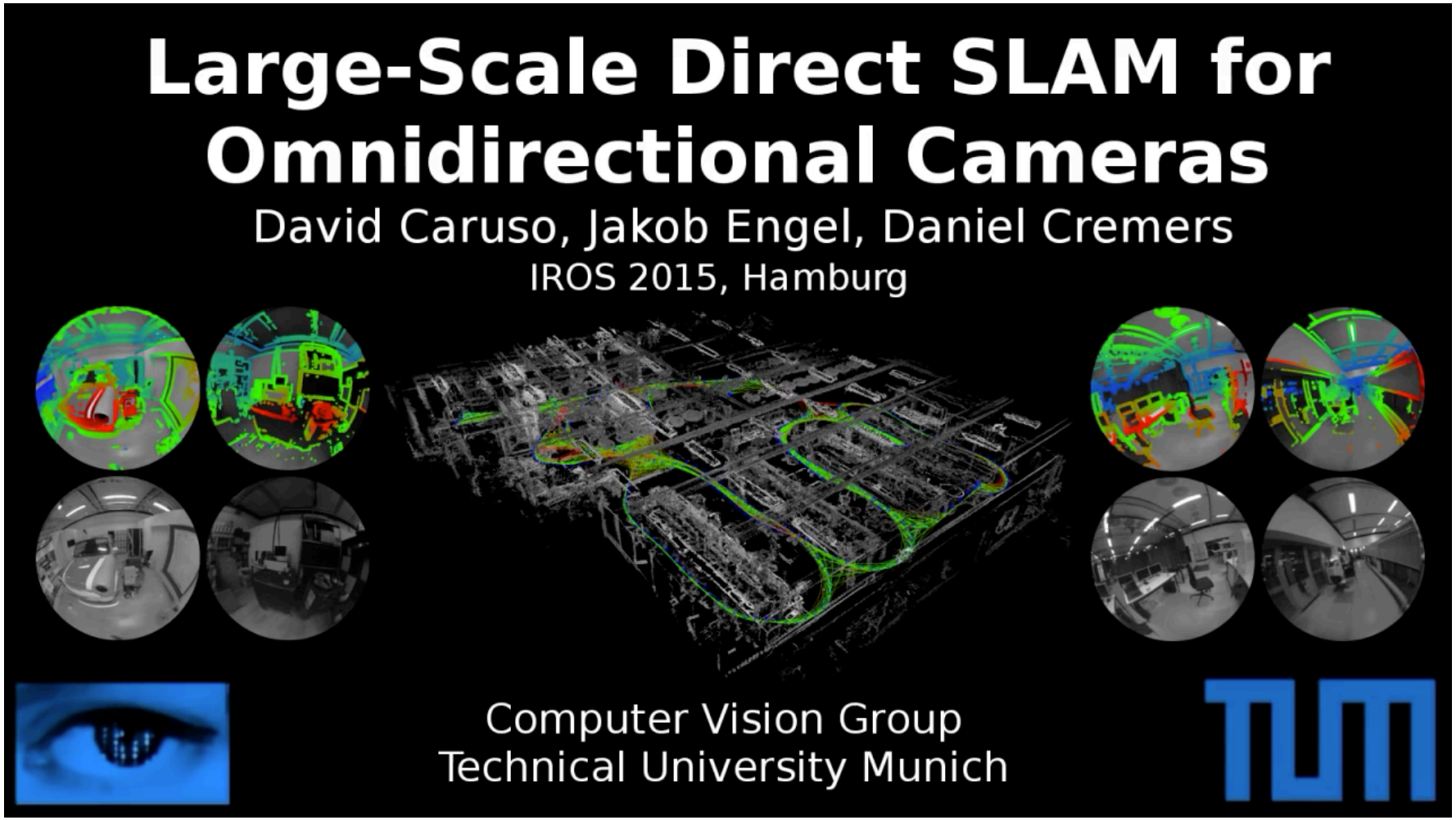


https://youtu.be/oJt3Ln8H03s

Omni-directional LSD-SLAM



https://youtu.be/v0NqMm7Q6S8

ROBOT INTELLIGENCE LAB

Monocular Visual SLAM

"Real-Time 6-DOF Monocular Visual SLAM in a Large-Scale Environment," 2014 (SNU)

Monocular Visual SLAM

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- "Real-Time 6-DOF Monocular Visual SLAM in a Large-Scale Environment," 2014 (SNU)
  - It continuously computes the current 6-DOF camera pose and 3D landmark position from a monocular video sequence.
  - A binary **feature descriptor** (FAST detector + BRIEF descriptor) is used for low-cost computation and metric-topological mapping is presented.
  - It considers loop-closure which is the key challenge for real-time visual SLAM in a large-scale environment.

Monocular Visual SLAM

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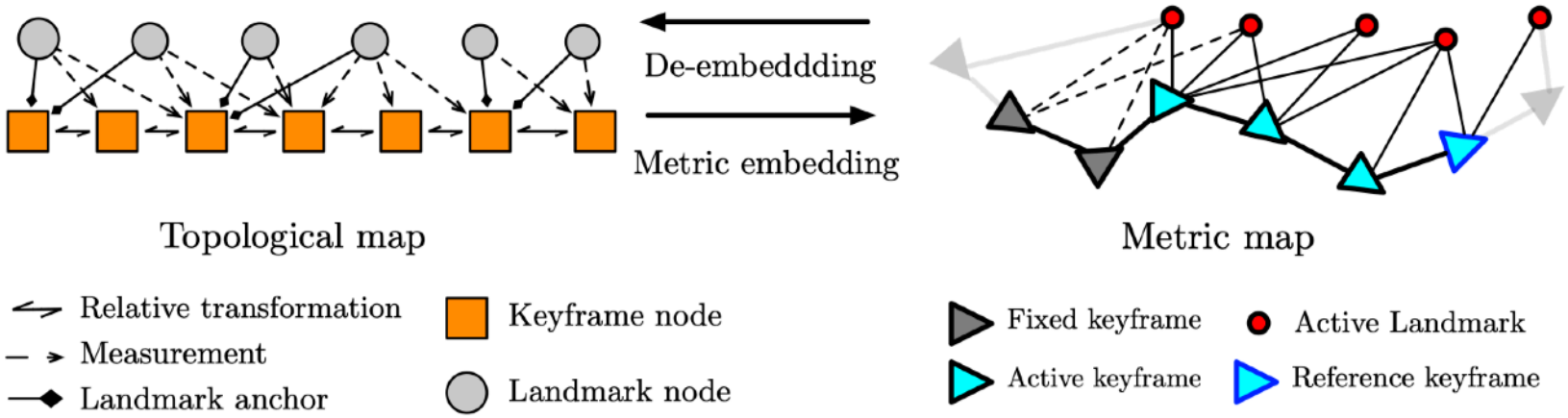
- Outline of the Algorithm
  - **Feature** extraction (BRIEF)
  - Feature tracking - Associate new features to previous extracted features.
  - Keyframe addition - Add a keyframe if the number of tracked features is small or the motion of the camera is larger than a threshold.
  - Pose computation - If enough number of features are matched to the most recent keyframe, the relative pose of the current frame is computed by **RANSAC**.

