Lecture 10.1
Introduction to Visual SLAM

Trym Vegard Haavardsholm

What is SLAM?

What is SLAM?

Simultaneous localization and mapping

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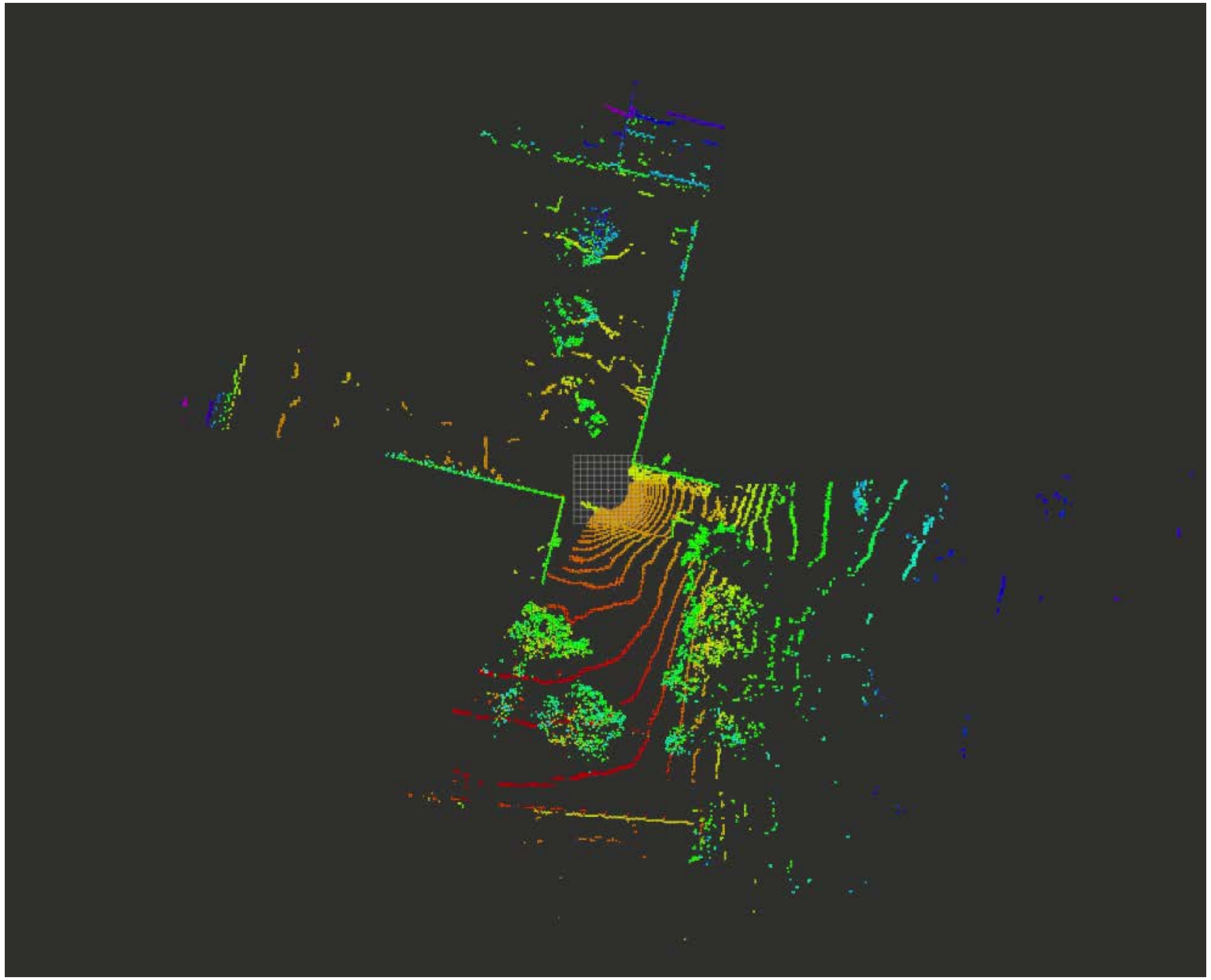
Simultaneous localization and mapping



Simultaneous

- estimation of the state of a robot using on-board sensors
- construction of a map of the environment that the sensors are perceiving

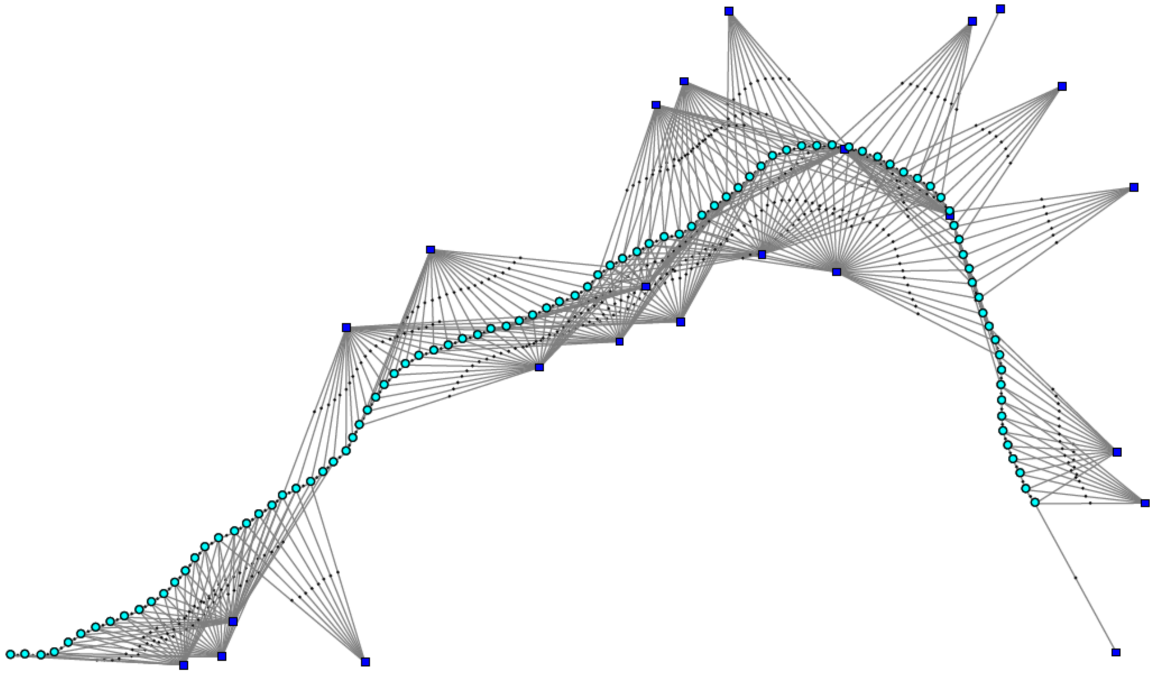
What is SLAM?

Simultaneous localization and mapping

Simultaneous

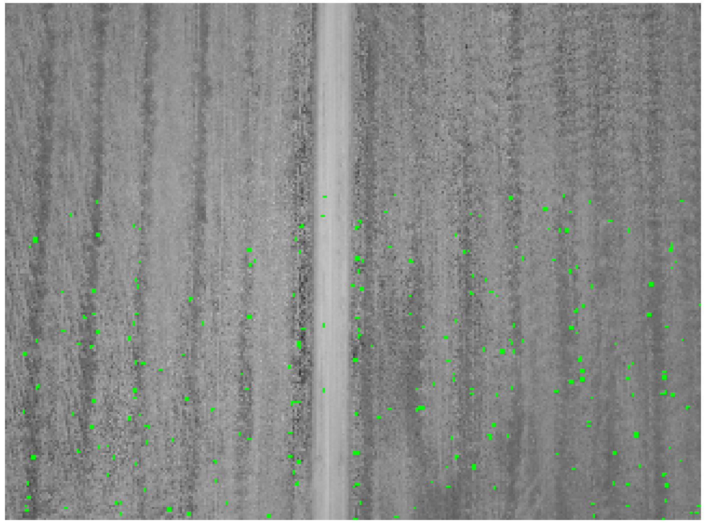
- **mapping**:
  Continuously expanding
  and optimizing a consistent map
  while exploring the environment

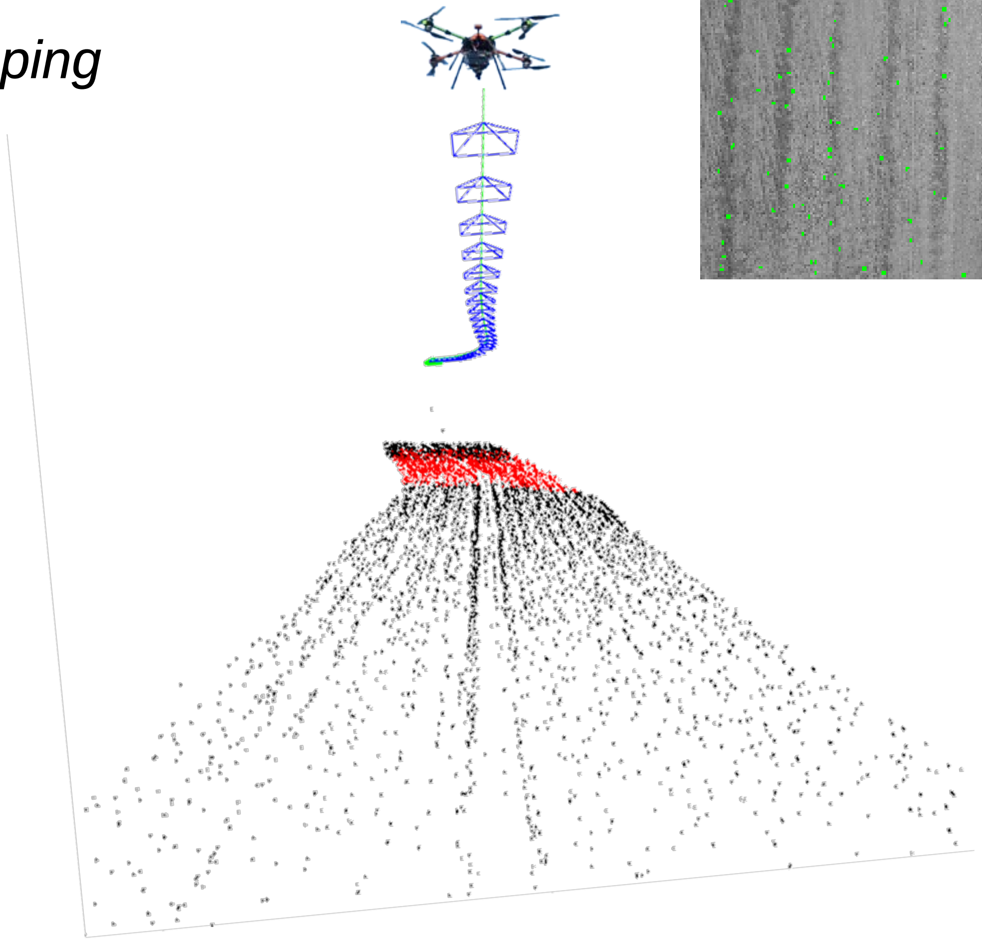
- **localization**:
  Localization within the map



What is Visual SLAM?

Visual simultaneous localization and mapping



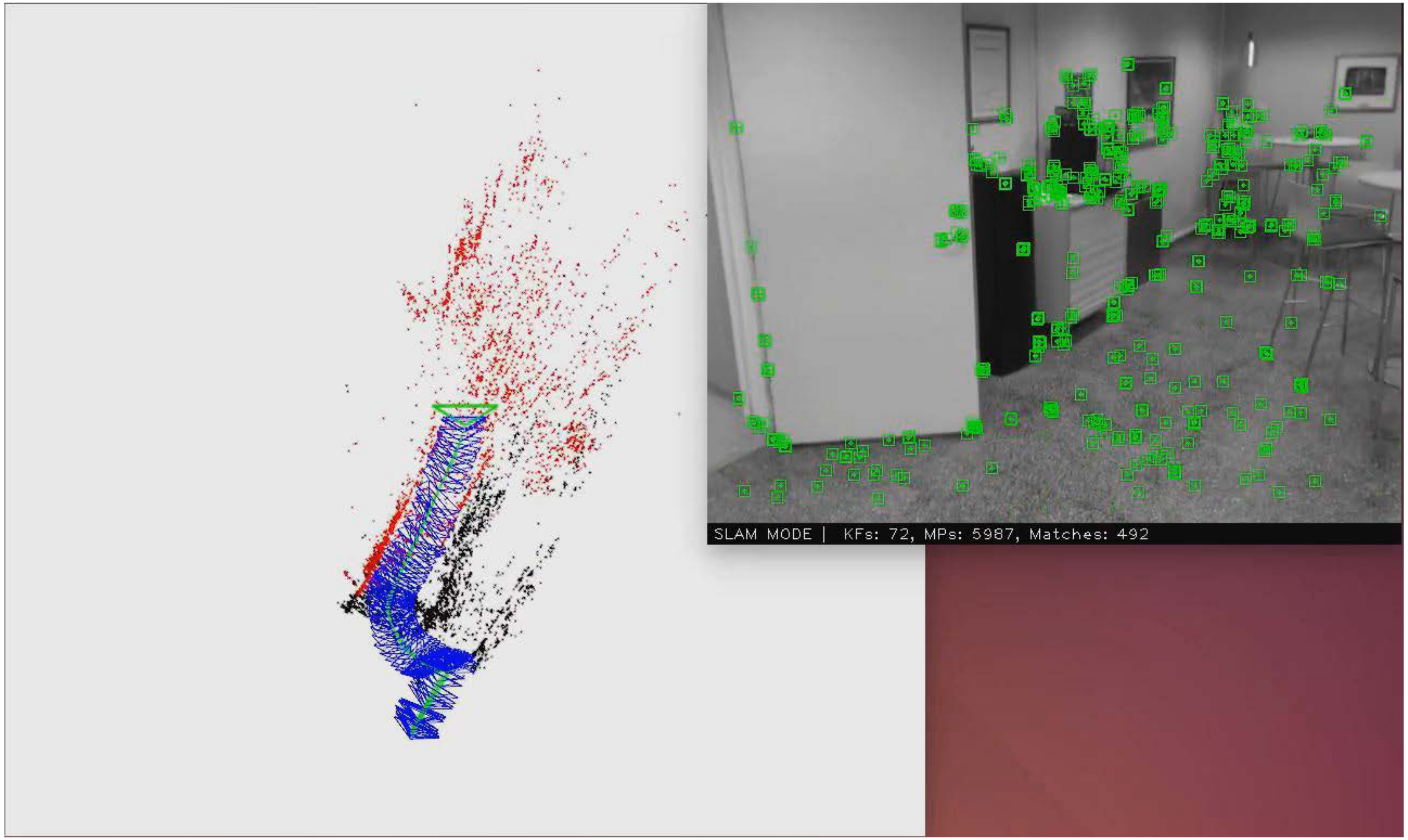


Simultaneous

- **mapping**:
  Continuously expanding
  and optimizing a consistent map
  while exploring the environment

- **localization (tracking)**:
  Localization within the map
  (tracking the map in image frames)

Visual SLAM example



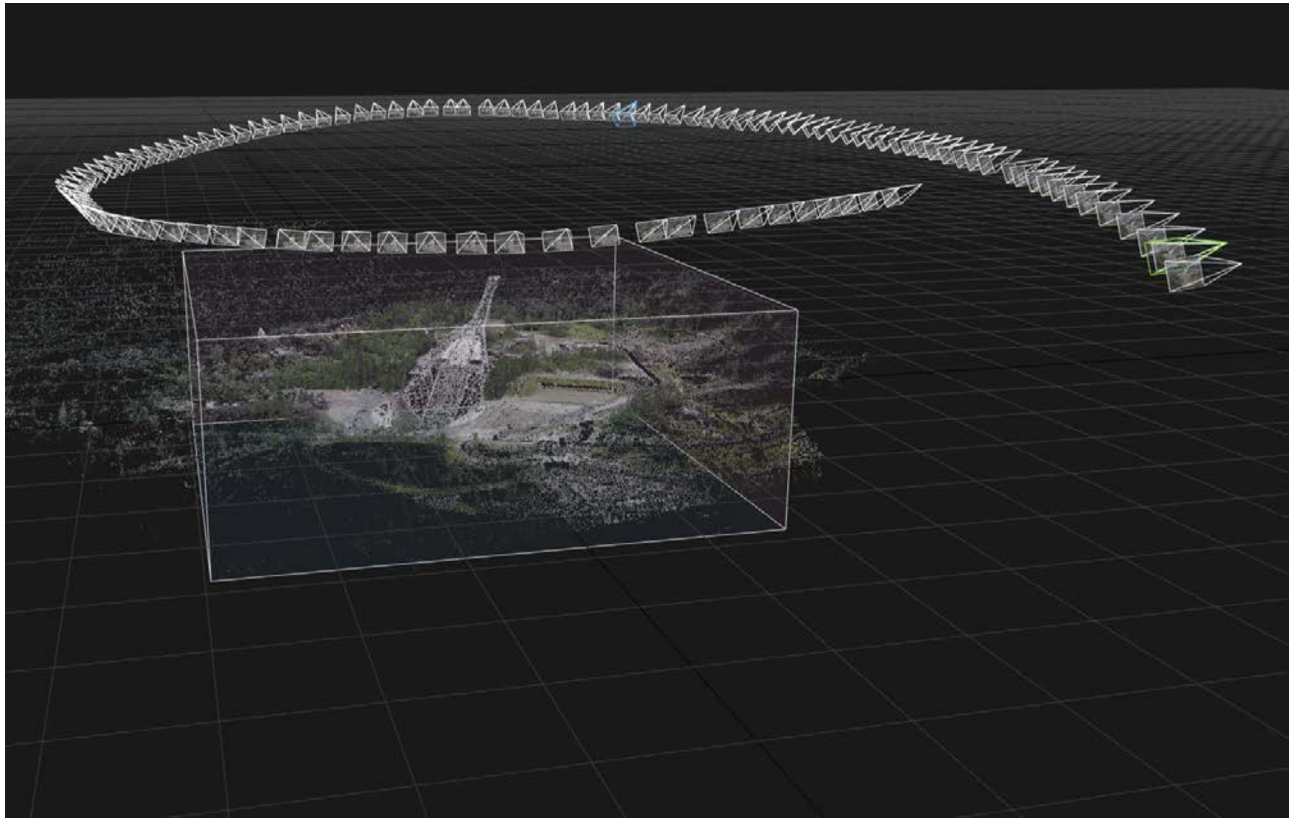
What is the map?