Monocular Visual SLAM

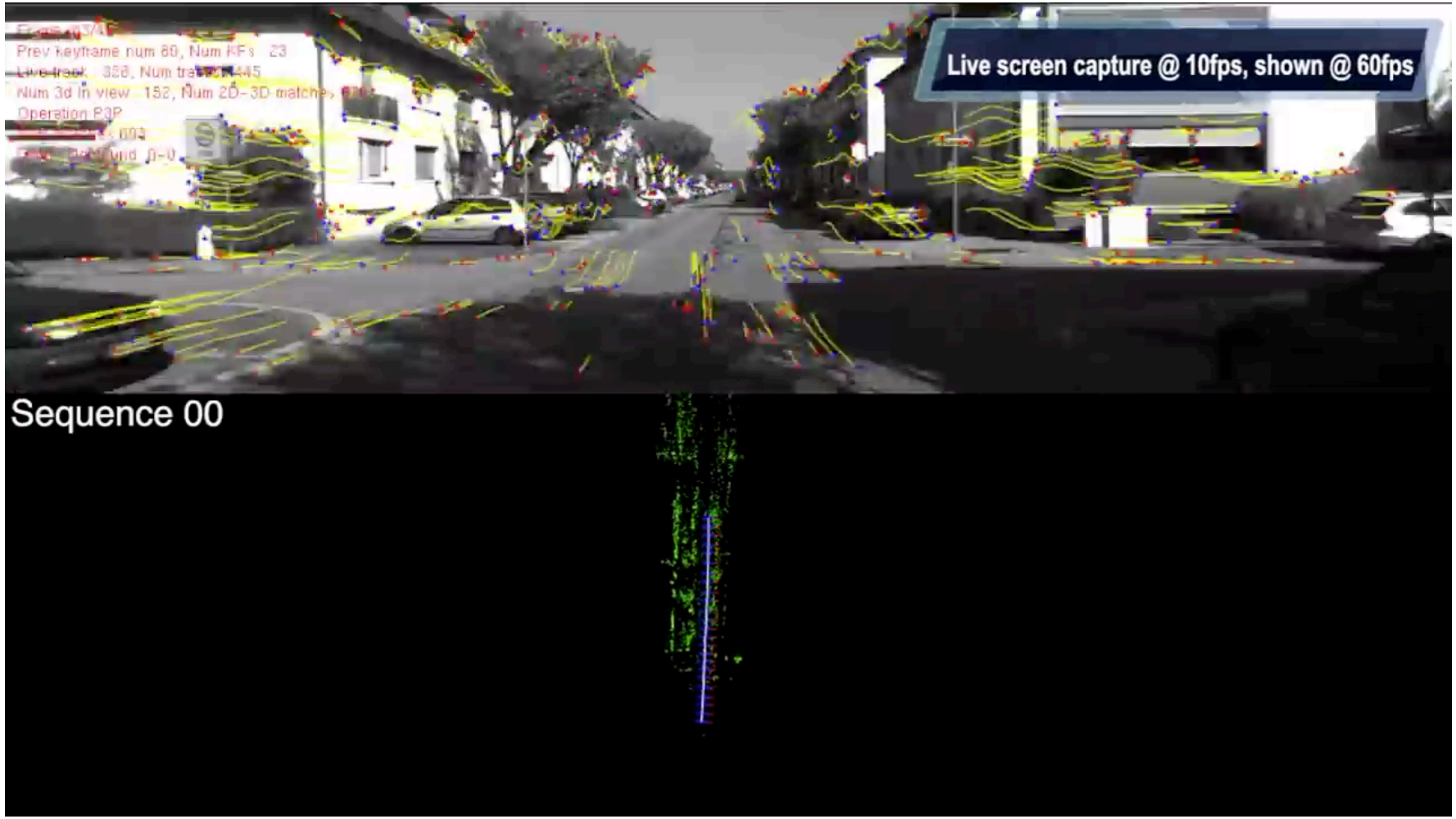
ROBOT INTELLIGENCE LAB

- **Metric-topological map**
  - The **topological** map only stores relative information in edges while the **metric** map contains the location of nodes (for loop closure).
  - As the **topological** map lacks the metric information for optimization, a metric embedding operation is performed.



Monocular Visual SLAM

ROBOT INTELLIGENCE LAB



https://youtu.be/JyG1EeqCmHY

ROBOT INTELLIGENCE LAB

SVO

"SVO: Fast Semi-Direct Monocular Visual Odometry," 2014 (UZH)

SVO

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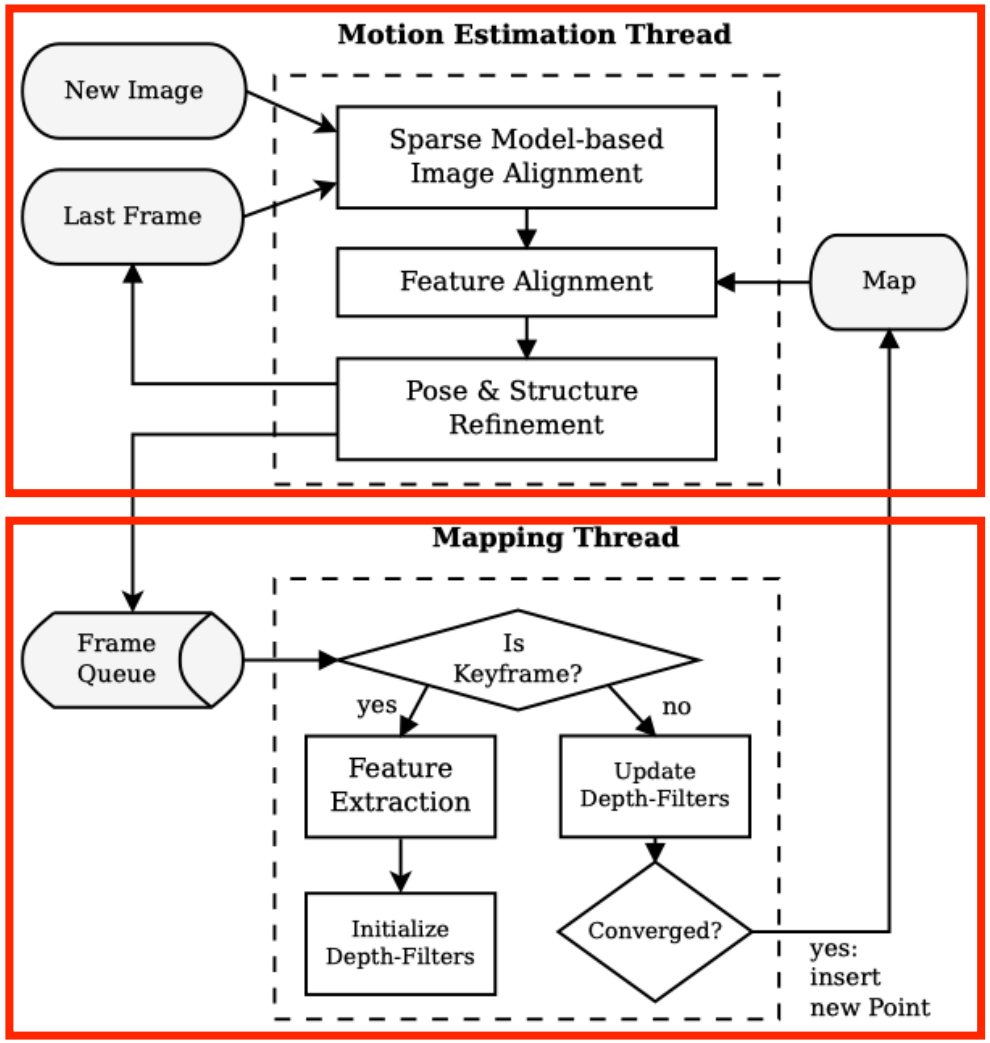
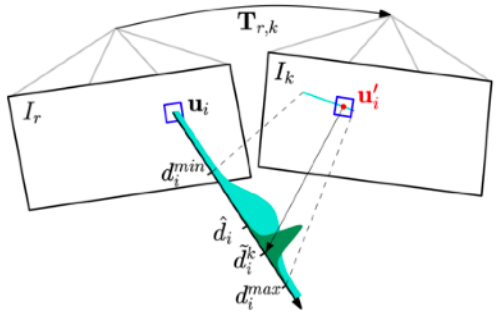
- "SVO: Fast Semi-Direct Monocular Visual Odometry," 2014 (UZH)
  - SVO eliminates the need of costly **feature** extraction and robust matching for motion estimation.
  - It operates **directly** on pixel intensities, which results in sub-pixel precision at high frame-rates with probabilistic mapping methods.
  - SVO uses feature-correspondences, but it is an implicit result of direct motion estimation rather than of explicit feature extraction and matching.
  - Thus, feature extraction is only required for initializing new 3D points.

SVO



The camera pose relative to the previous frame is found through minimizing the photometric error between patches.

The depth of 2D features is estimated.



SVO

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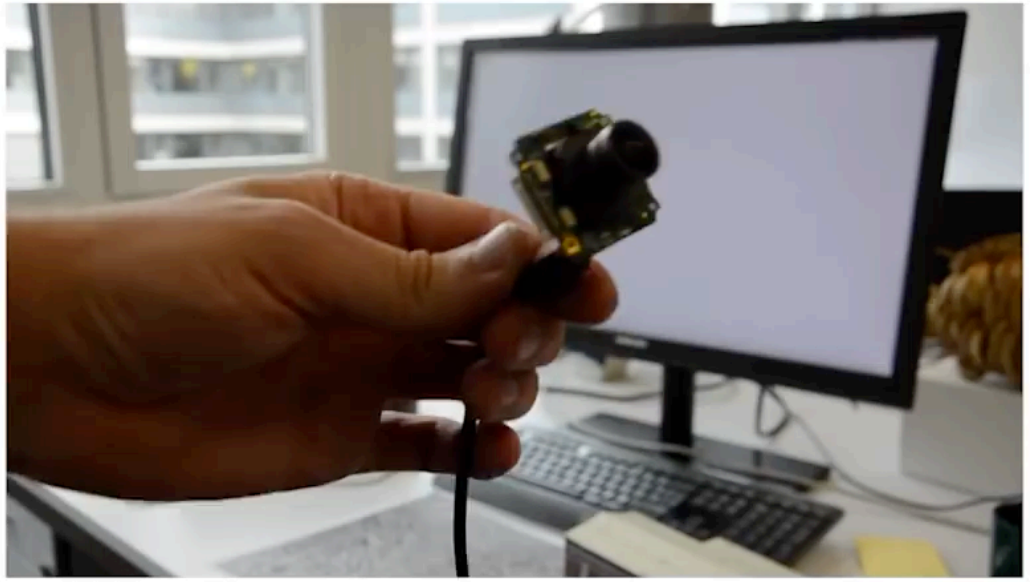

https://youtu.be/2YnIMfw6bJY

ROBOT INTELLIGENCE LAB

DynamicFusion

"DynamicFusion: Reconstruction and Tracking of Non-rigid Scenes in Real-Time," 2015

DynamicFusion

ROBOT INTELLIGENCE LAB

- "DynamicFusion: Reconstruction and Tracking of Non-rigid Scenes in Real-Time," 2015
  - It presents the first dense SLAM system capable of reconstruction non-rigidly deforming scenes in real-time by fusing together RGBD scans.
  - DynamicFusion reconstructs scene geometry while simultaneously estimating a dense volumetric 6D motion field that warps the estimated geometry into a live frame.

DynamicFusion

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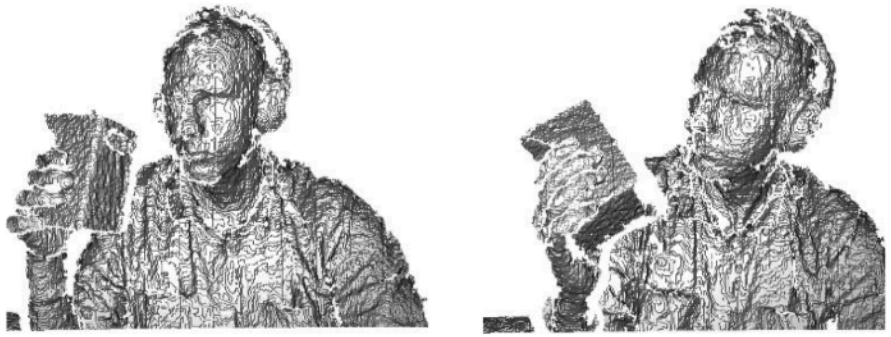
(a) Initial Frame at $t = 0s$



(b) Raw (noisy) depth maps for frames at $t = 1s, 10s, 15s, 20s$

(c) Node Distance

(d) Canonical Model

(e) Canonical model warped into its live frame

(f) Model Normals

DynamicFusion

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Live Input Depth Map

Live Model Output

Live RGB Image (unused)

Canonical Model Reconstruction

Warped Model

https://youtu.be/i1eZekcc_lM

ROBOT INTELLIGENCE LAB

ORB-SLAM

"ORB-SLAM: a Versatile and Accurate Monocular SLAM System," 2015

ORB-SLAM

ROBOT INTELLIGENCE LAB

- "ORB-SLAM: a Versatile and Accurate Monocular SLAM System," 2015
  - It presents a **feature**-based monocular SLAM system that operates in real time in versatile environments.
  - It is built on the main ideas of **PTAM**.
  - ORB-SLAM uses the same features for all SLAM tasks: tracking, mapping, re-localization, and loop closing.
  - **ORB feature (binary) descriptor** [1] is used (which is rotation invariant and resistant to noise and faster than SIFT or SURF).

ORB-SLAM

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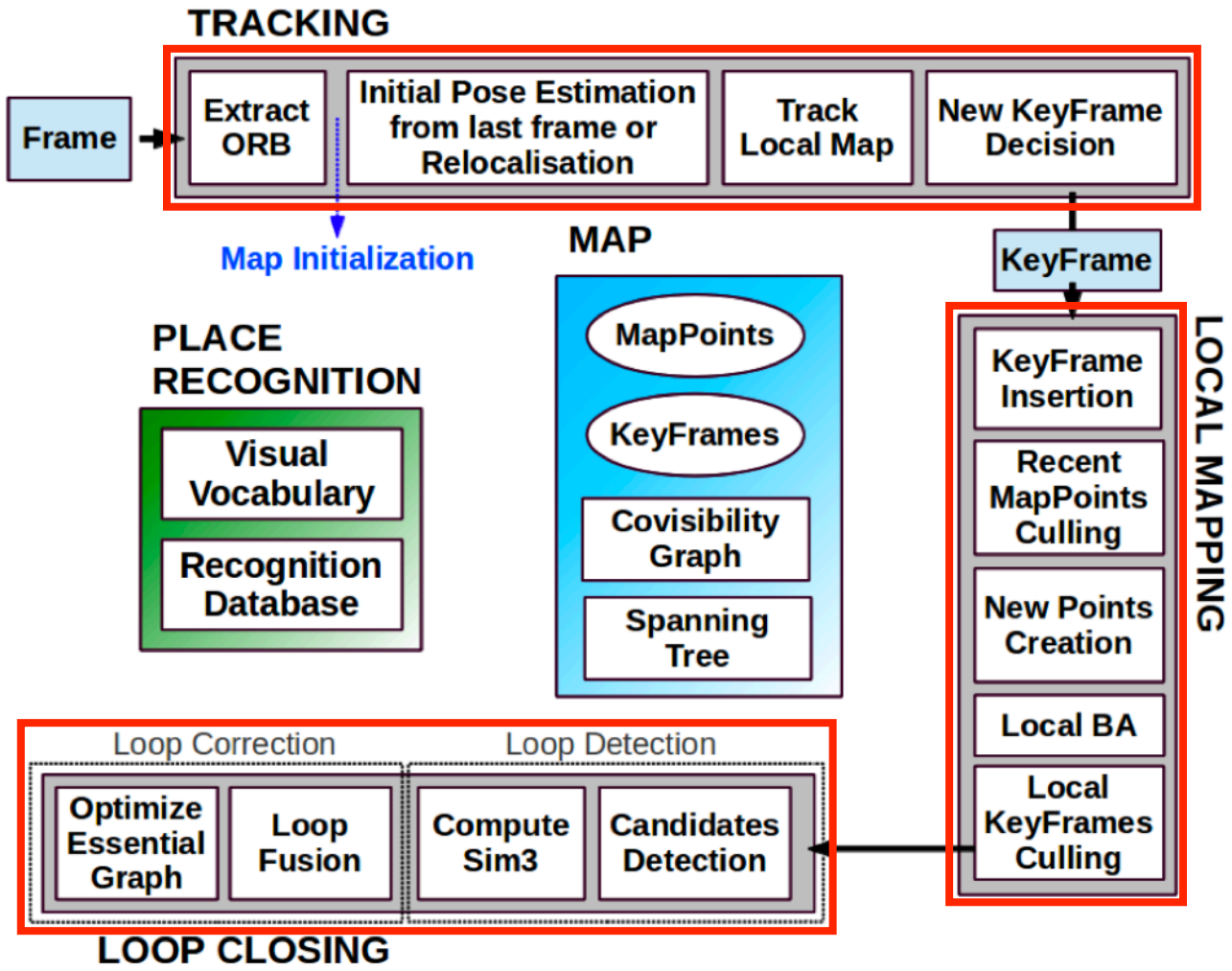
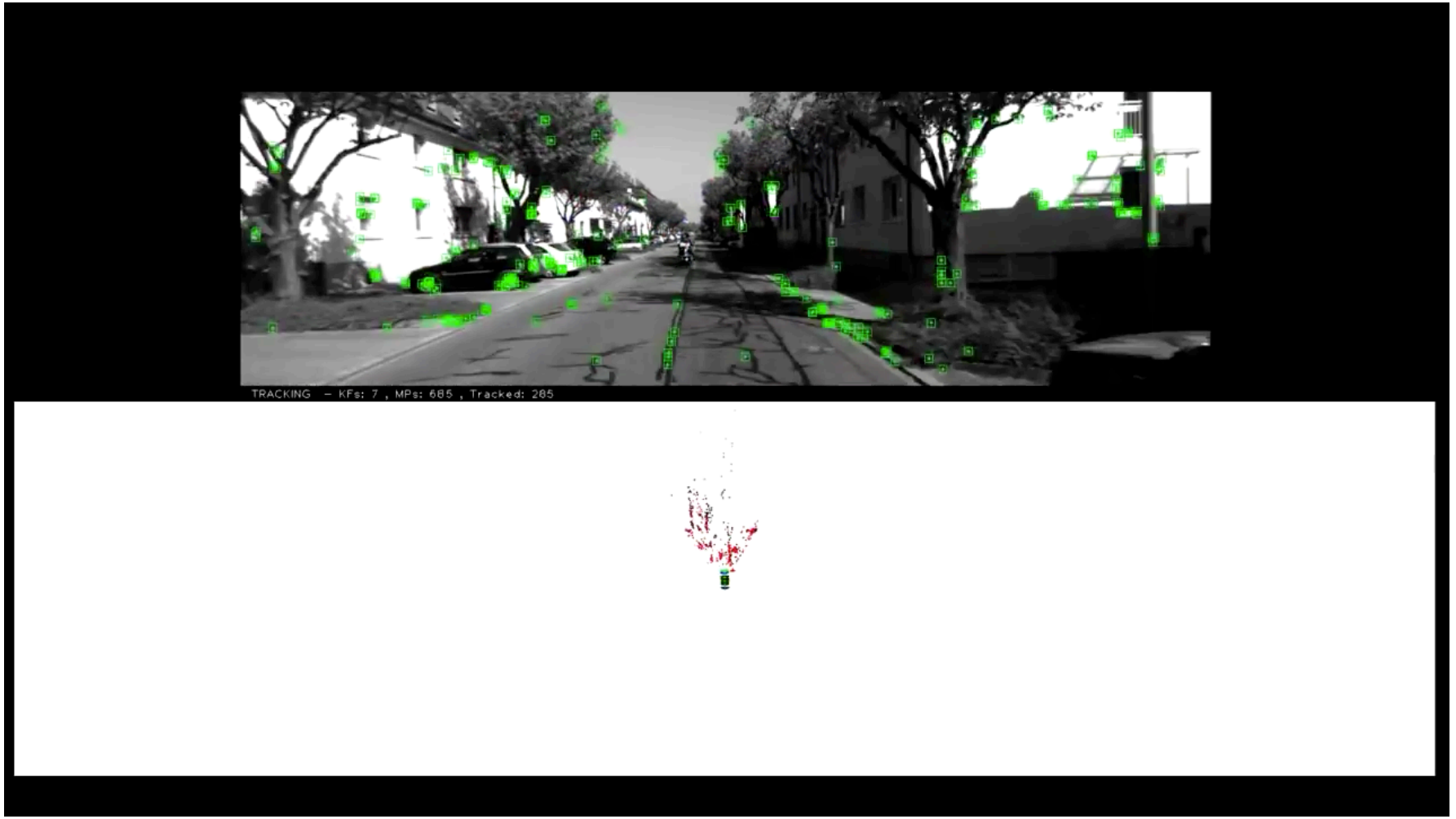
- Main contributions
  - Use of the same **features** (ORB features).
  - Real time loop closing based on the Essential Graph.
  - Real time camera relocalization.
  - Novel initialization technique.