What is the map?

A model of the environment that lets us

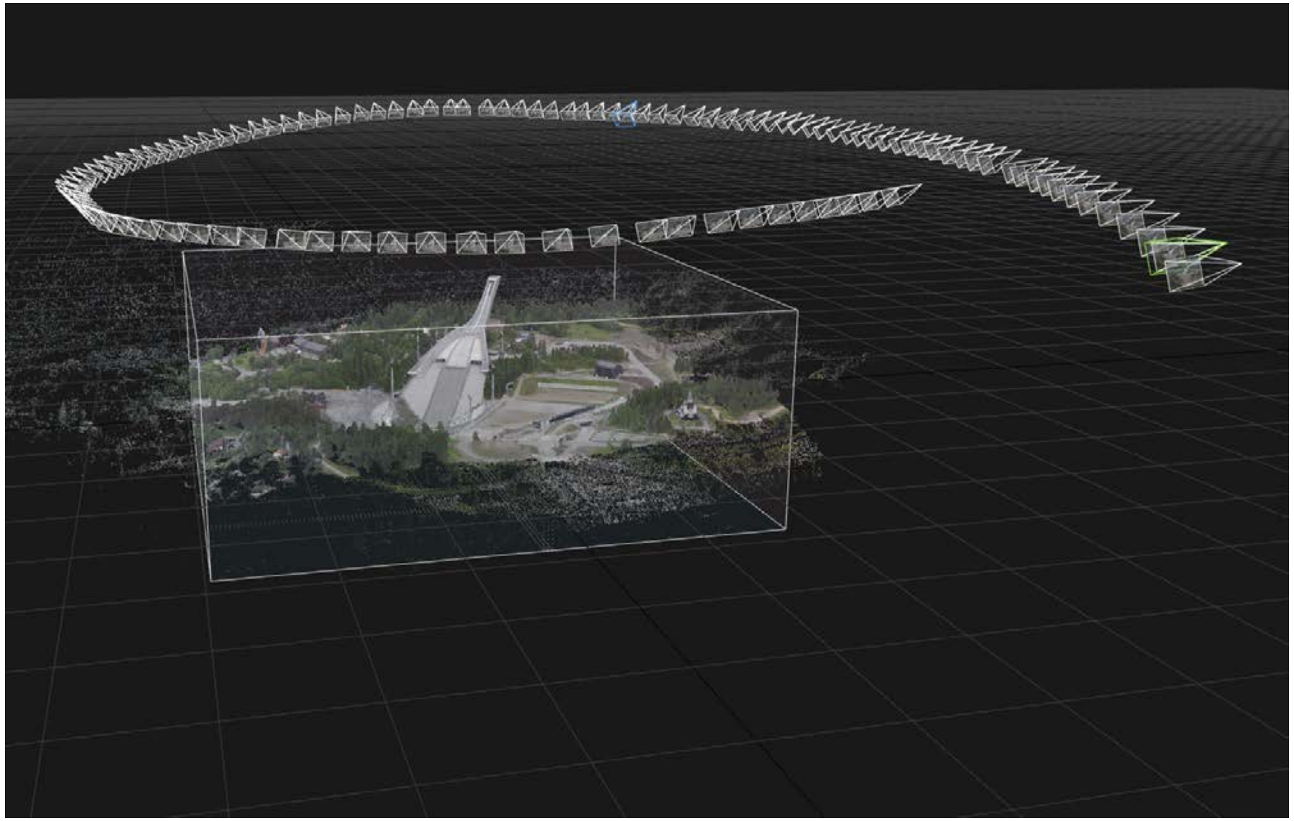
- limit the localization error
  by recognizing previously visited areas

- (support other tasks,
  such as obstacle avoidance
  and path planning)



What is the map?

A model of the environment that lets us



- limit the localization error
  by recognizing previously visited areas

- (support other tasks,
  such as obstacle avoidance
  and path planning)

  Maybe best left as auxiliary processing?

Examples of map representations

Feature-based metric maps

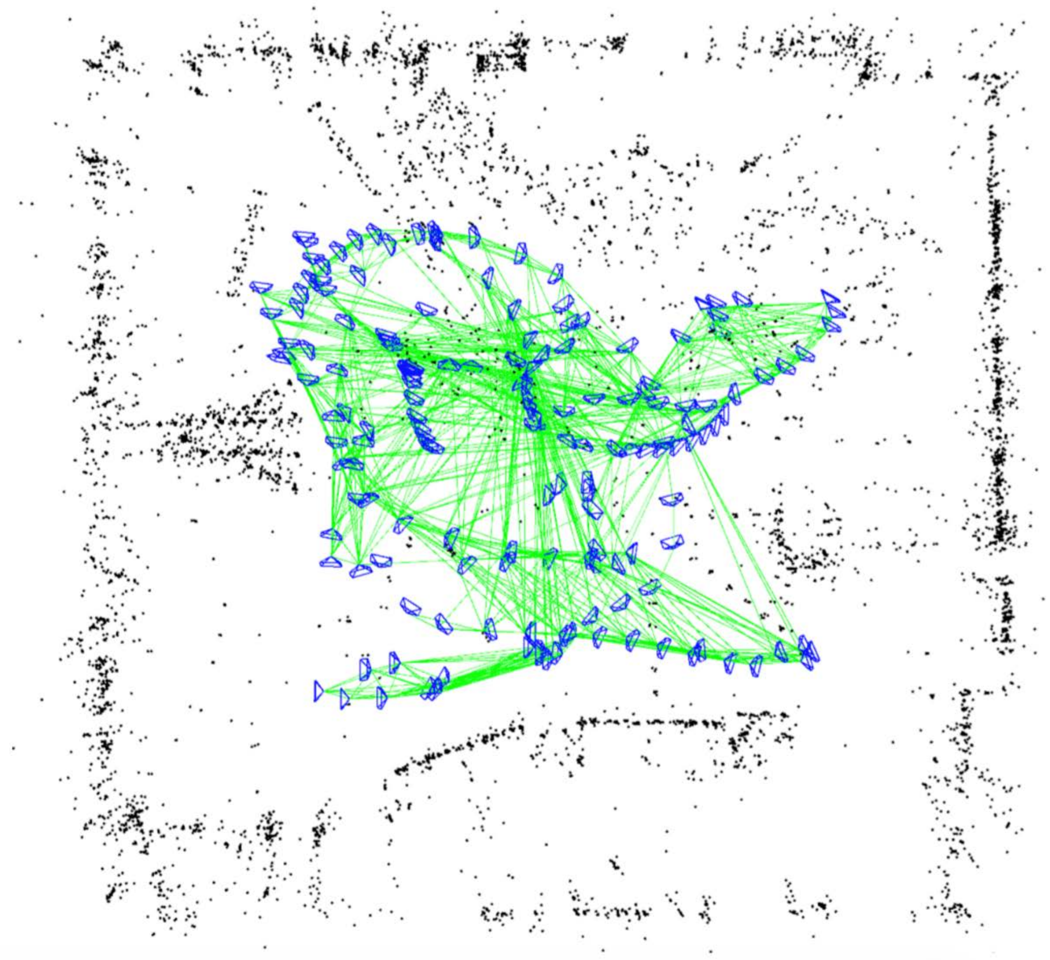


Image: Cadena, C., et al. (2016). Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. *IEEE Transactions on Robotics*, *32*(6), 1309–1332

Mur-Artal, R., Montiel, J. M. M., & Tardos, J. D. (2015). ORB-SLAM: A Versatile and Accurate Monocular SLAM System. IEEE Transactions on Robotics, 31(5), 1147–1163. https://doi.org/10.1109/TRO.2015.2463671

Examples of map representations

Dense metric maps

[DTAM:
Dense Tracking and Mapping in Real-Time]

Image: Cadena, C., et al. (2016). Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. *IEEE Transactions on Robotics*, *32*(6), 1309–1332

Newcombe, R. A., Lovegrove, S. J., & Davison, A. J. (2011). DTAM: Dense tracking and mapping in real-time. In 2011 International Conference on Computer Vision (pp. 2320–2327). IEEE

Examples of map representations

Topological maps

[FABMAP]

Image: YouTube: ORI - Oxford Robotics Institute

Cummins, M., & Newman, P. (2008). FAB-MAP: Probabilistic Localization and Mapping in the Space of Appearance. The International Journal of Robotics Research, 27(6), 647–665

Examples of map representations

Topological-metric maps

[Visual Teach & Repeat]()

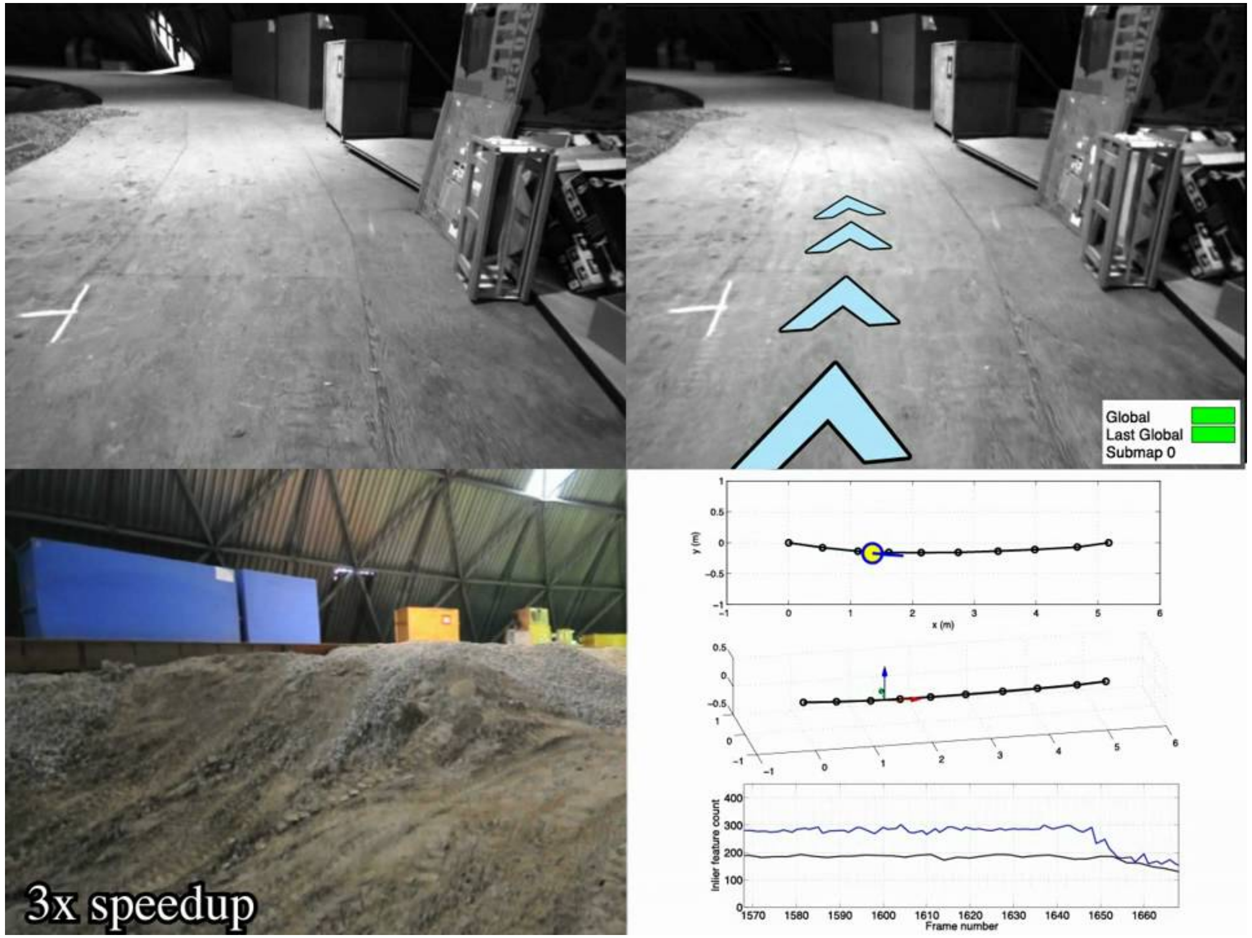
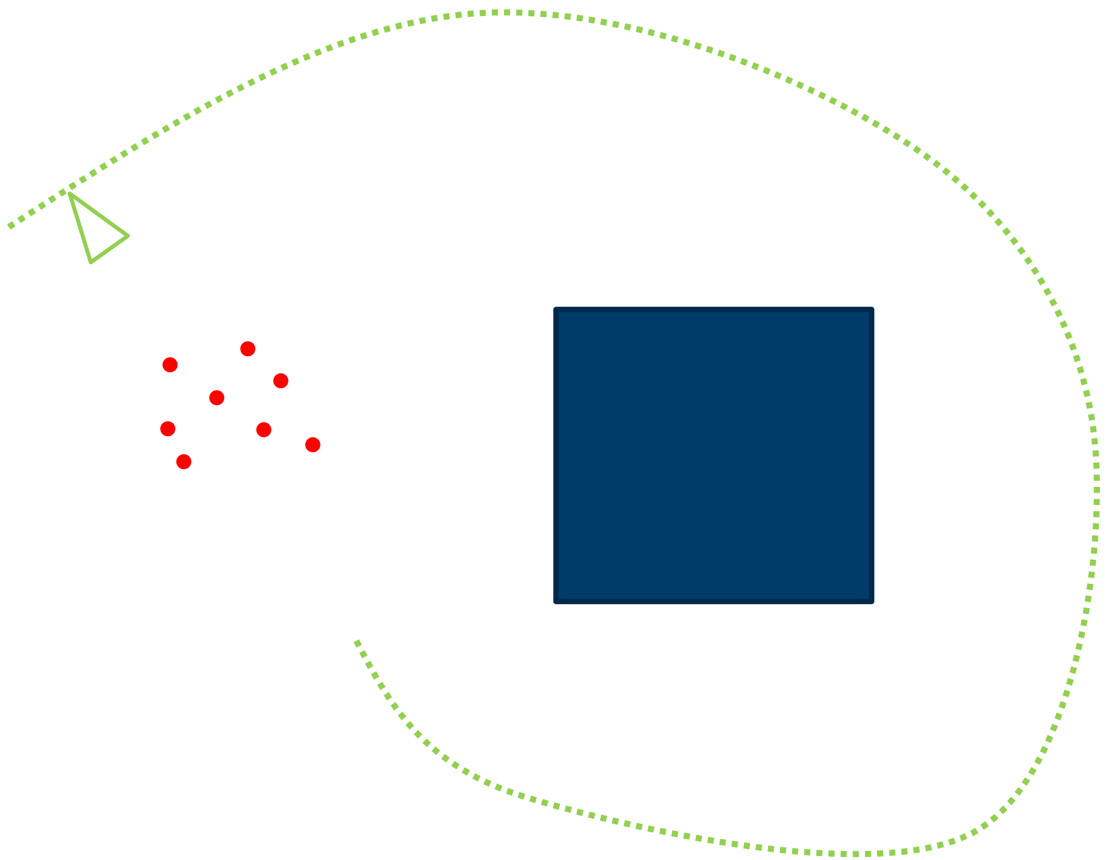


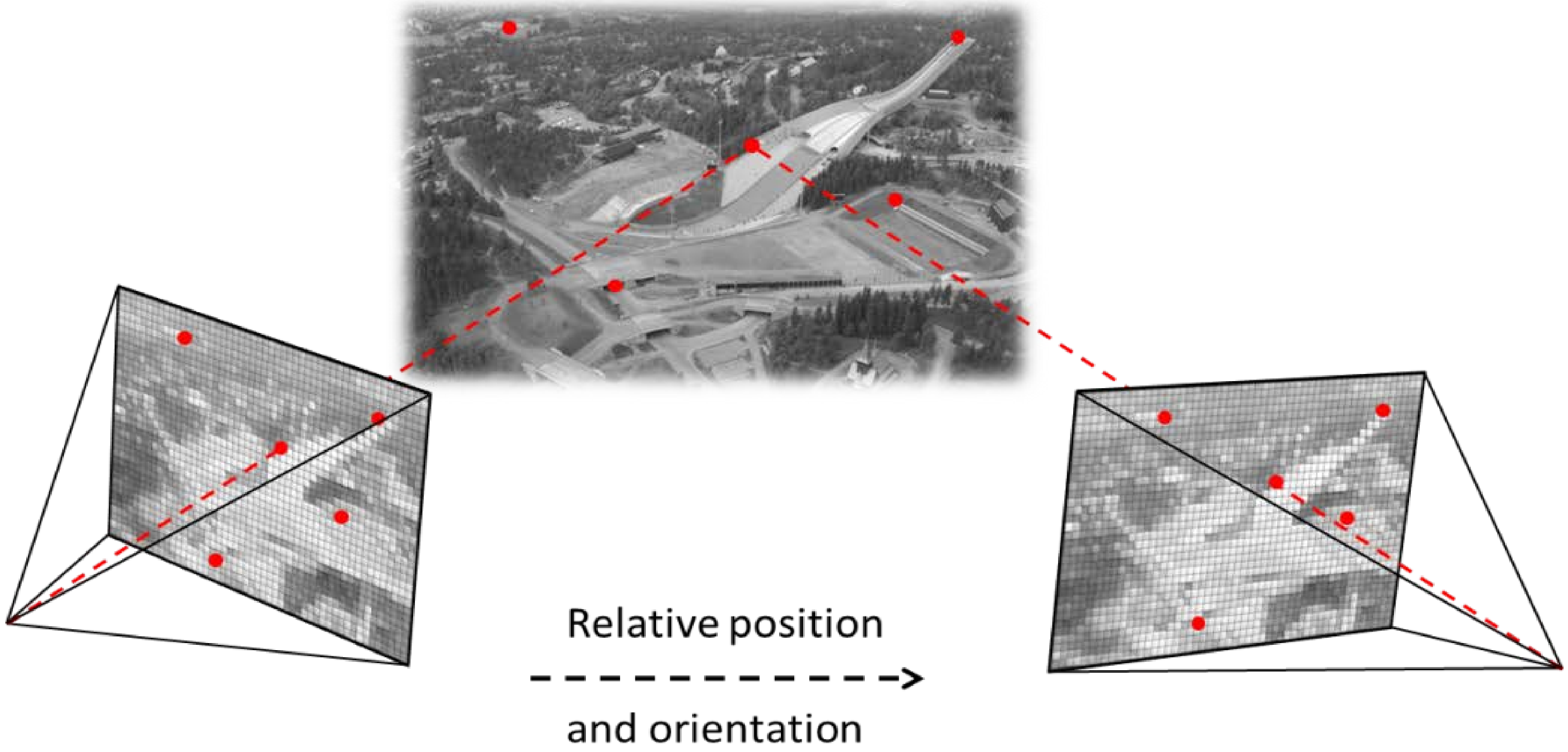
Image: YouTube: utiasASRL

Furgale P T and Barfoot T D. Visual Teach and Repeat for Long-Range Rover Autonomy.
Journal of Field Robotics, special issue on Visual mapping and navigation outdoors, 27(5): 534-560, 2010.