ORB-SLAM



- Three threads:
  - Tracking
  - Local Mapping
  - Loop Closing
- It outperforms **PTAM** (indirect) and **LSD-SLAM** (direct).

ORB-SLAM



https://youtu.be/8DISRmsO2YQ

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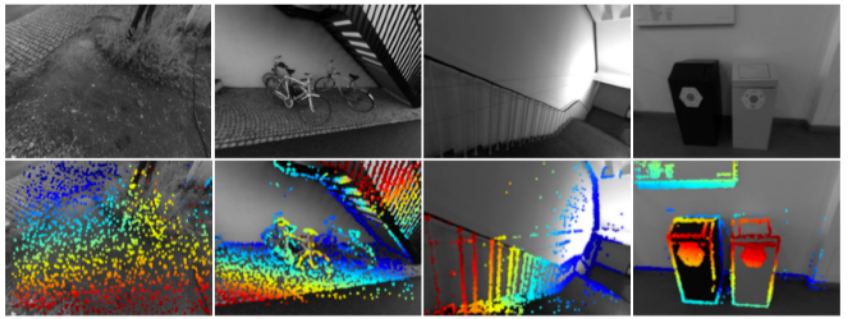
Direct Sparse Odometry

"Direct Sparse Odometry," 2016 (TUM)

Direct Sparse Odometry

ROBOT INTELLIGENCE LAB

- "Direct Sparse Odometry," 2016 (TUM)
  - **Direct** (feature-less) vs. Indirect and Sparse vs.Dense
    - Sparse+Indirect: Most widely-used, estimating 3D geometry from a set of key-point matches (monoSLAM, PTAM, ORB-SLAM)
    - Dense+Indirect: Estimate 3D geometry from a dense optical flow field.
    - Dense+**Direct**: Employs a photometric error with a geometric prior (DTAM, LSD-SLAM)
    - Sparse+**Direct**: The one proposed here.
  - Same author of LSD-SLAM (**direct**).



Example depth maps used for initial frame tracking.

Direct Sparse Odometry

- Why **direct** and sparse?
  - **Direct**: Whereas one of the main benefits of key-points (indirect) is their robustness, direct methods does not require a point to be recognizable by itself, hence allows a more finely grained geometry representation (e.g., pixel-wise inverse depth).
  - Sparse: Less restrictive to geometric prior.
- Unlike SVO that takes hybrid approaches (semi-direct), it is the first fully direct method that jointly optimizes camera poses, camera intrinsics, and geometry parameters (inverse depth).

Direct Sparse Odometry

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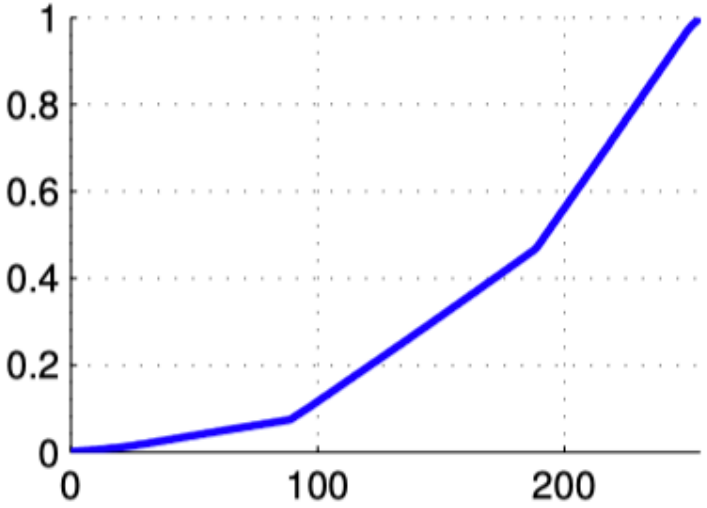
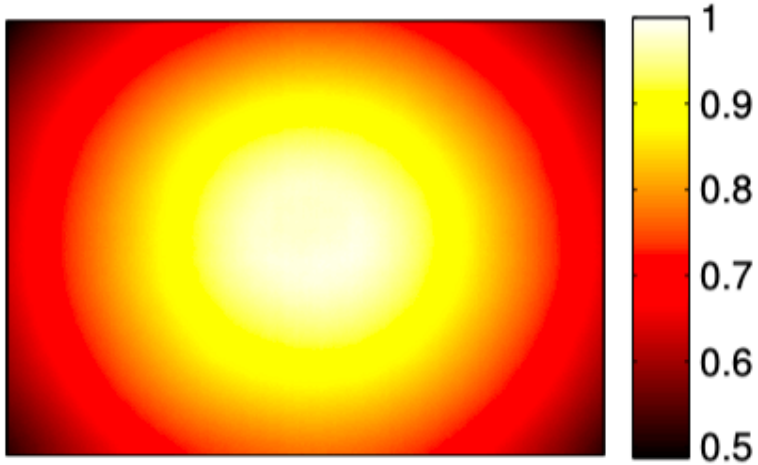
- Photometric Calibration
  - DSO leverages extensive photometric calibration to achieve fully-Direct SLAM.



Inverse response function G^{-1}
(pixel intensity $[0,255]$ to $[0,1]$)



Lens attenuation model
$V : \Omega \rightarrow [0,1]$

Direct Sparse Odometry

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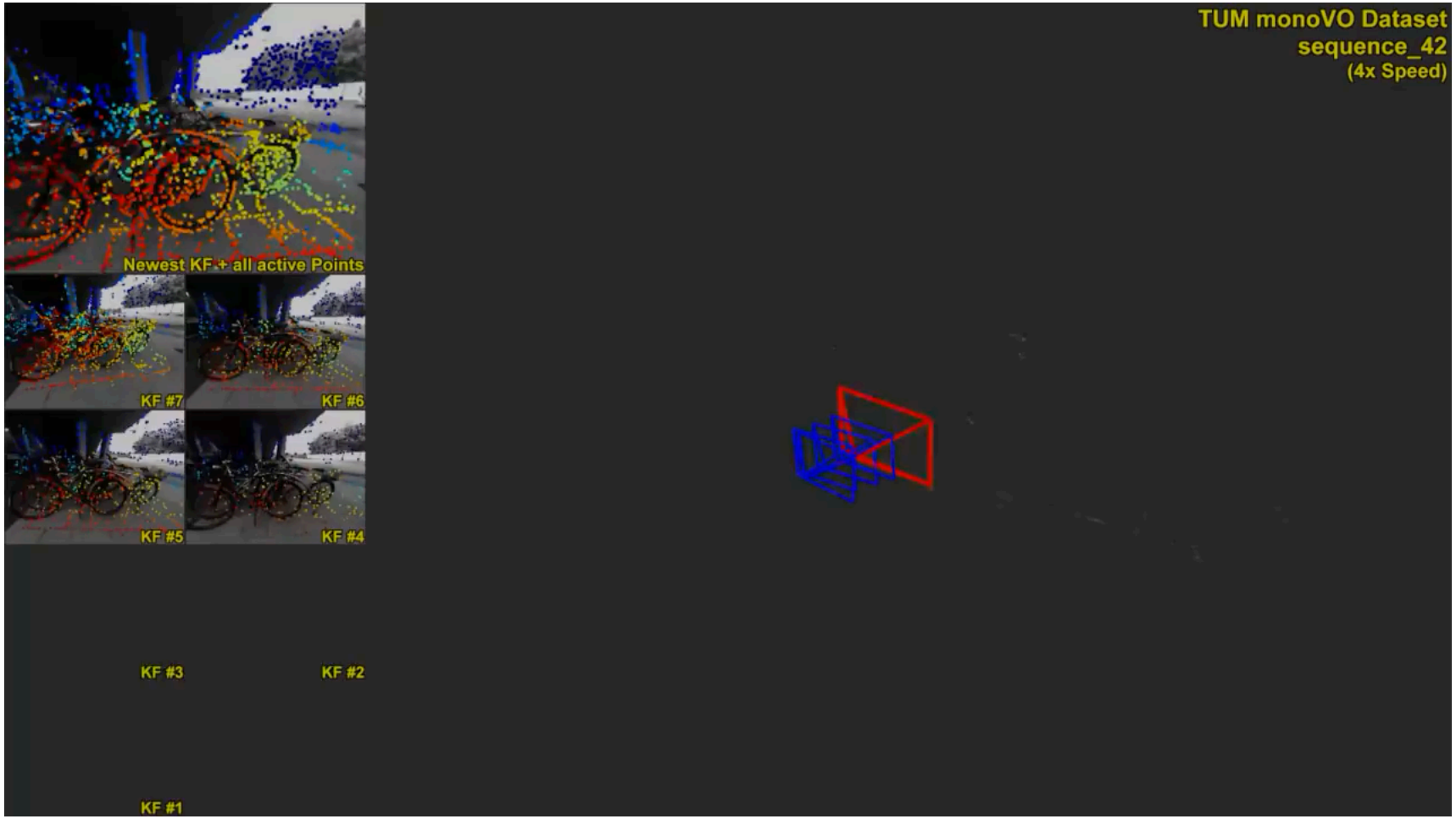