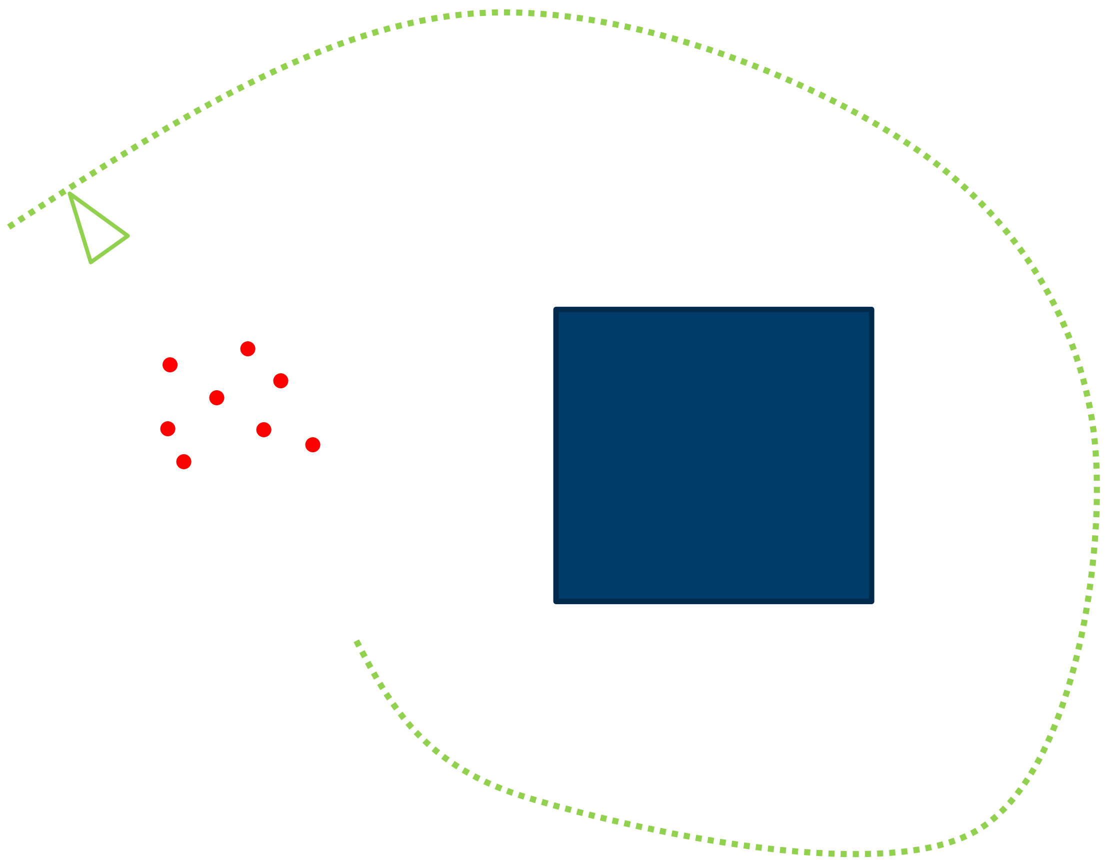
How do we build a map?



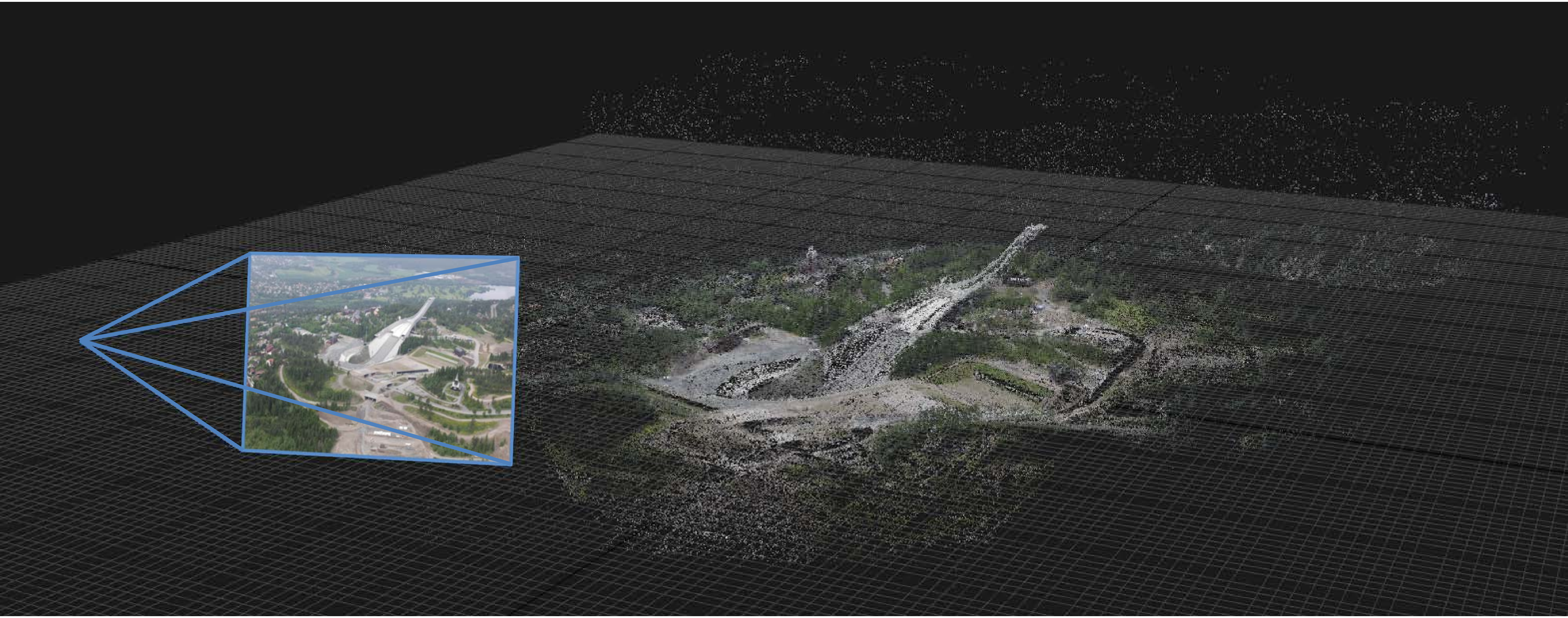
Relative pose and 3D from two views



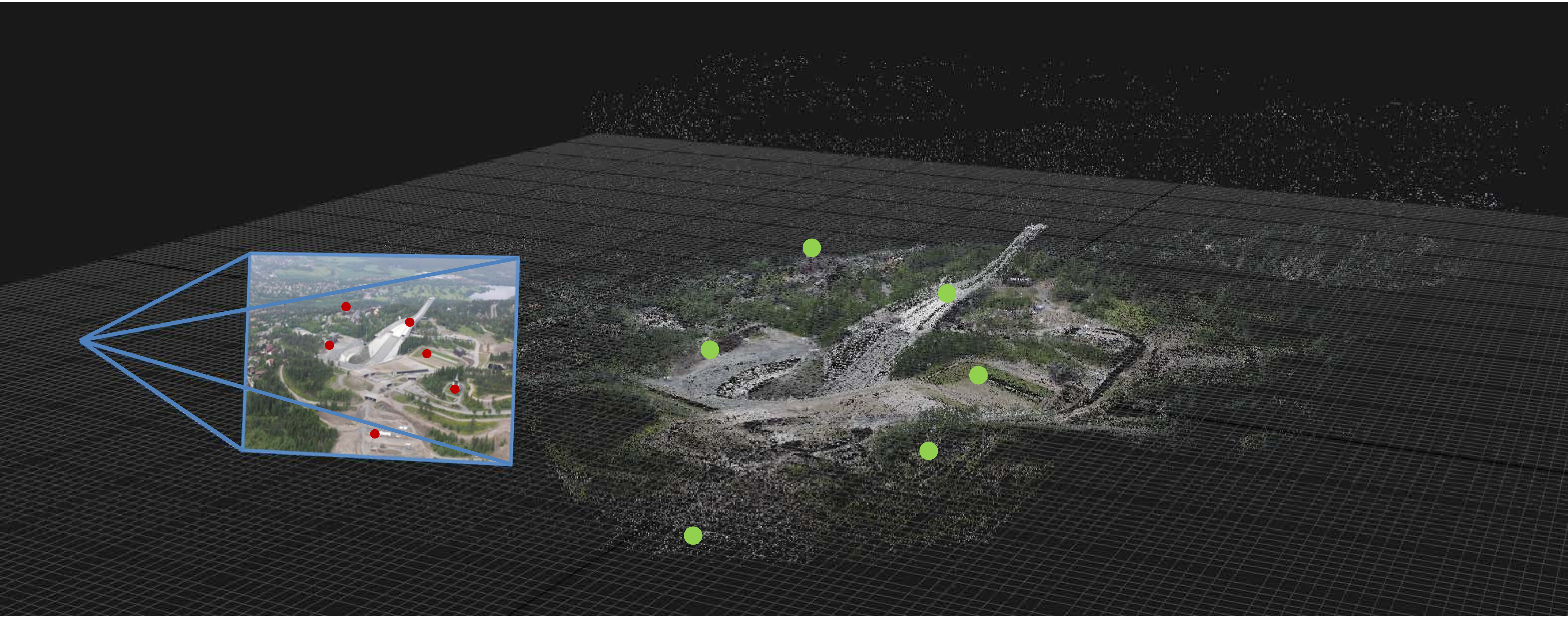
How do we track a map?