https://youtu.be/C6-xwSOOdqQ

ROBOT INTELLIGENCE LAB

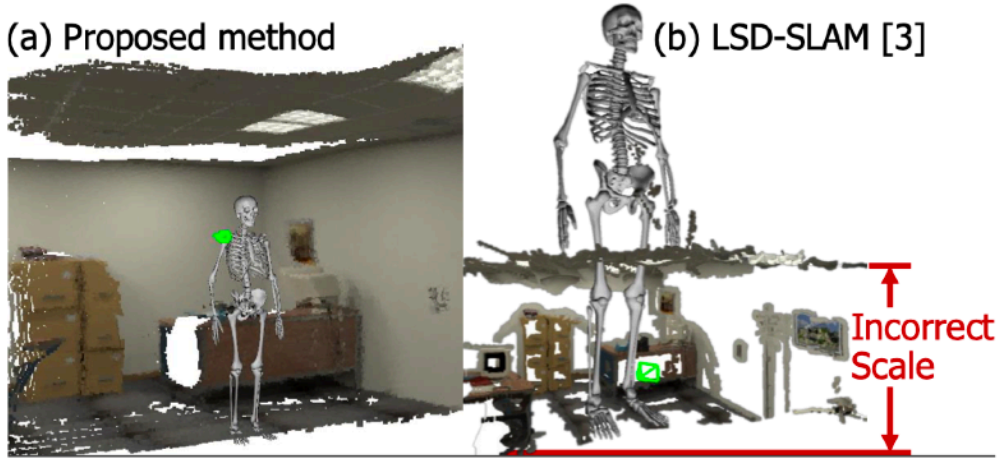
CNN-SLAM

"CNN-SLAM: Real-time dense monocular SLAM with learned depth prediction," 2017

CNN-SLAM

ROBOT INTELLIGENCE LAB

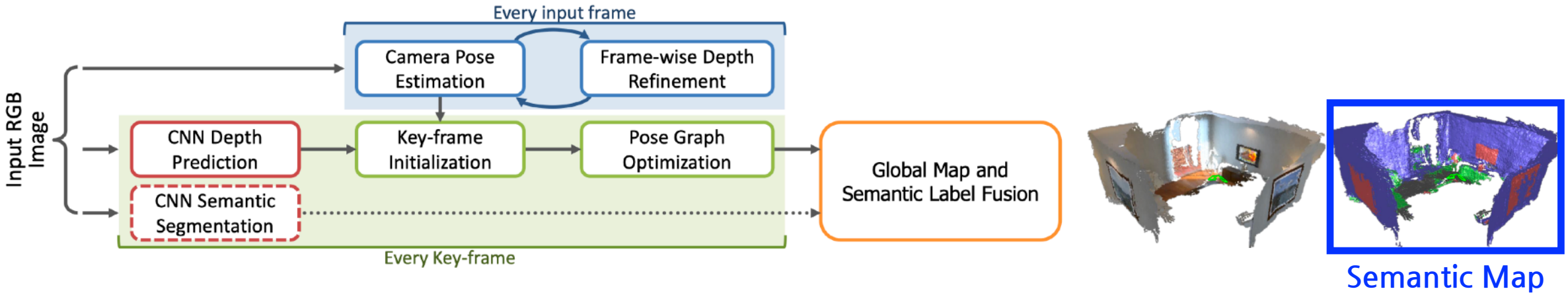
- "CNN-SLAM: Real-time dense monocular SLAM with learned depth prediction," 2017
  - This paper investigates how predicted depth maps (from CNN) can be deployed from accurate and dense monocular reconstruction.
  - CNN-predicted dense depth maps are fused with depth measurements obtained from direct monocular SLAM overcoming existing limitations (e.g., low-textured regions).
  - The use of depth prediction enables better absolute scale estimations.



CNN-SLAM

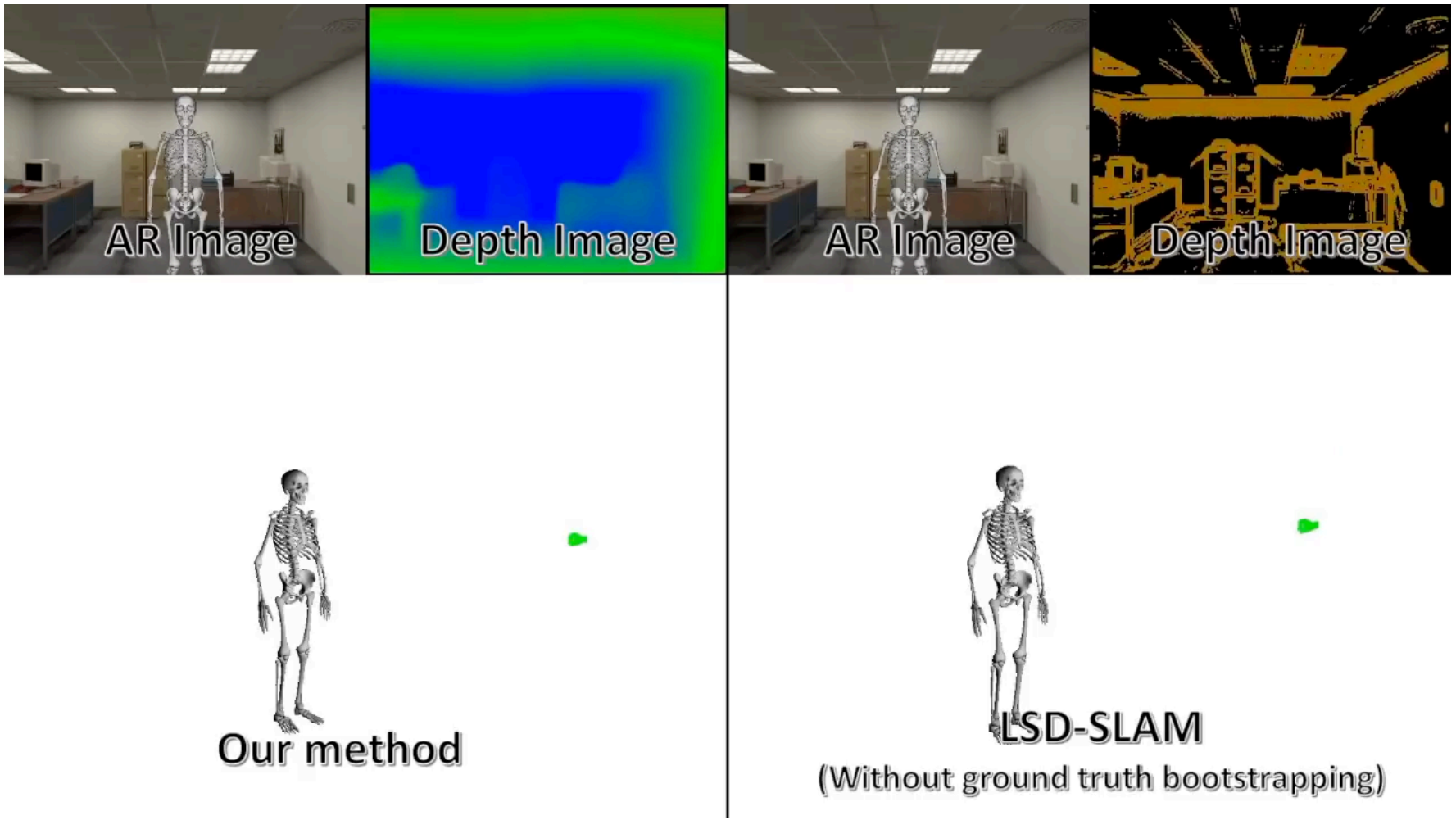
ROBOT INTELLIGENCE LAB

- It also fuses semantic labels from Semantic Segmentation yielding semantically coherent scene reconstruction from a single view.
- CNN-SLAM shows superior performances compared to LSD-SLAM and ORB-SLAM with respect to estimating the absolute scale.