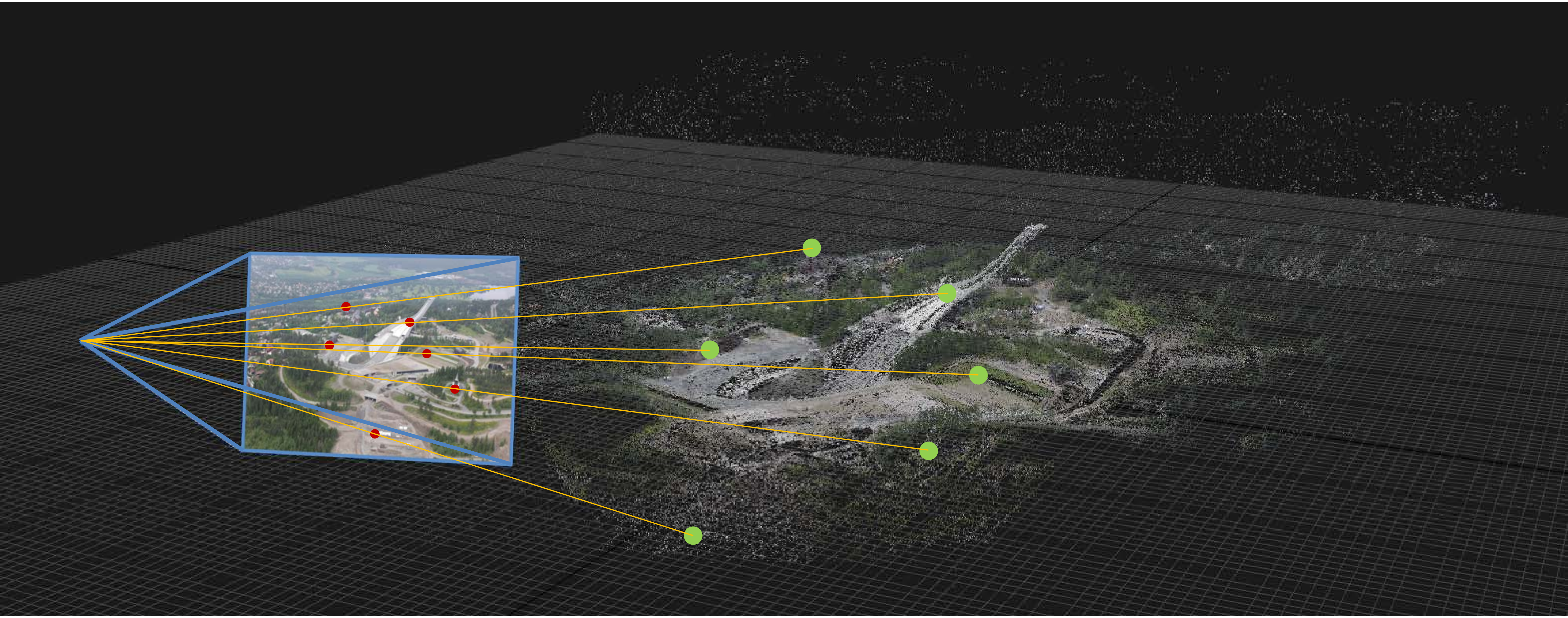
Pose from known 3D map



Pose from point correspondences



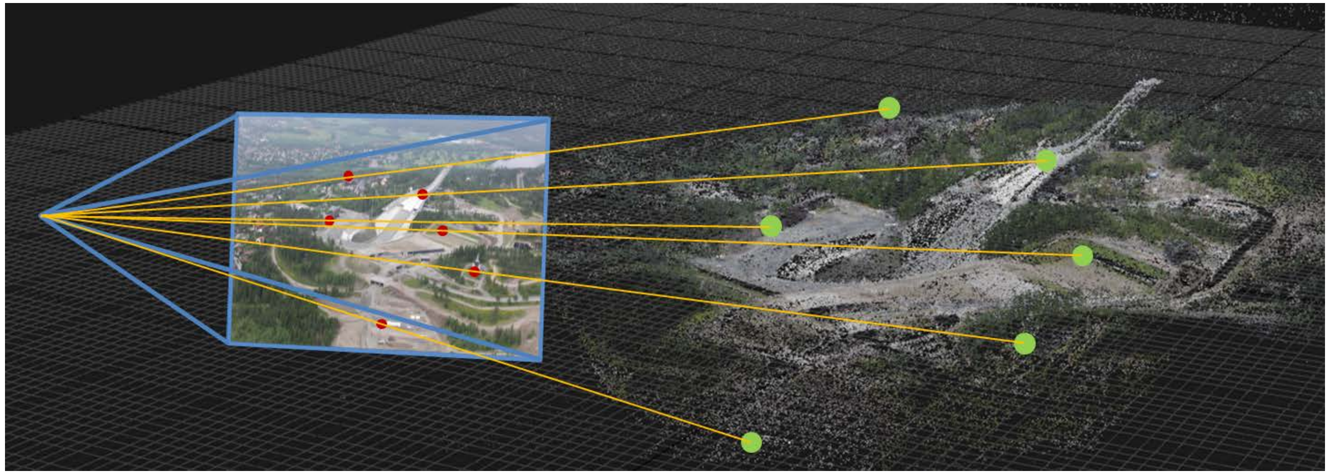
Pose from point correspondences



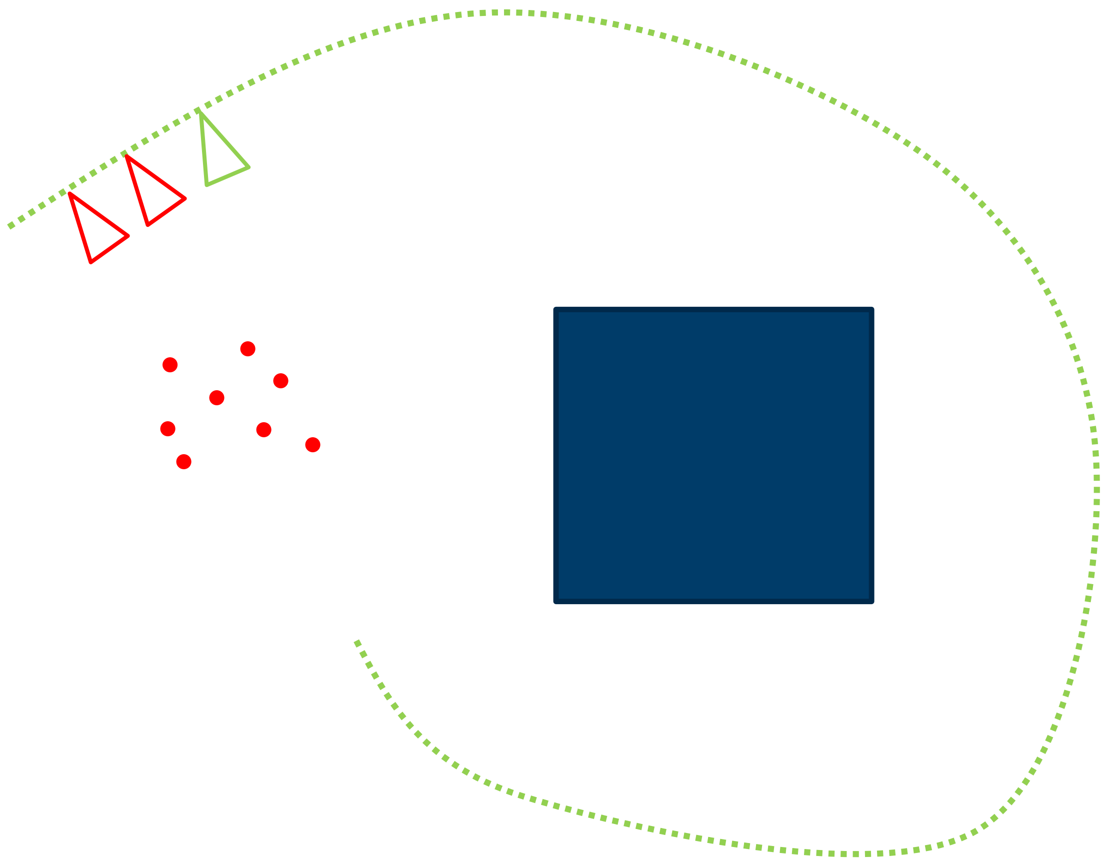
Pose from point correspondences

Minimize *geometric error*

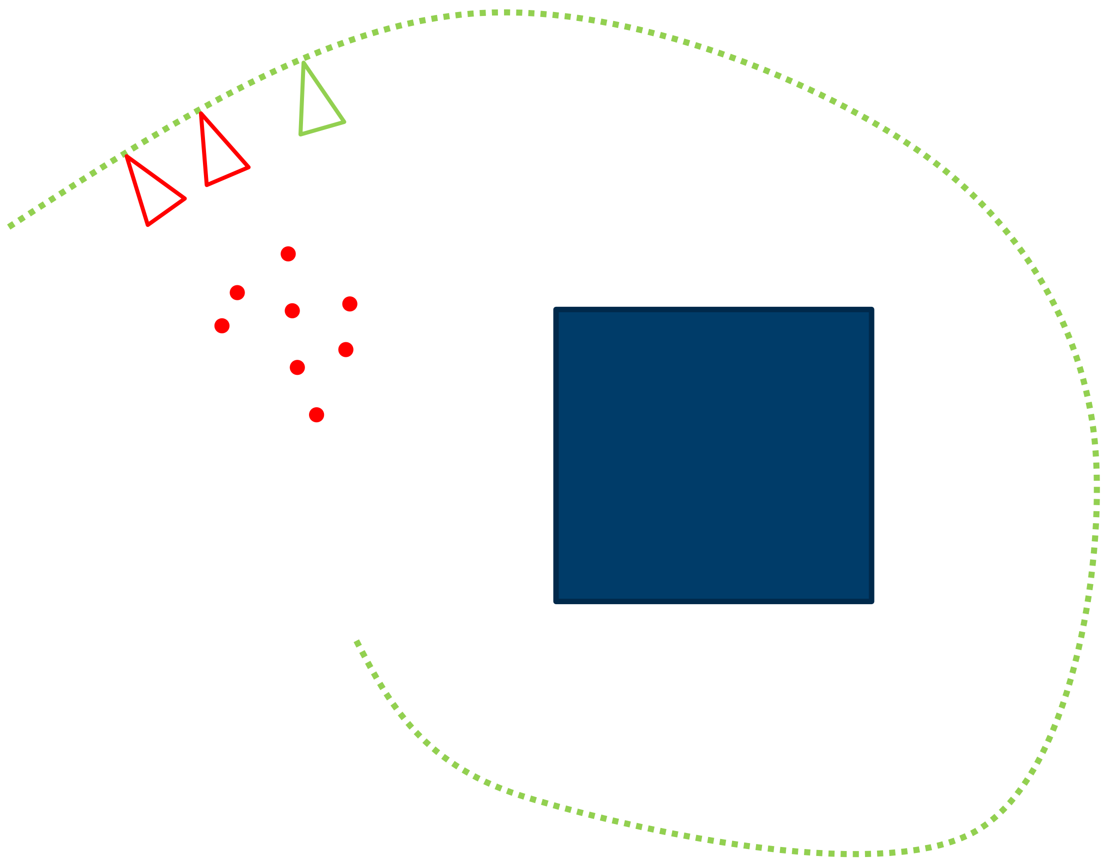
$$\mathbf{T}_{wc}^{*} = \underset{\mathbf{T}_{wc}}{\operatorname{argmin}} \sum_{i} \left\| \pi\left(\mathbf{T}_{wc}^{-1} \cdot \mathbf{x}_{i}^{w}\right) - \mathbf{u}_{i} \right\|^{2}$$



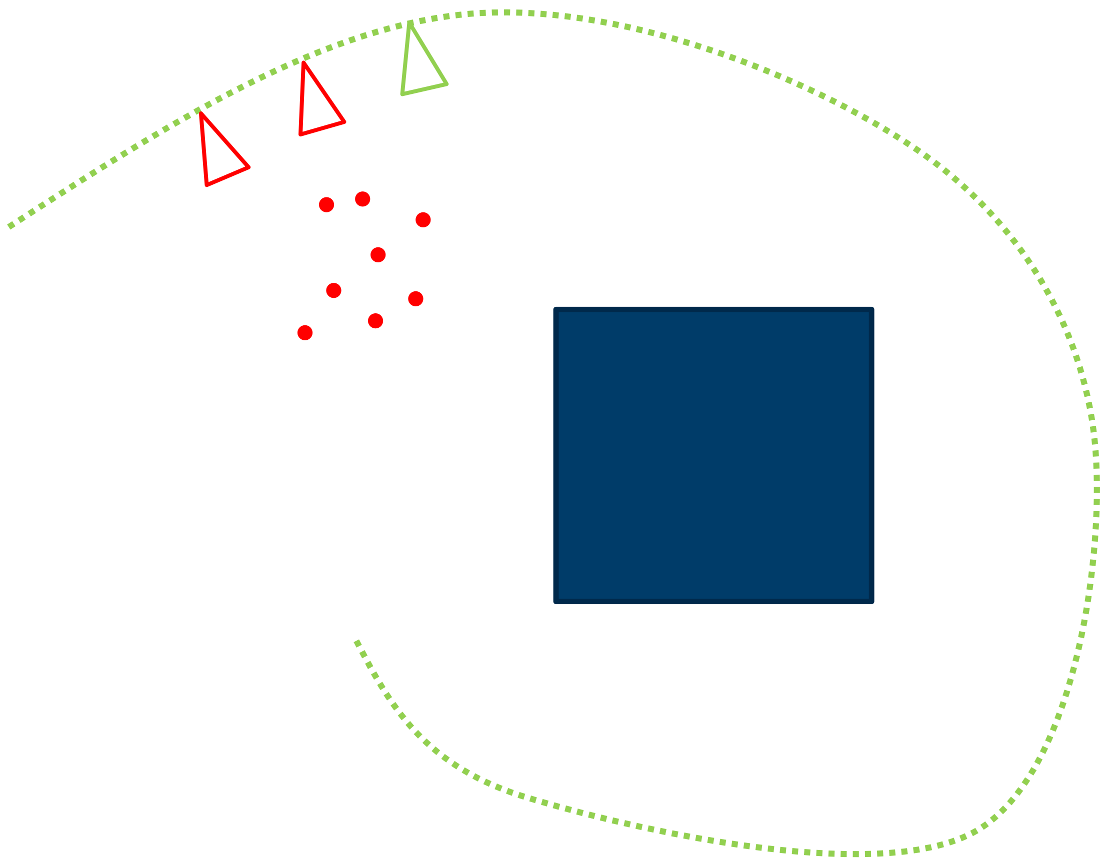
Map initialization and tracking



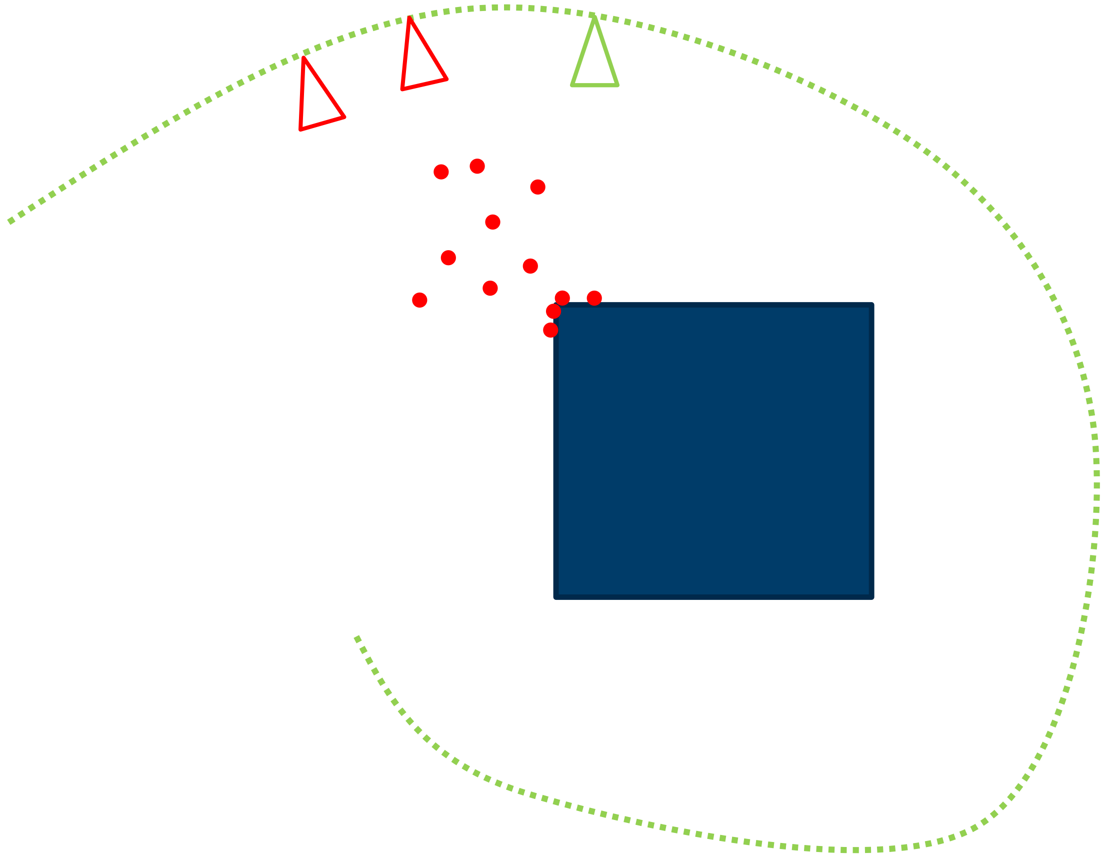
Map reinitialization and tracking



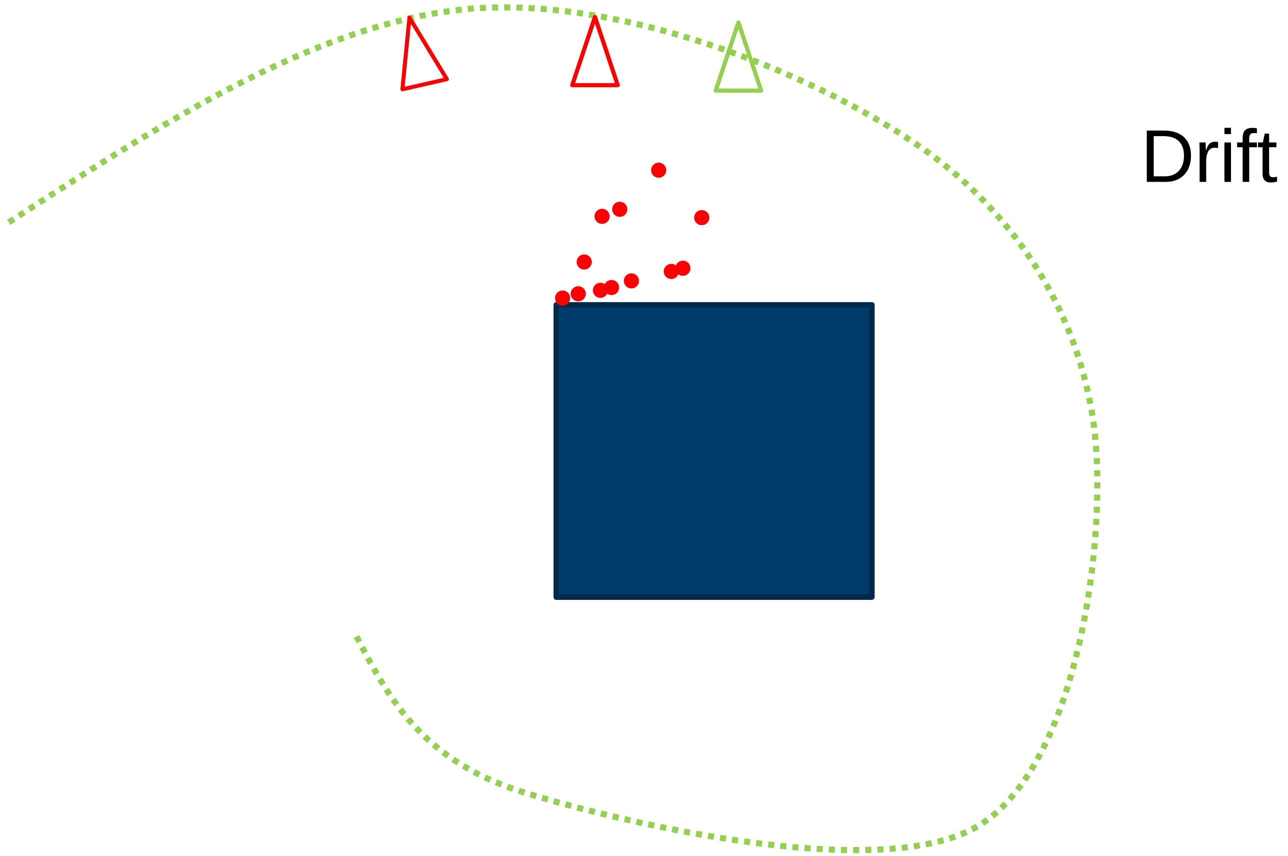
Map reinitialization and tracking



Map reinitialization and tracking



Map reinitialization and tracking



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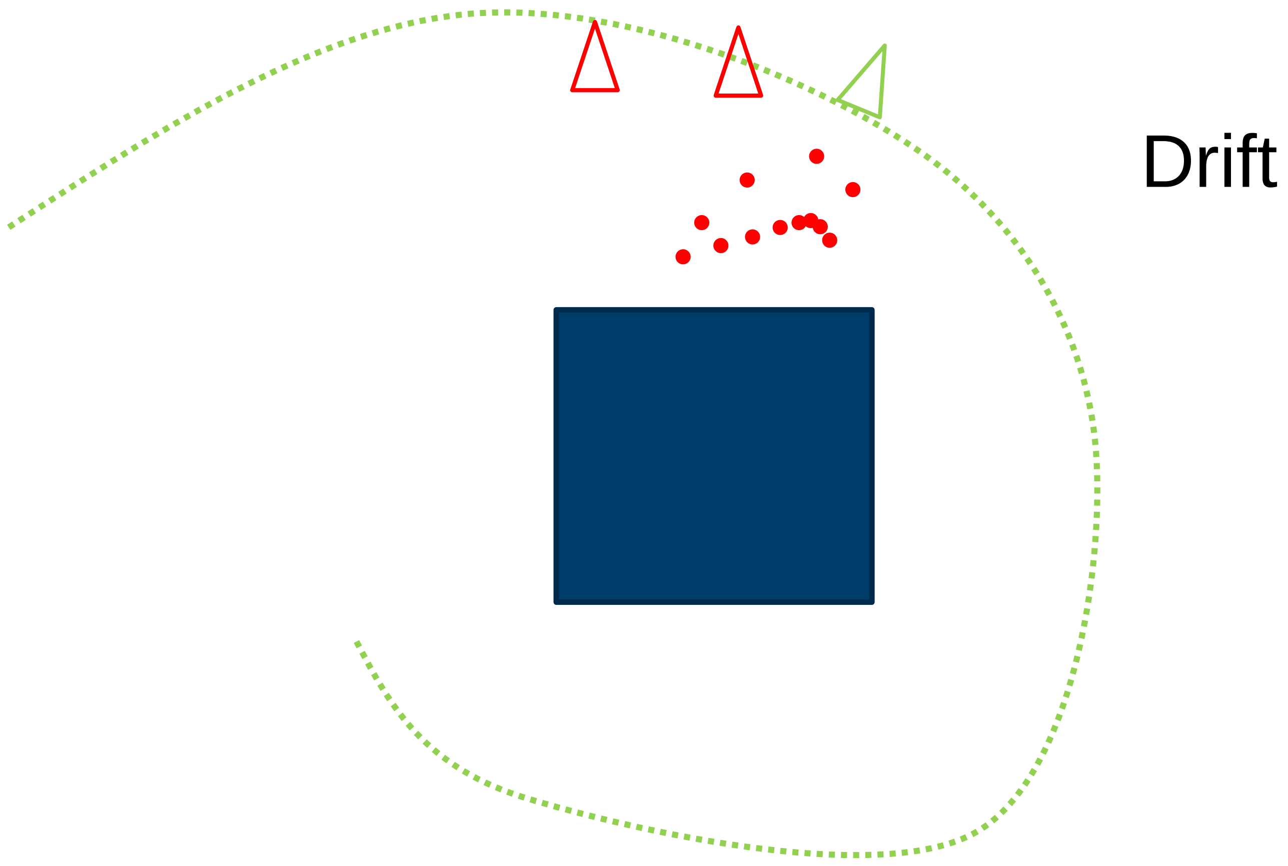
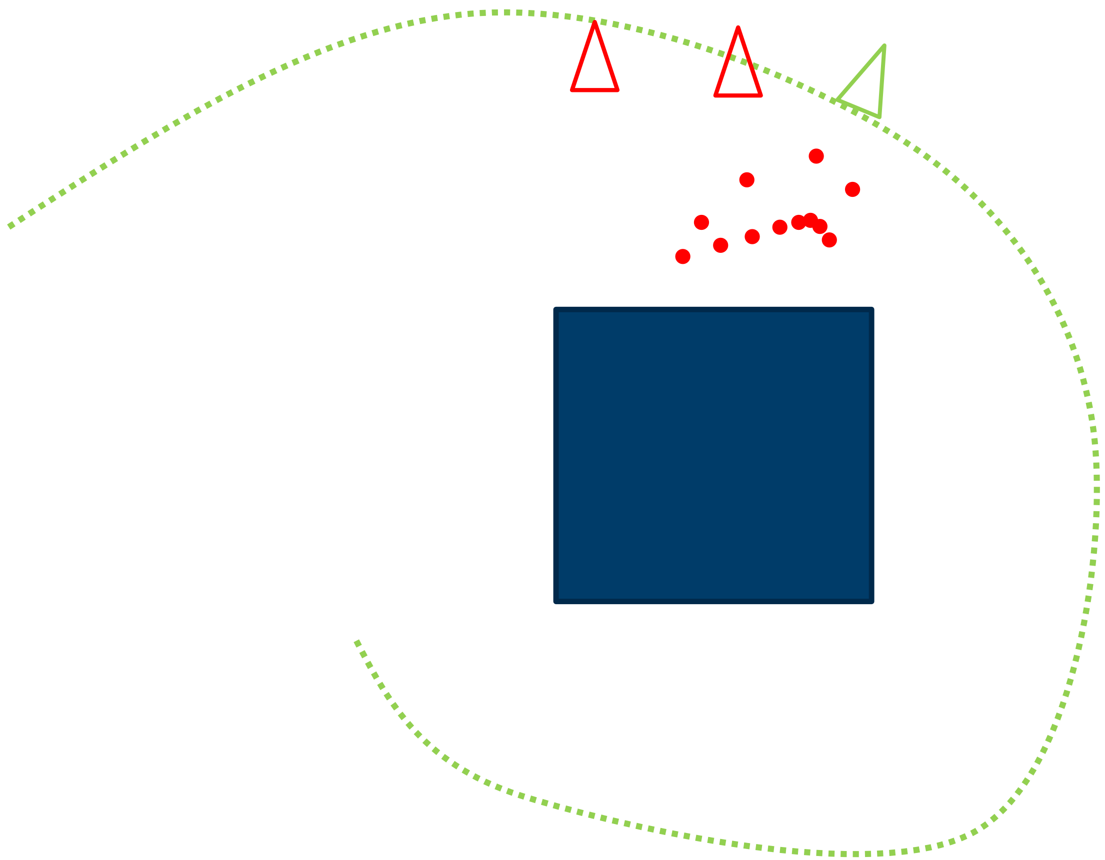


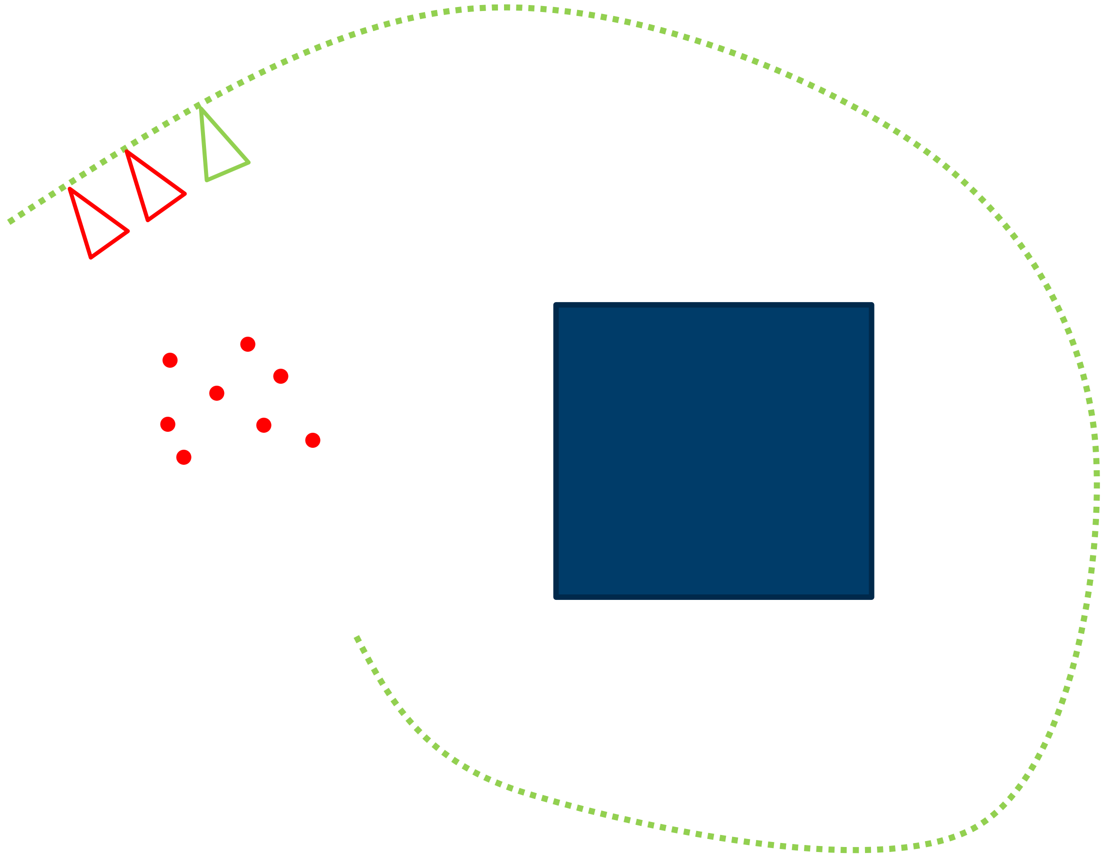
Map reinitialization and tracking



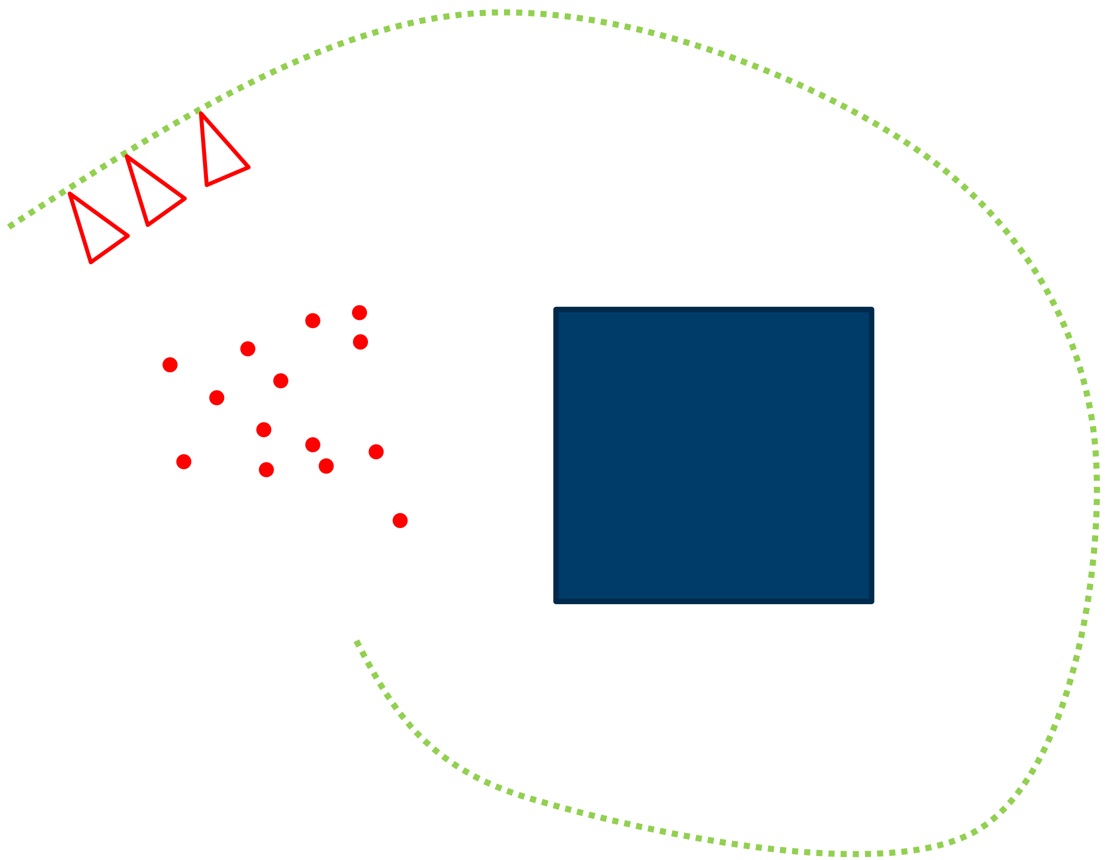
Drift

Very naïve
Visual Odometry (VO)

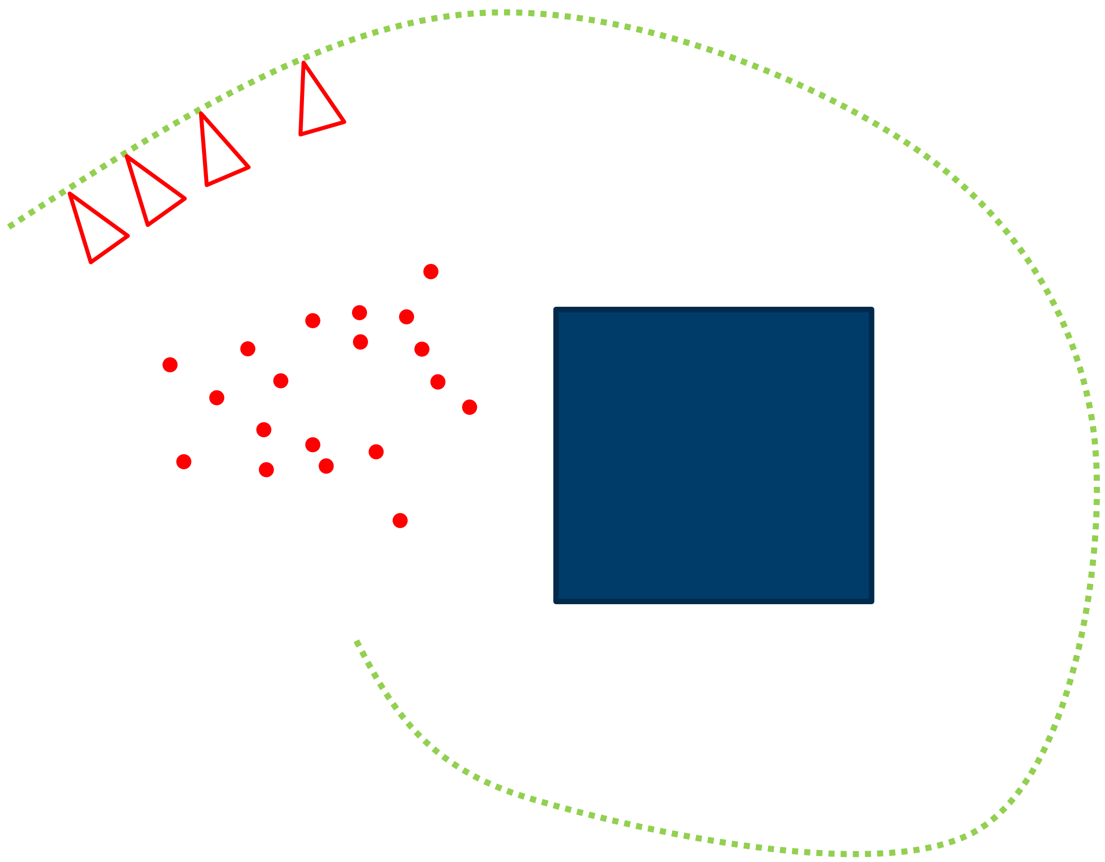
Multi-view mapping



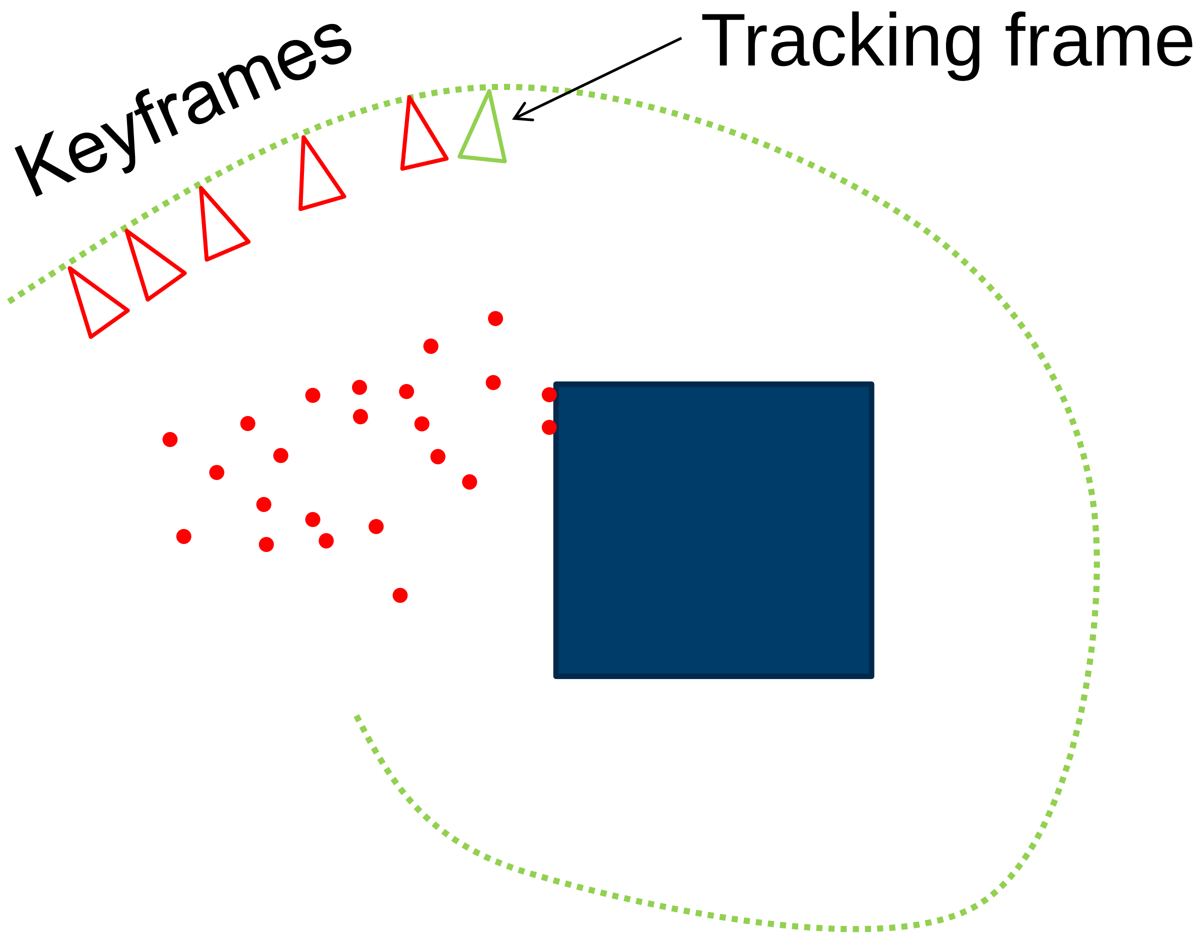
Multi-view mapping



Multi-view mapping



Multi-view mapping

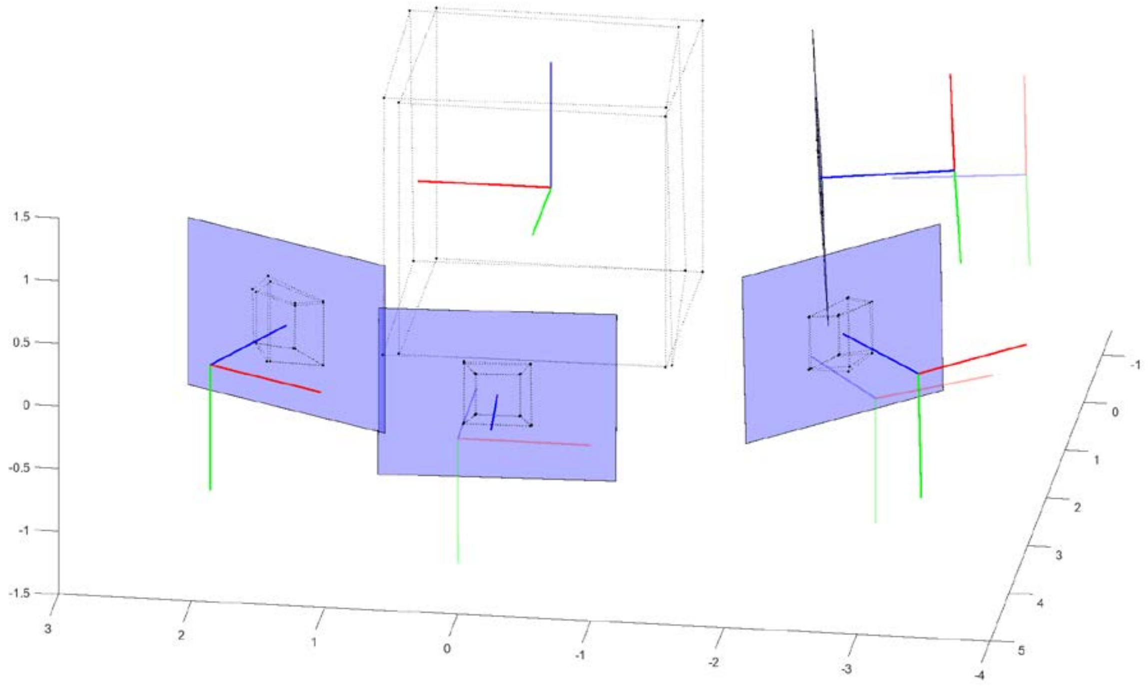


Maximum a Posteriori Inference

Interested in the unknown state variables X,
given the measurements Z.