CNN-SLAM

ROBOT INTELLIGENCE LAB



https://youtu.be/z_NJxbkQnBU

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ORB-SLAM2

"ORB-SLAM2: an Open-Source SLAM System for Monocular, Stereo and RGB-D Cameras," 2017

ORB-SLAM2

ROBOT INTELLIGENCE LAB

- "ORB-SLAM2: an Open-Source SLAM System for Monocular, Stereo and RGB-D Cameras," 2017
  - This work presents a complete SLAM system for monocular, stereo and RGB-D cameras, including map reuse, loop closing and re-localization capabilities and works in real-time on standard CPUs.
  - It is the first open-source SLAM system for monocular, stereo, and RGB-D cameras.
  - Of course, ORB-SLAM2 also leverages ORB features.

ORB-SLAM2

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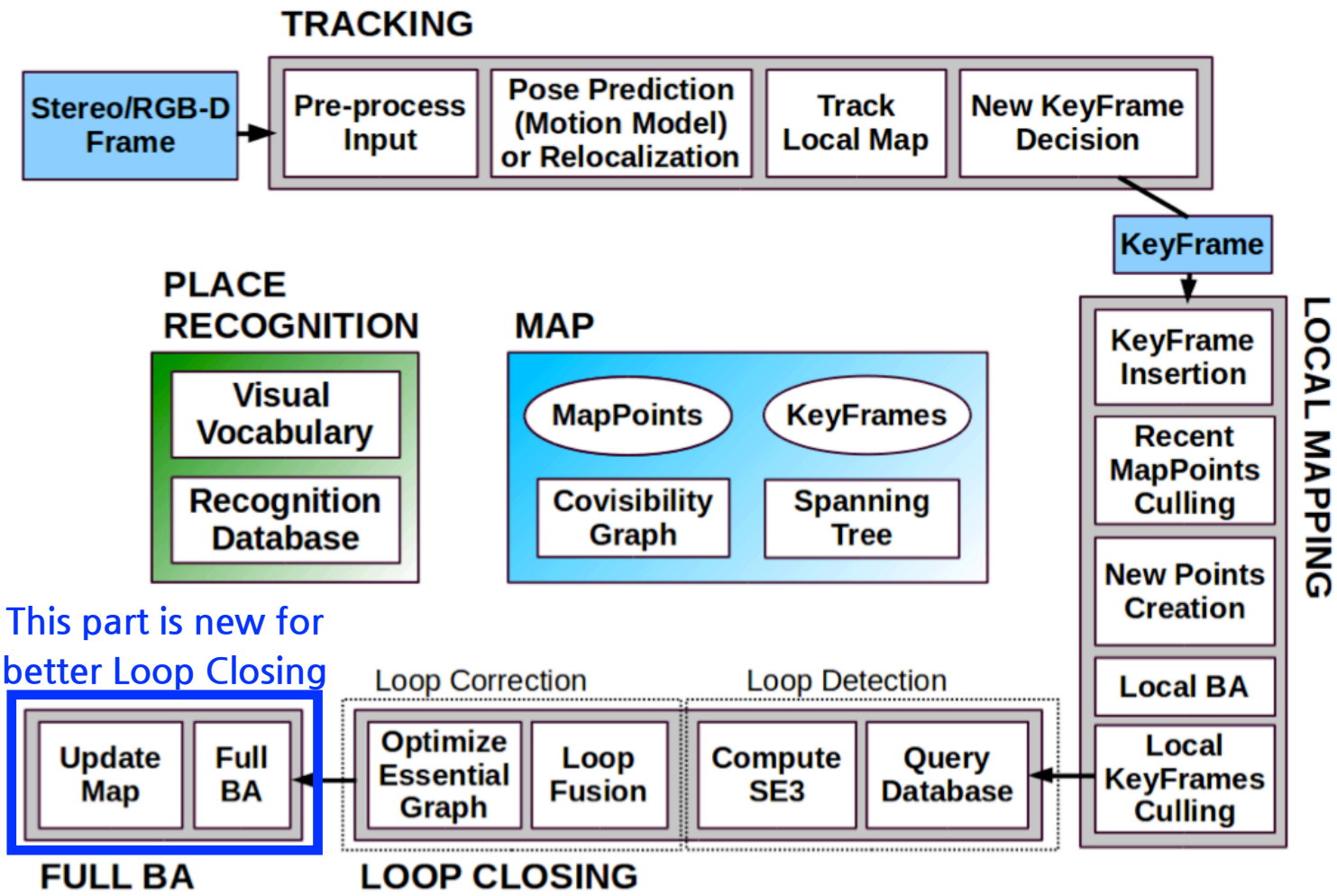

ORB-SLAM2

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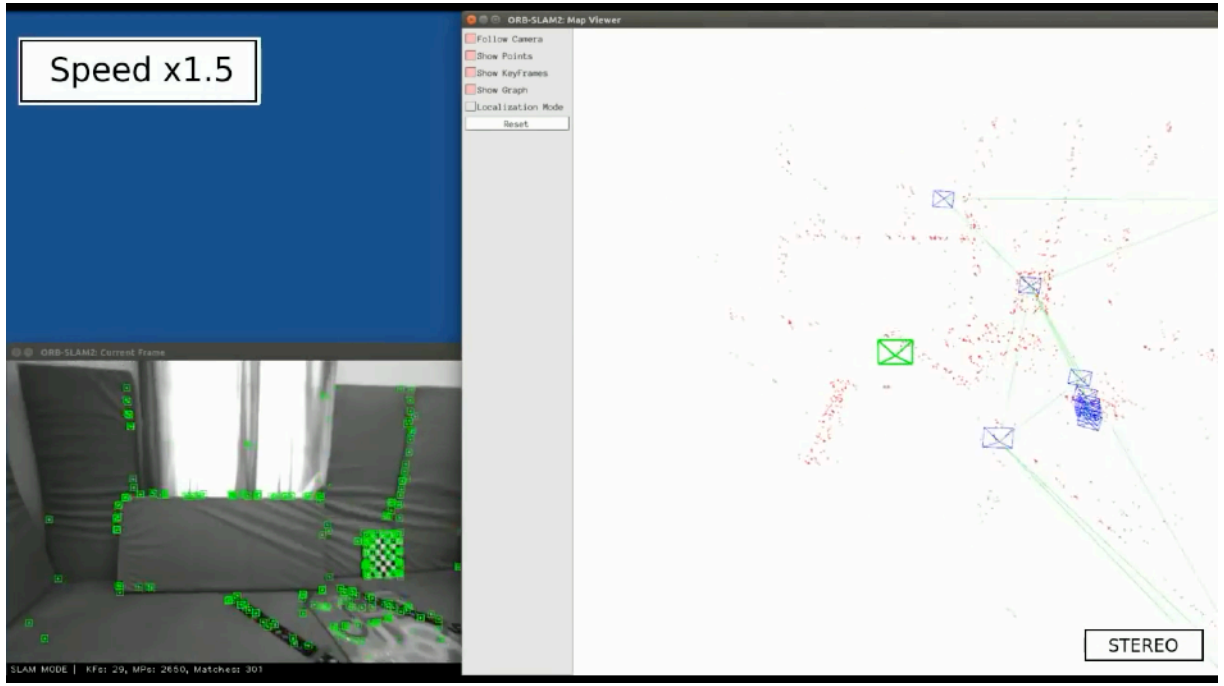
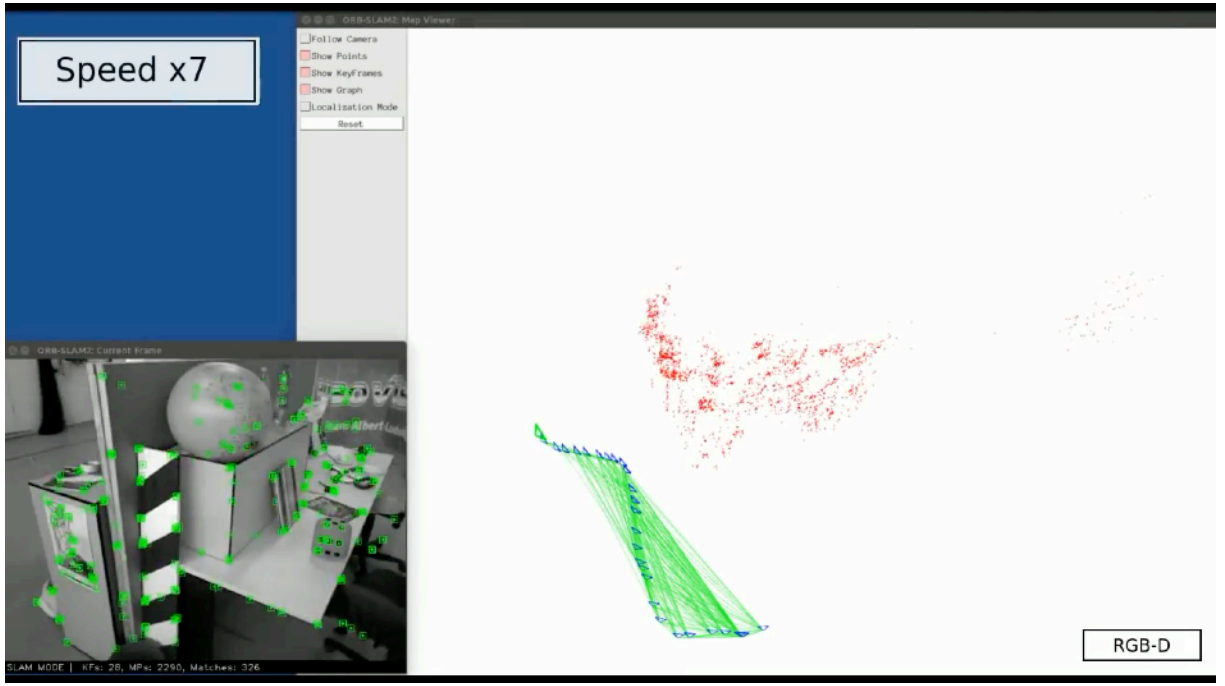


Stereo Camera



RGBD Camera

ORB-SLAM2

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Dense RGB-D reconstruction **without** any fusion.