The most often used estimator for X
is the MAP estimate:

$$X^{\text{MAP}} = \underset{X}{\operatorname{argmax}}\; p(X \mid Z)$$



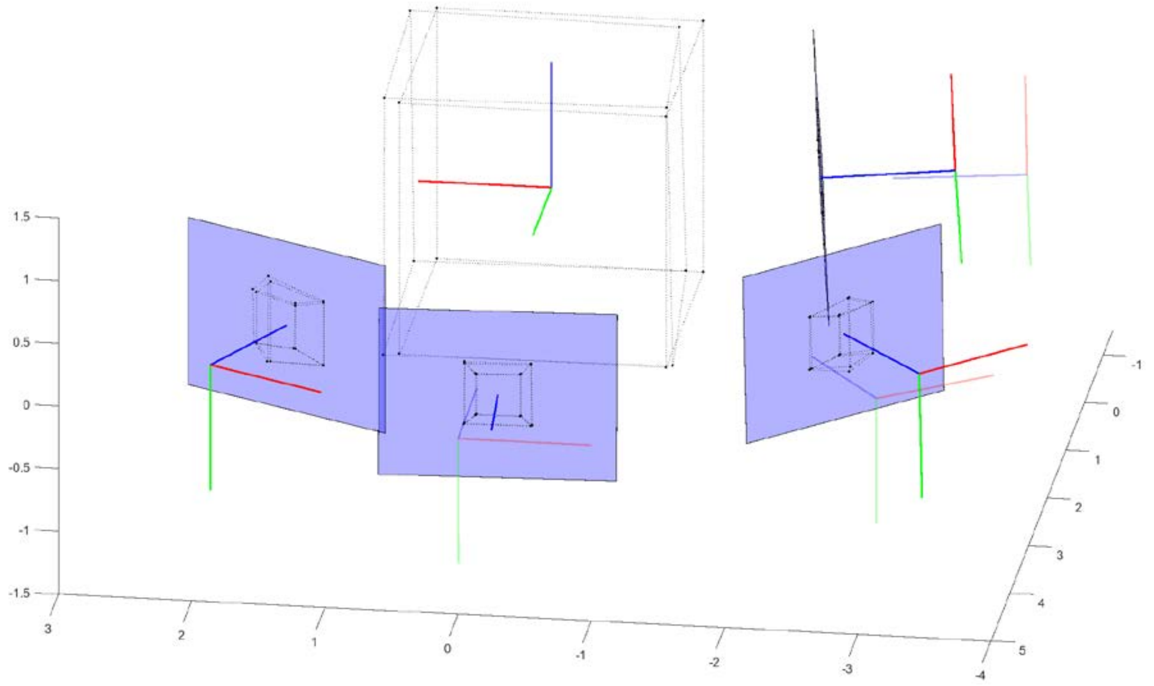
Maximum a Posteriori Inference

Interested in the unknown state variables X, given the measurements Z.

The most often used estimator for X is the MAP estimate:

$$
\begin{aligned}
X^{\text{MAP}} &= \underset{X}{\operatorname{argmax}}\, p(X \mid Z) \\
&= \underset{X}{\operatorname{argmax}} \frac{p(Z \mid X)\, p(X)}{p(Z)} \\
&= \underset{X}{\operatorname{argmax}}\, l(X;Z)\, p(X)
\end{aligned}
$$

$$l(X;Z) \propto p(Z \mid X)$$



Maximum a Posteriori Inference

Measurement model:

$$\mathbf{z}_i = h_i(X_i) + \eta, \qquad \eta \sim N(\mathbf{0}, \mathbf{\Sigma}_i)$$

Measurement prediction function:

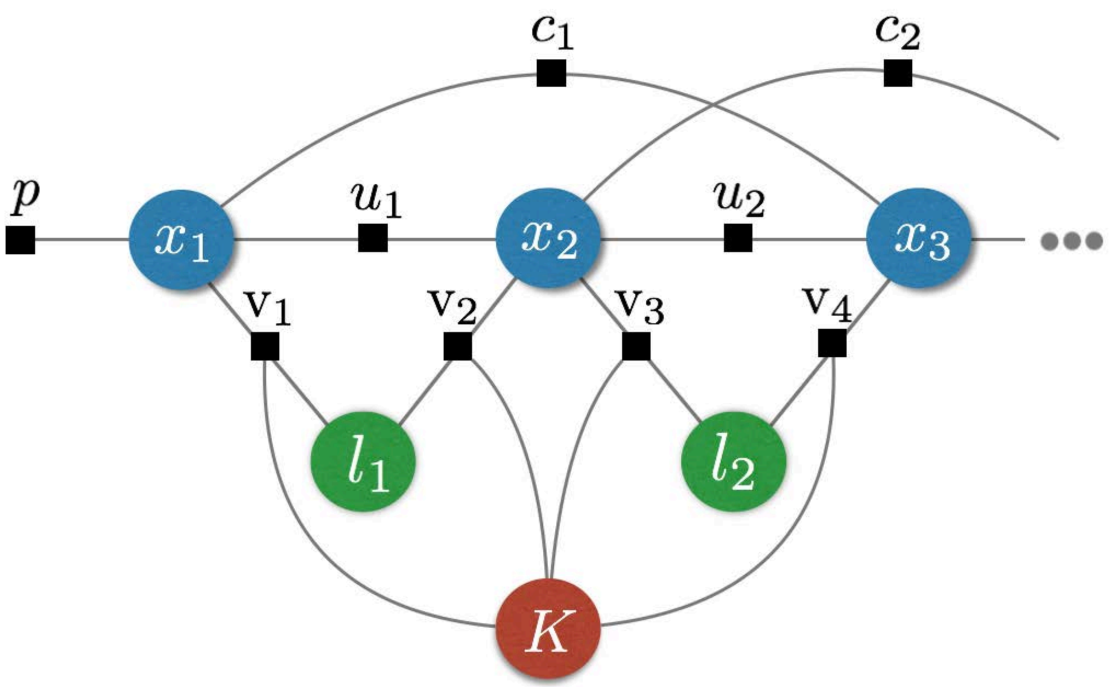
$$\hat{\mathbf{z}}_i = h_i(X_i)$$

Measurement likelihood:

$$p(\mathbf{z}_i \mid X_i) \propto l(X_i; \mathbf{z}_i) = \exp\left(-\frac{1}{2} \left\| h_i(X_i) - \mathbf{z}_i \right\|_{\mathbf{\Sigma}_i}^2 \right)$$

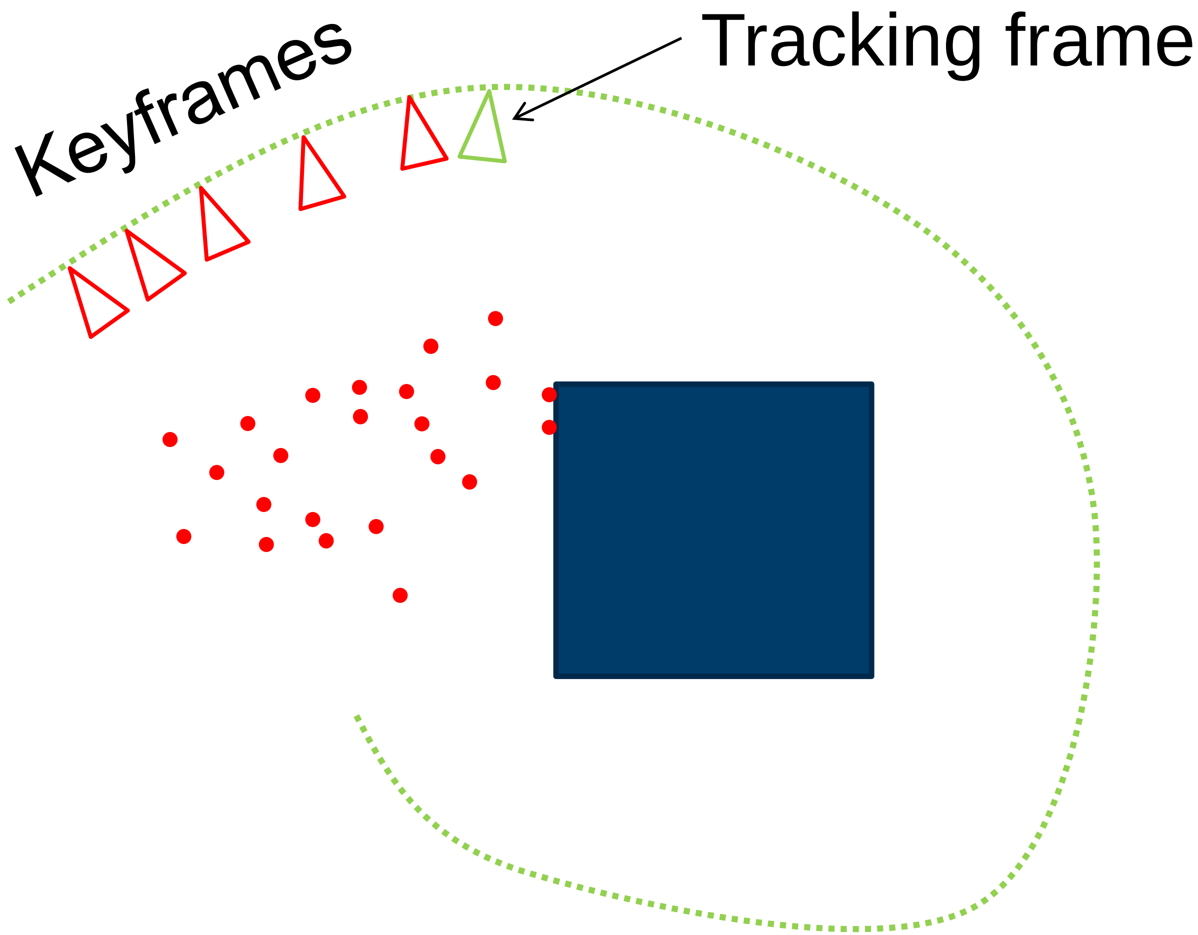
MAP estimate:

$$X^{\text{MAP}} = \underset{X}{\operatorname{argmin}} \sum_i \left\| h_i(X_i) - \mathbf{z}_i \right\|_{\mathbf{\Sigma}_i}^2$$

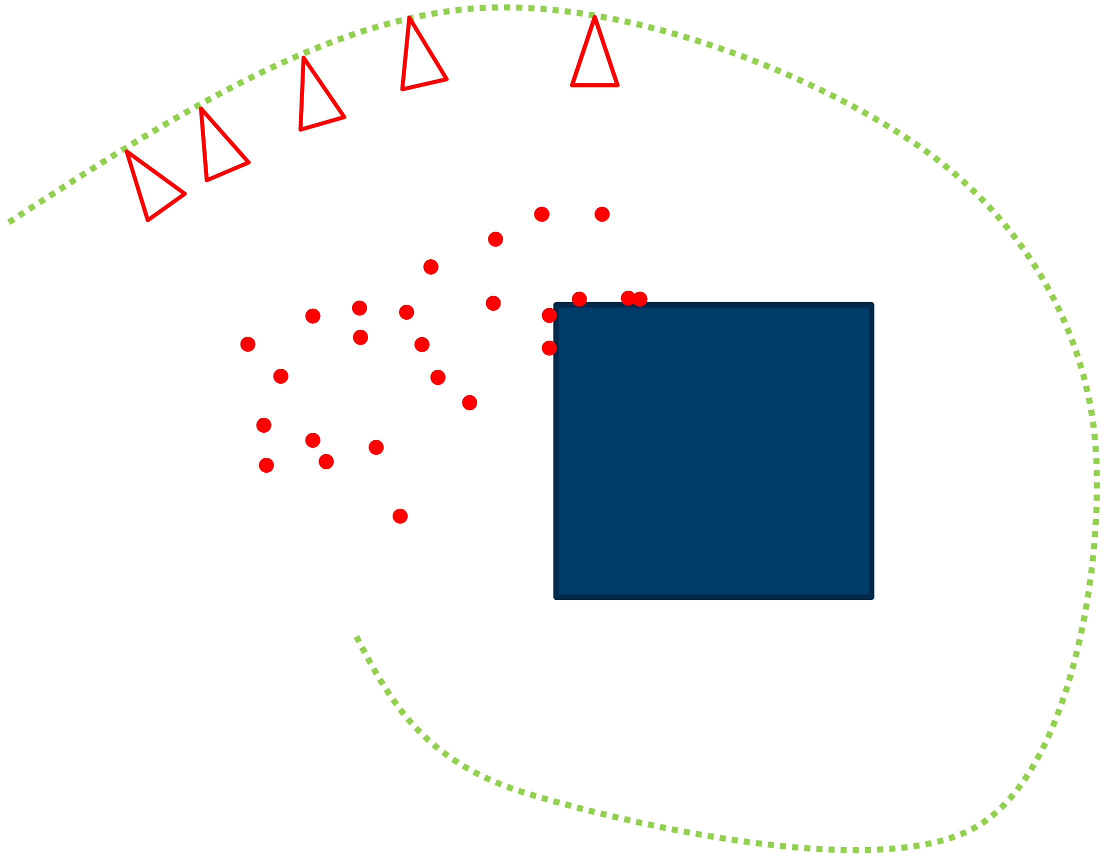


Cadena, C., et al. (2016). Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. *IEEE Transactions on Robotics*, *32*(6), 1309–1332

Multi-view mapping



Sliding window mapping



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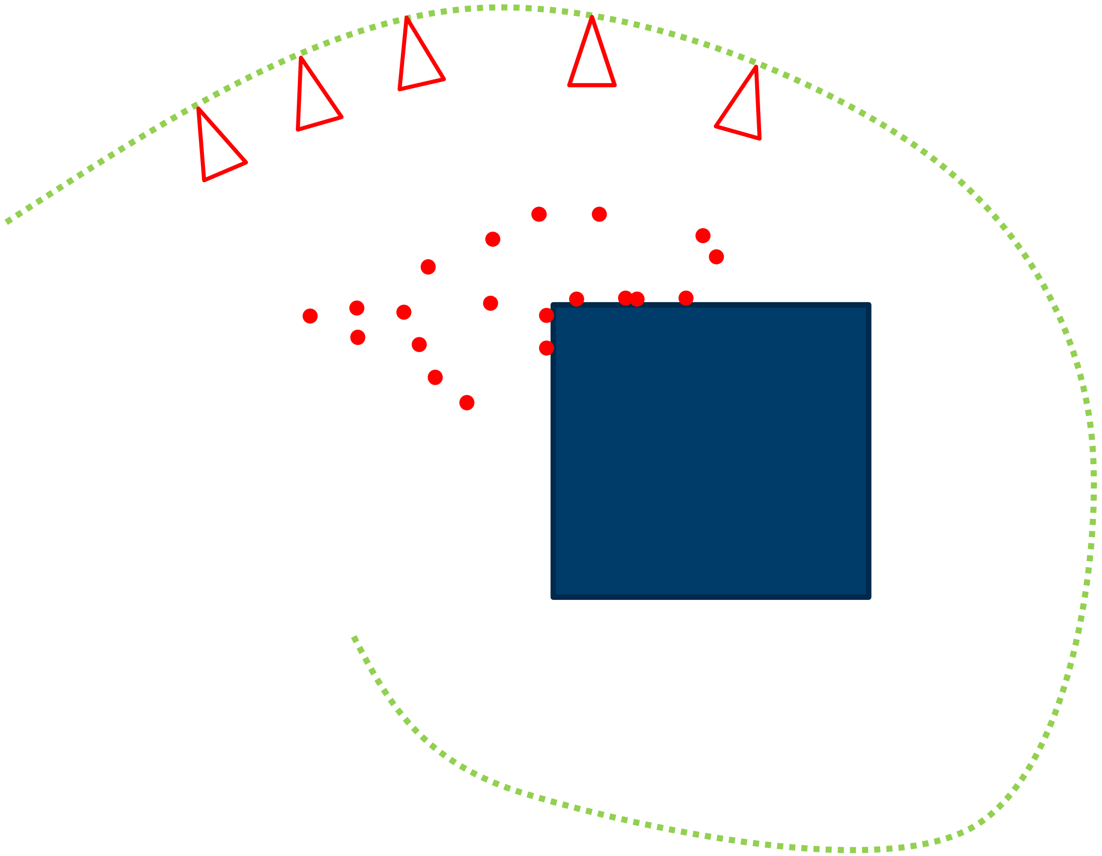
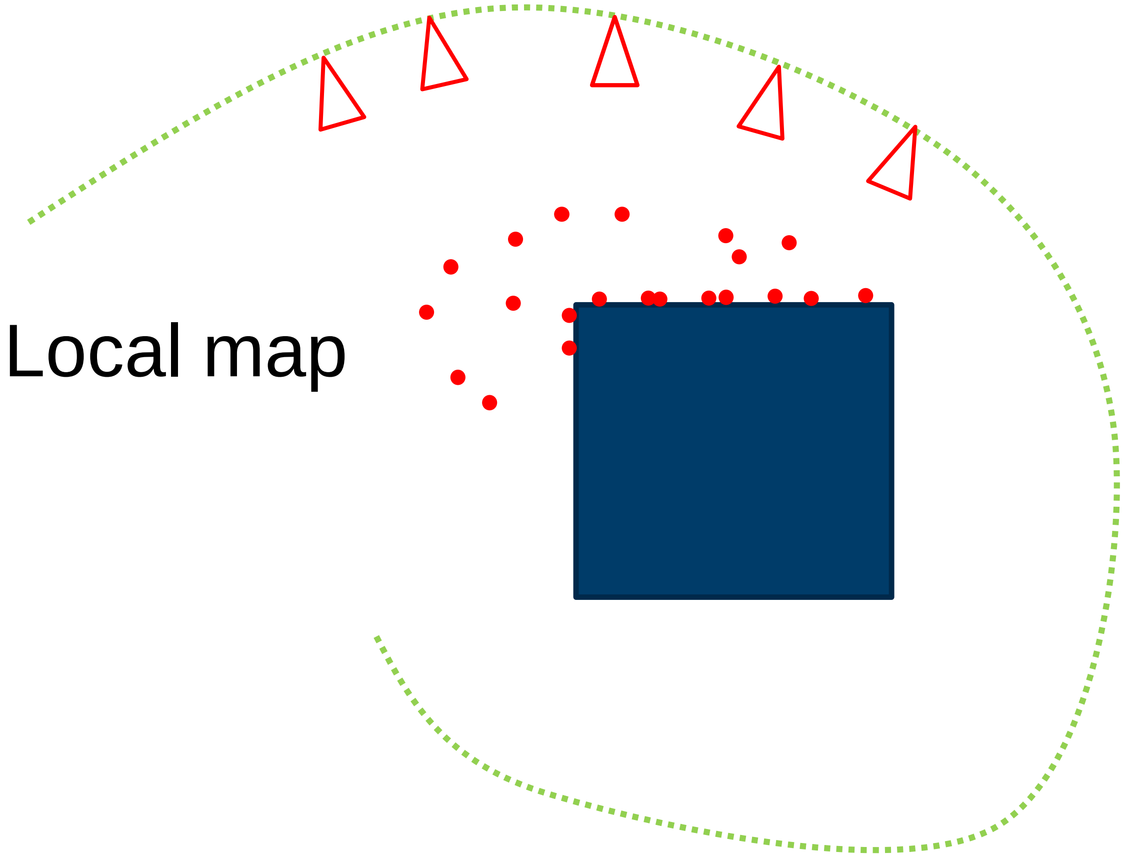
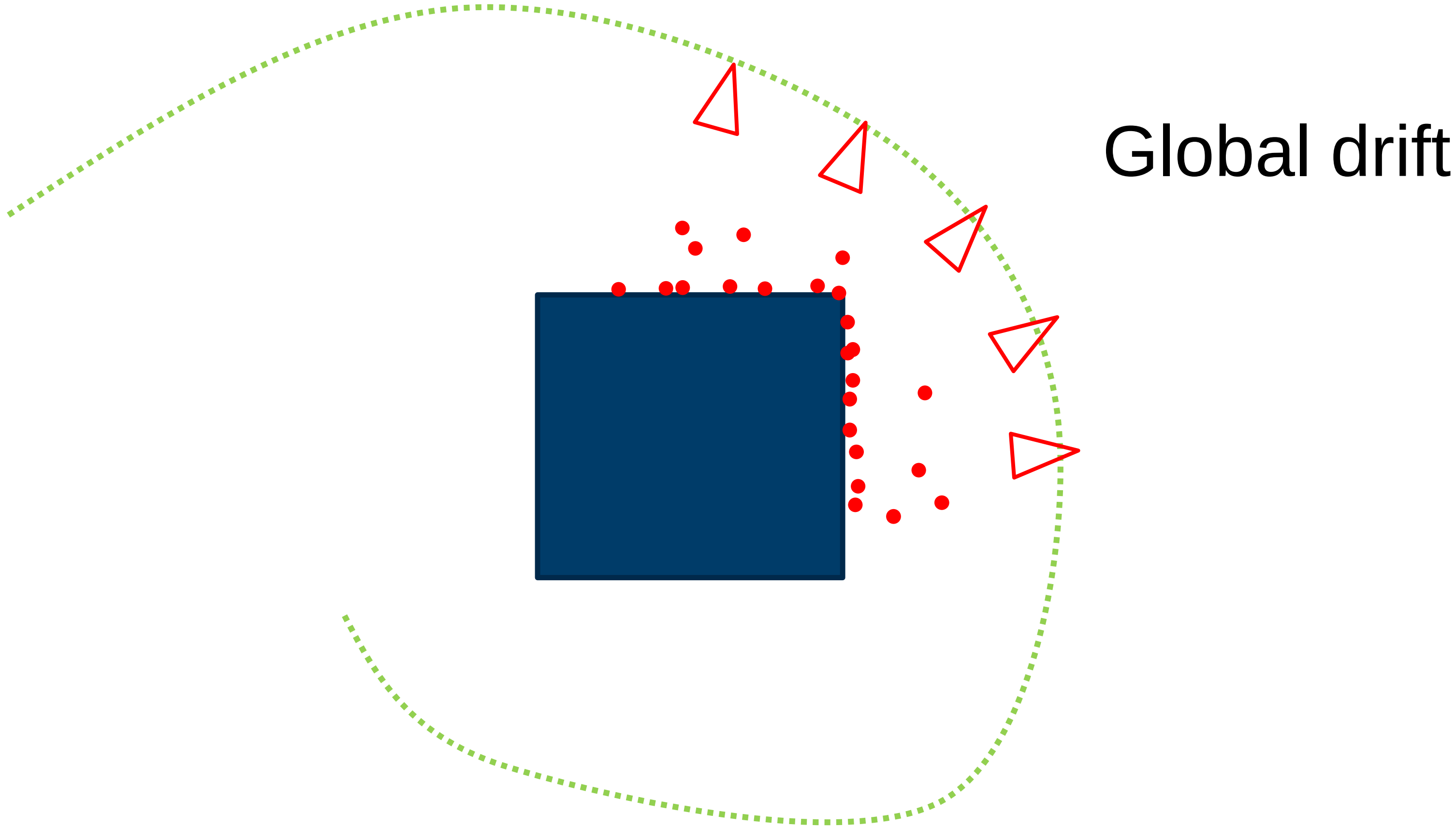


Sliding window mapping



Sliding window mapping



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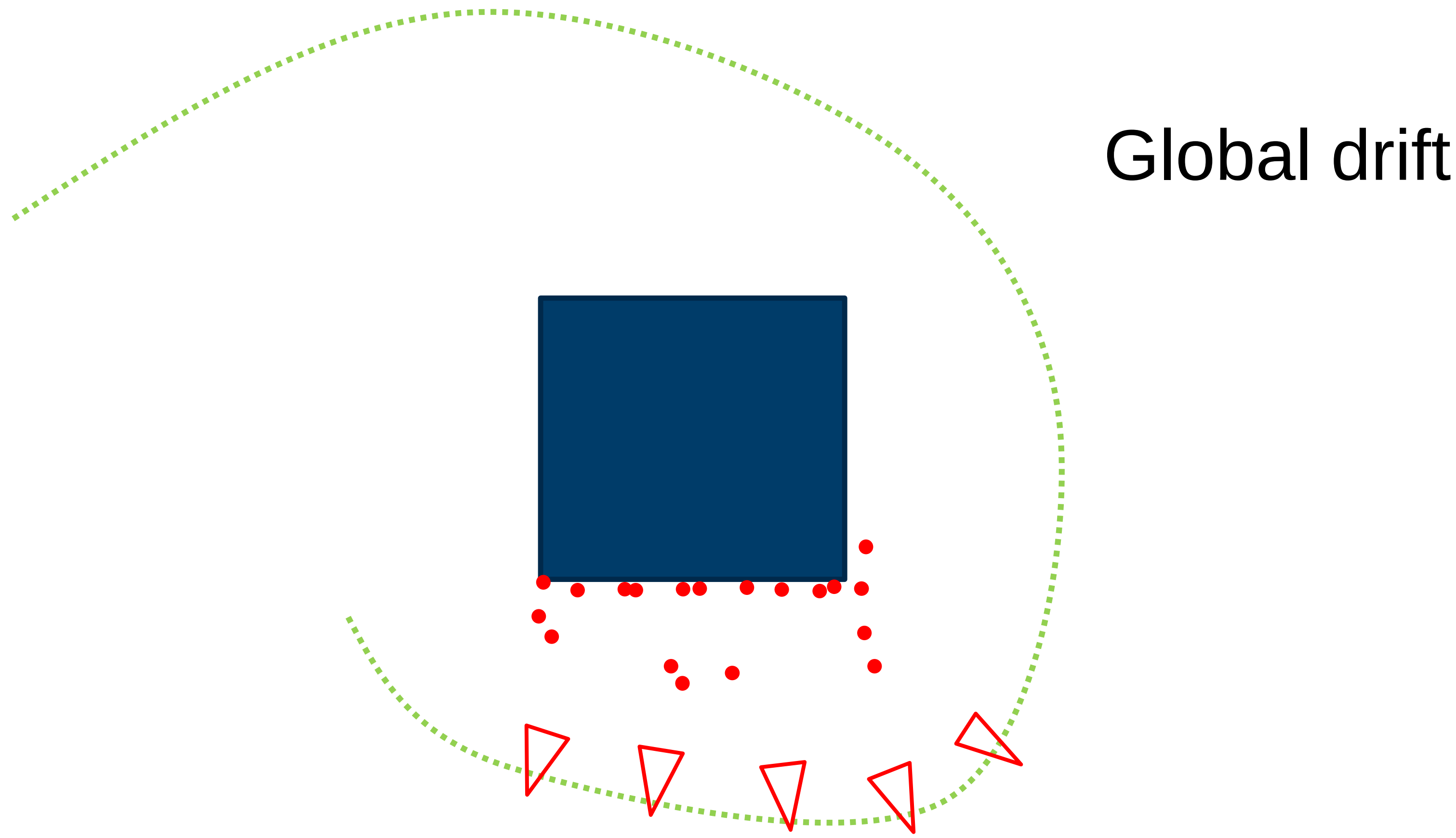

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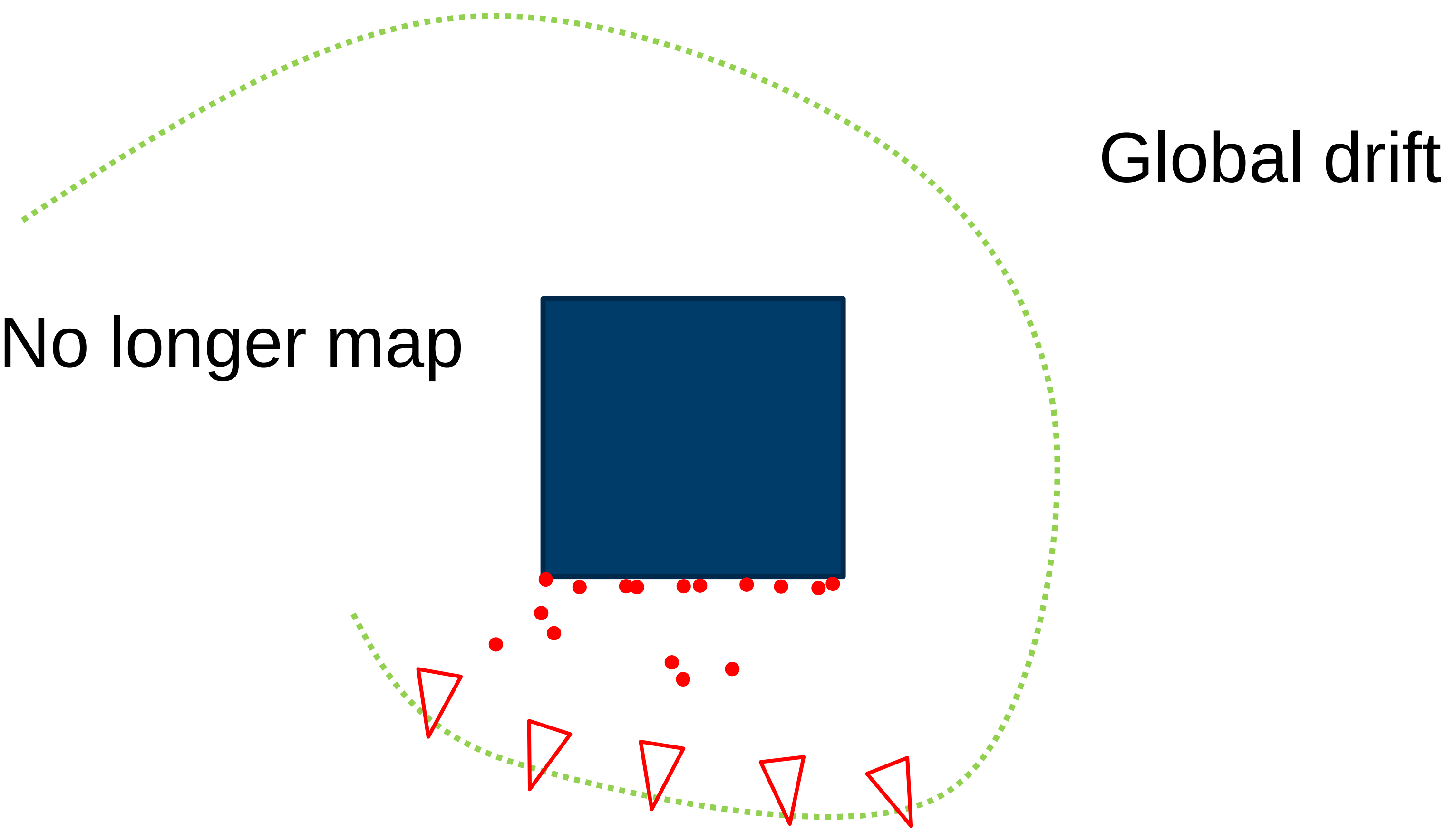