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ProSLAM

"ProSLAM: Graph SLAM from a Programmer's Perspective," 2017

ProSLAM

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- "ProSLAM: Graph SLAM from a Programmer's Perspective," 2017
  - It presents a lightweight stereo visual SLAM system designed with simplicity in mind highlighting the data structures and the algorithmic aspects.
  - **Feature** based SLAM: FAST detector + BRIEF descriptor
  - Eigen (matrix calculation), OpenCV (feature extraction), g2o (pose graph optimization)

ProSLAM

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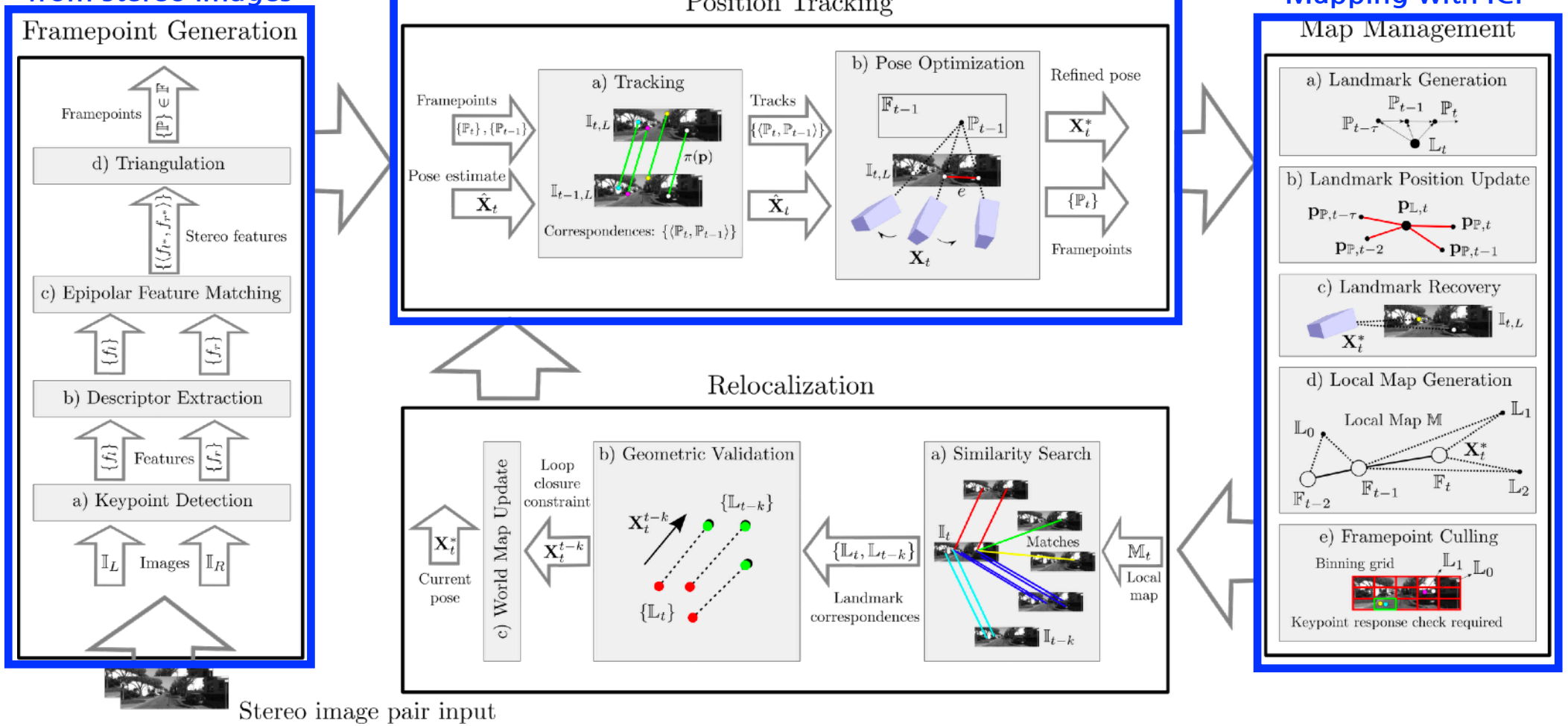
Generate 3D point cloud from stereo images

Camera position tracking

Mapping with ICP



ProSLAM

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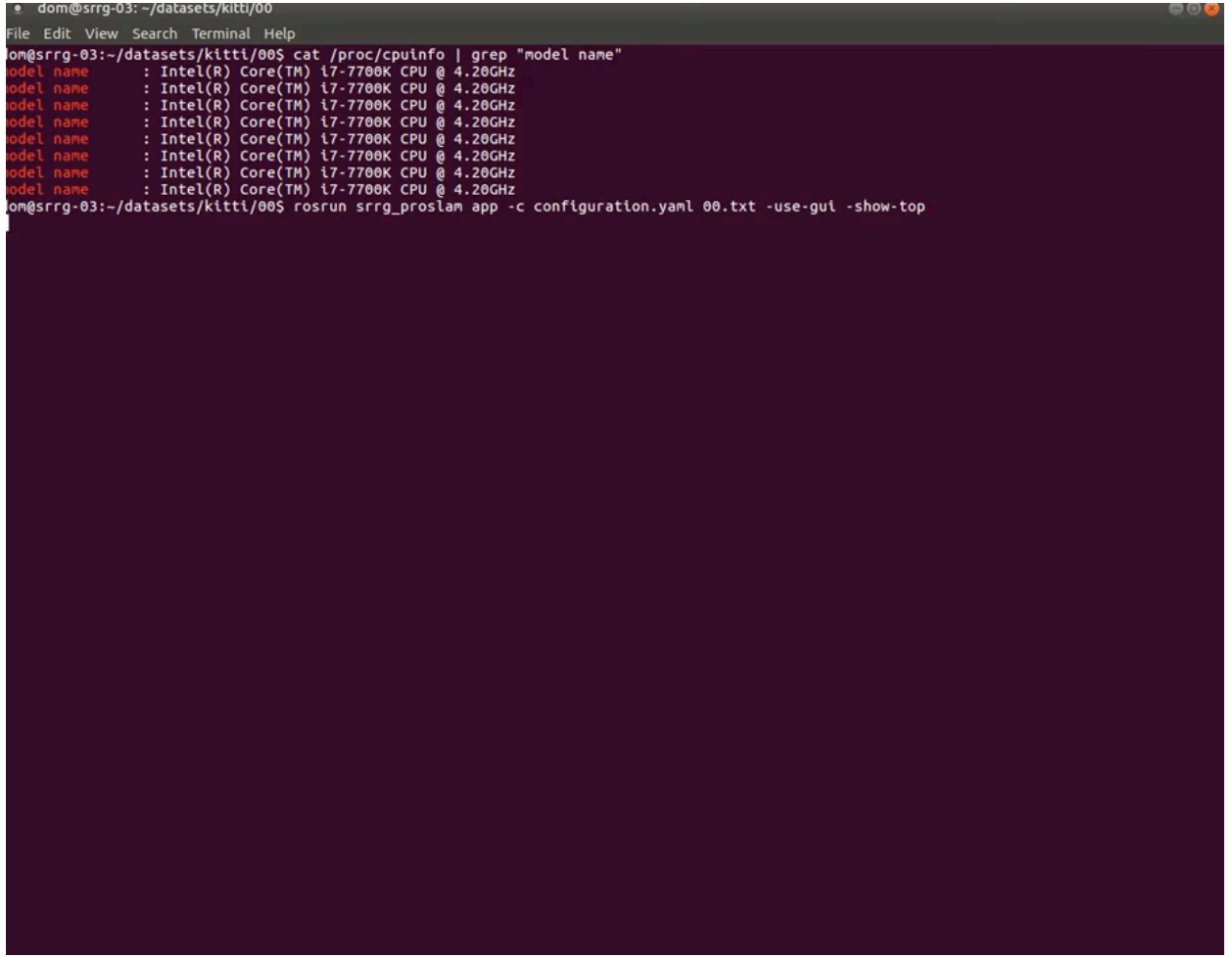

✦ **ProSLAM** outperformed **LSD-SLAM** in 7/11 and **ORB-SLAM2** in 3/11 cases in KITTI SLAM evaluation.

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Geometric Deep SLAM

"Toward Geometric Deep SLAM," 2017

Geometric Deep SLAM

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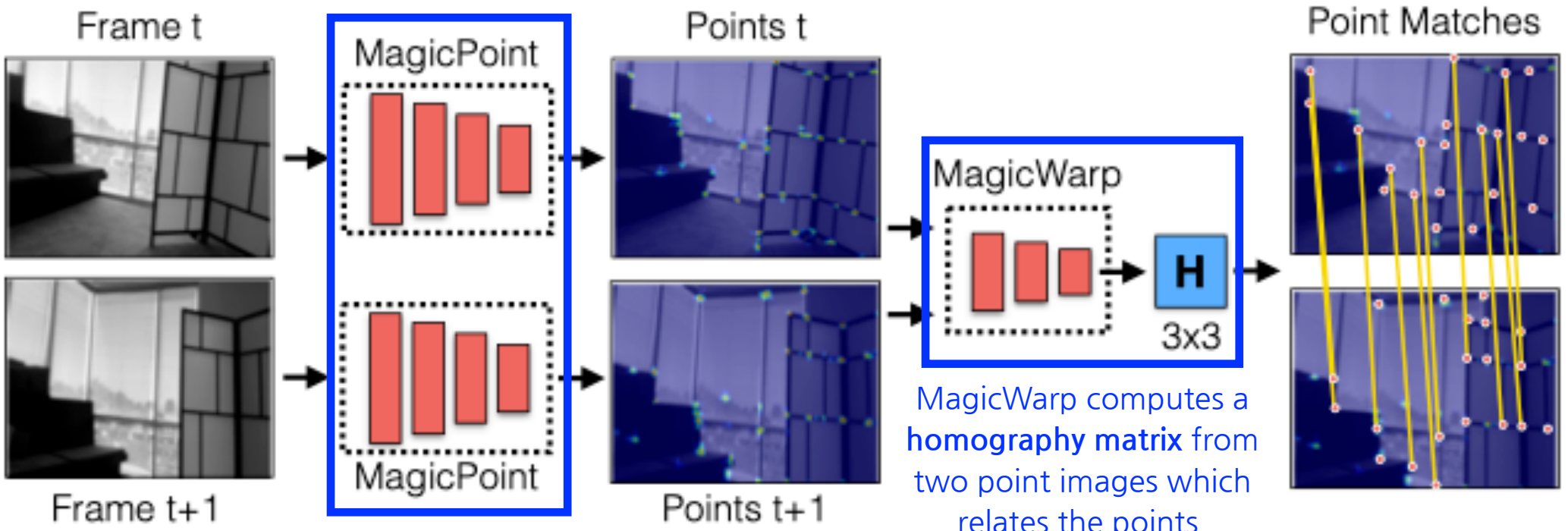
- "Toward Geometric Deep SLAM," 2017
  - It presents a point tracking system by two deep CNNs:
    - **MagicPoint** extracts salient 2D points on single images
    - **MagicWarp** estimates the homography from the pairs of point images (output of MagicPoint).
  - It shows its robustness in the presence of image noise and runs 30+ FPS on a single CPU as it is free from local point descriptors.

Geometric Deep SLAM

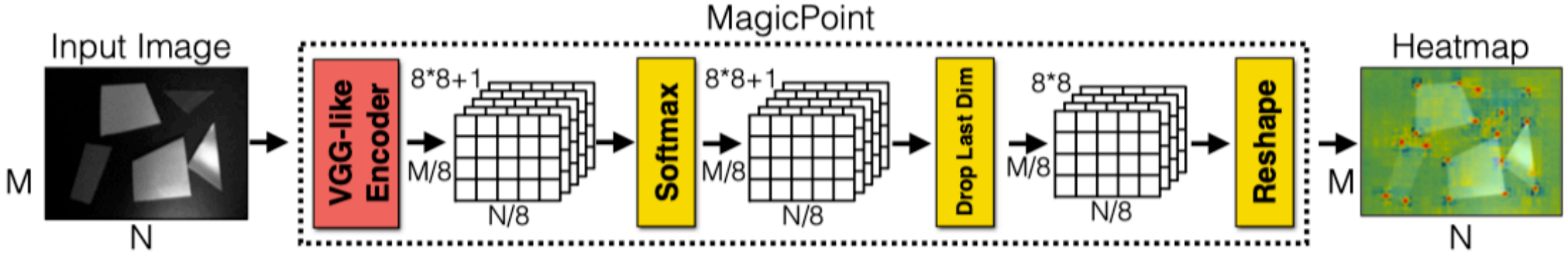
ROBOT INTELLIGENCE LAB



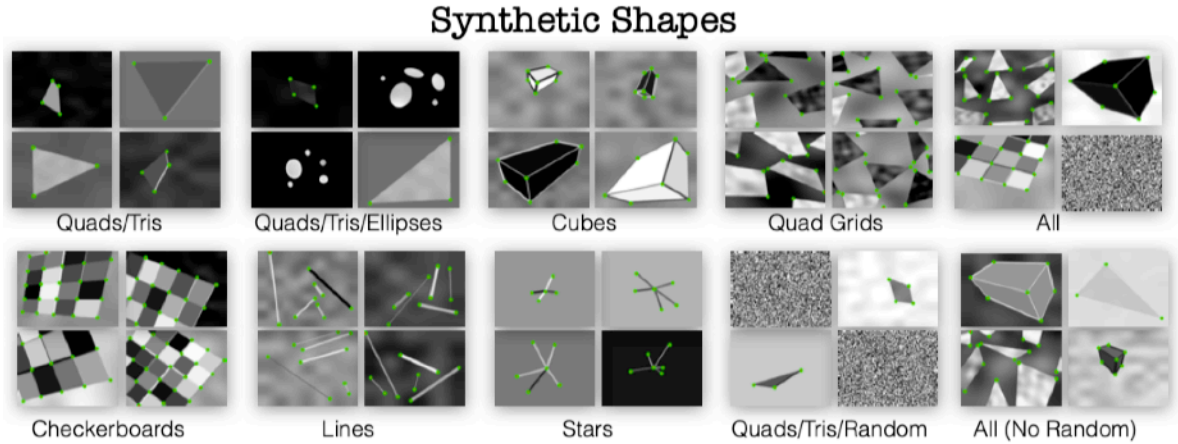
Magic Point is trained to detect salient corners in the image.

MagicWarp computes a **homography matrix** from two point images which relates the points.

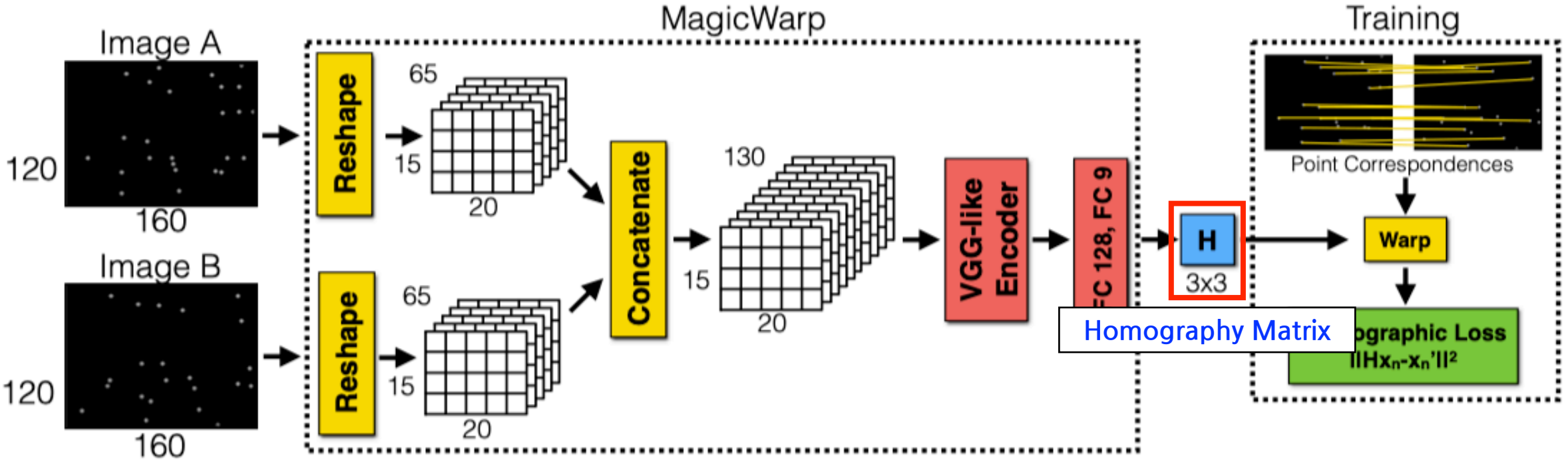
Geometric Deep SLAM



- **MagicPoint** is trained with synthetic dataset to output a "point-ness" probability for each pixel (corner detection).



Geometric Deep SLAM



- **MagicWarp** is optimized to estimate the **homography matrix** by minimizing the **Homographic Loss**.

Super Glue

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- Geometric Deep SLAM does not have a video available. Following is **SuperGlue** from the same author:

https://github.com/magicleap/SuperGluePretrainedNetwork

Thank You