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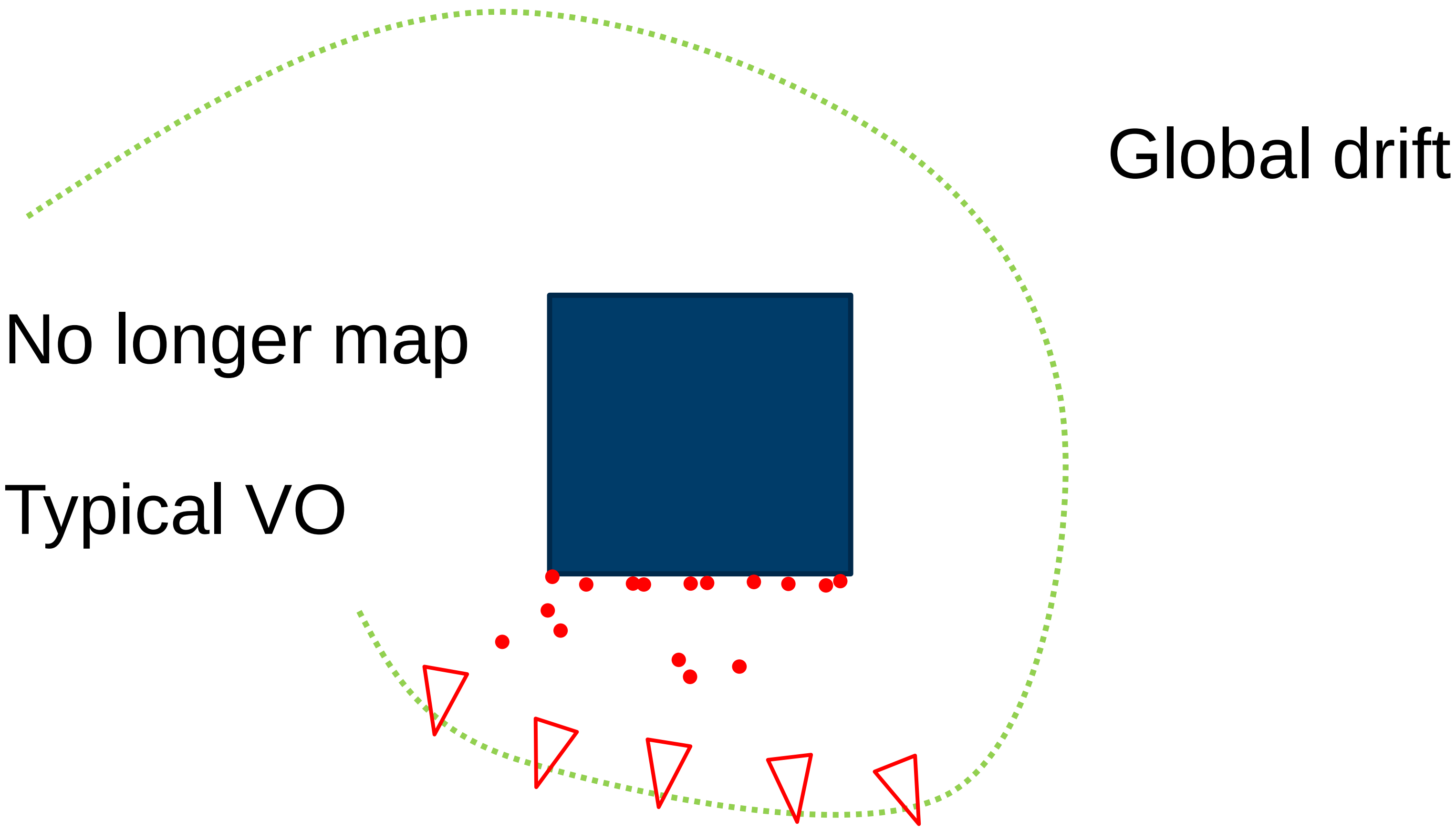
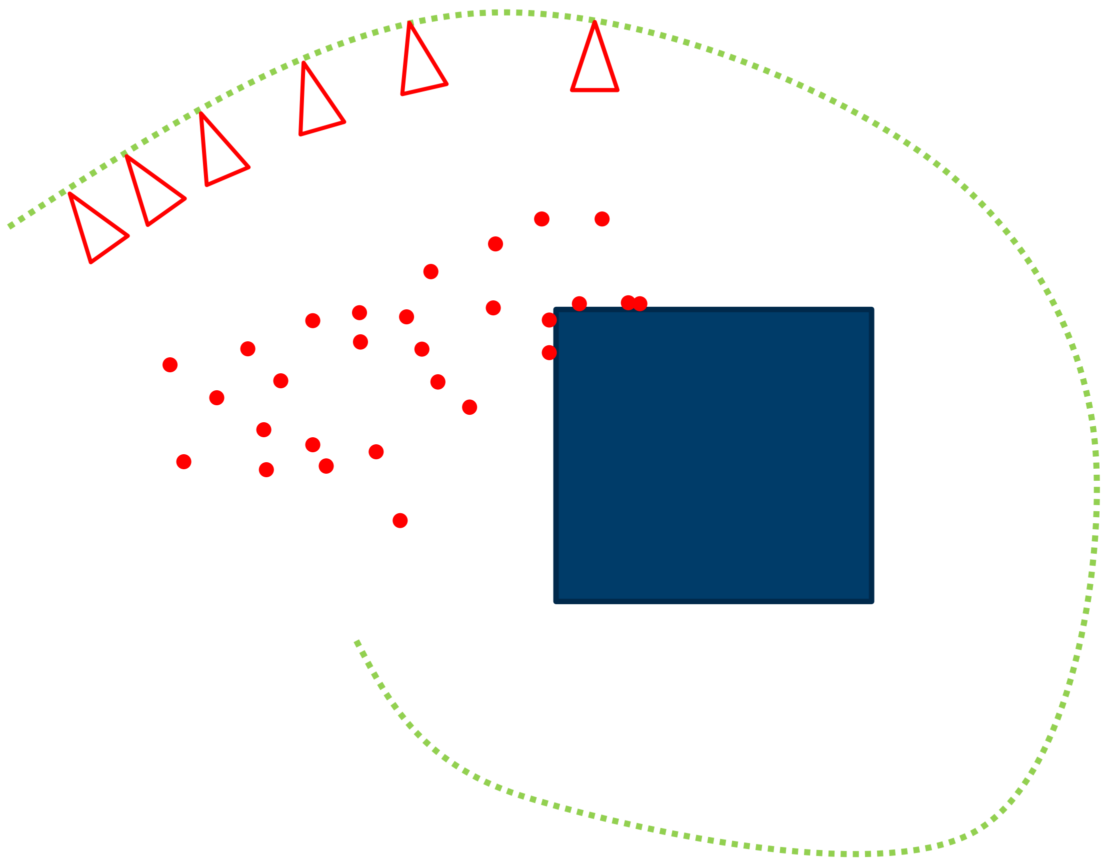


Monocular Visual SLAM



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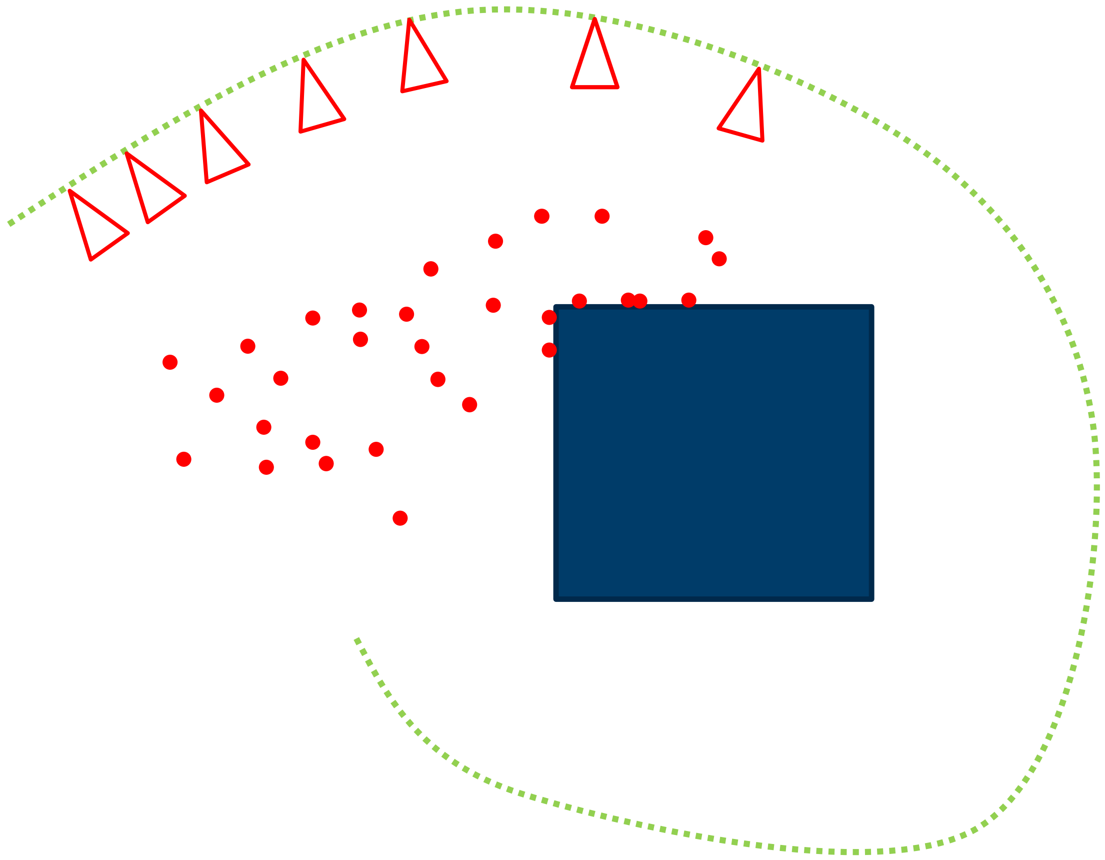

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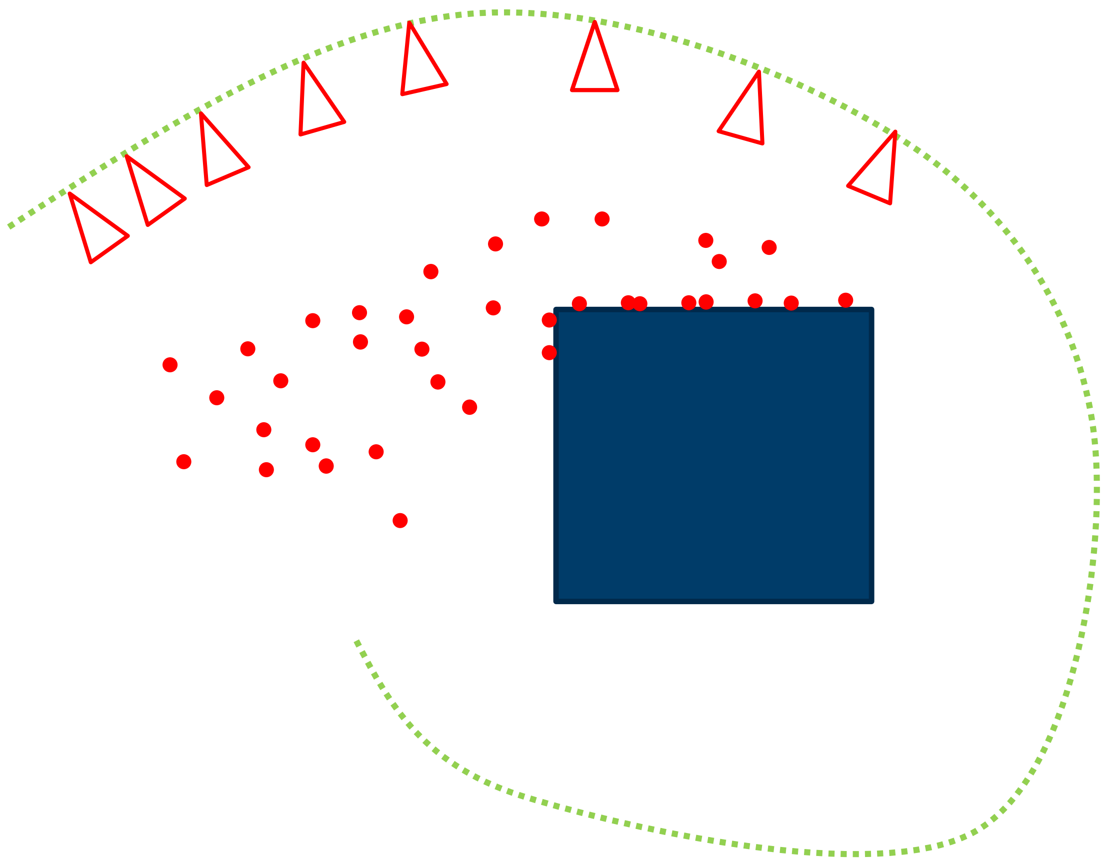

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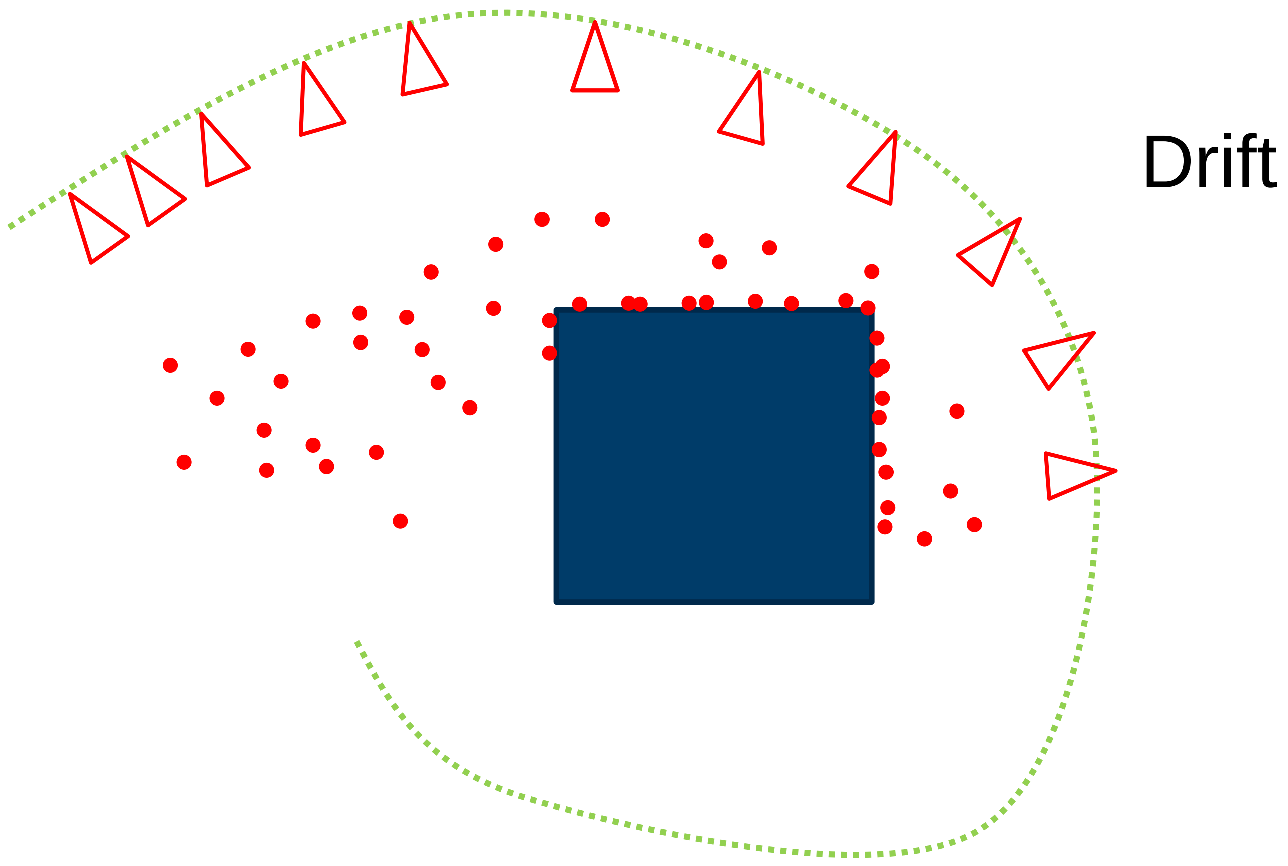

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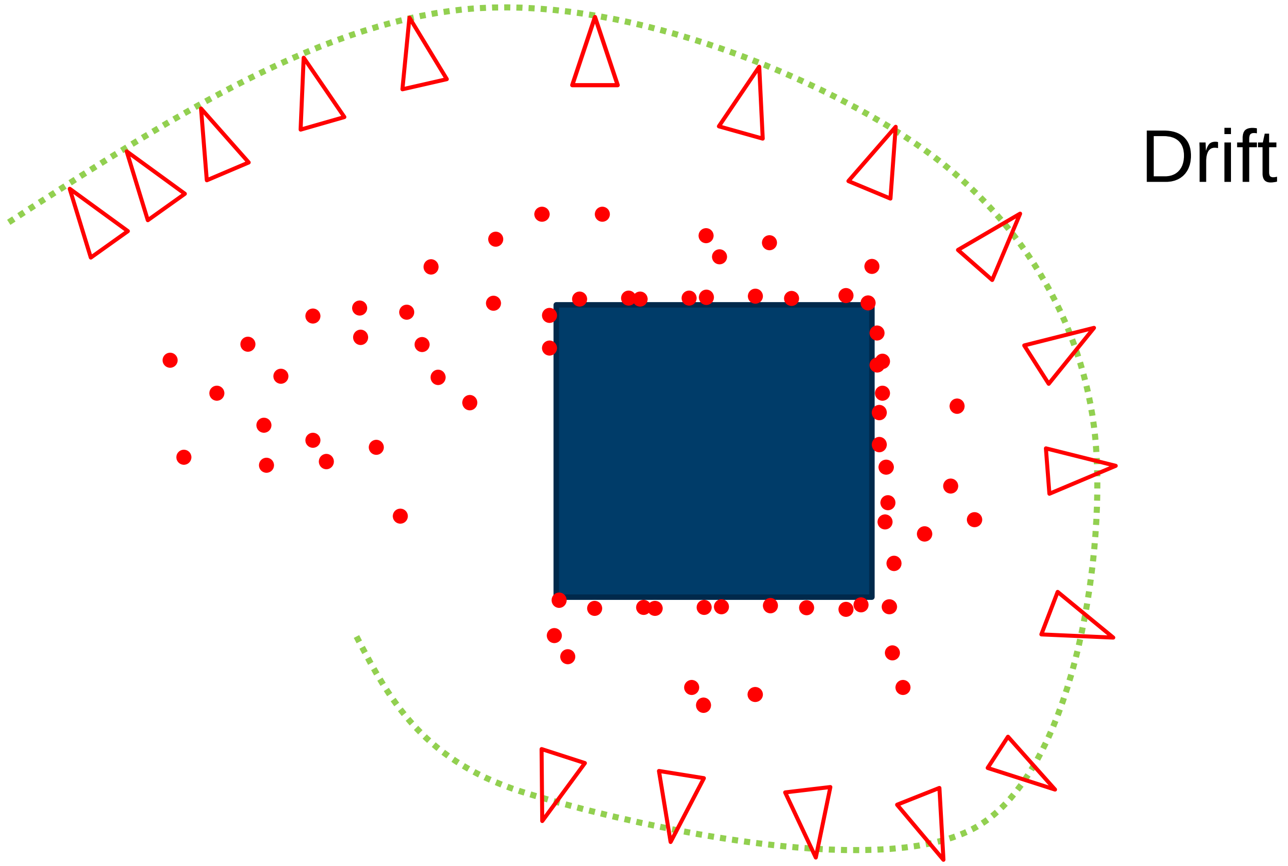
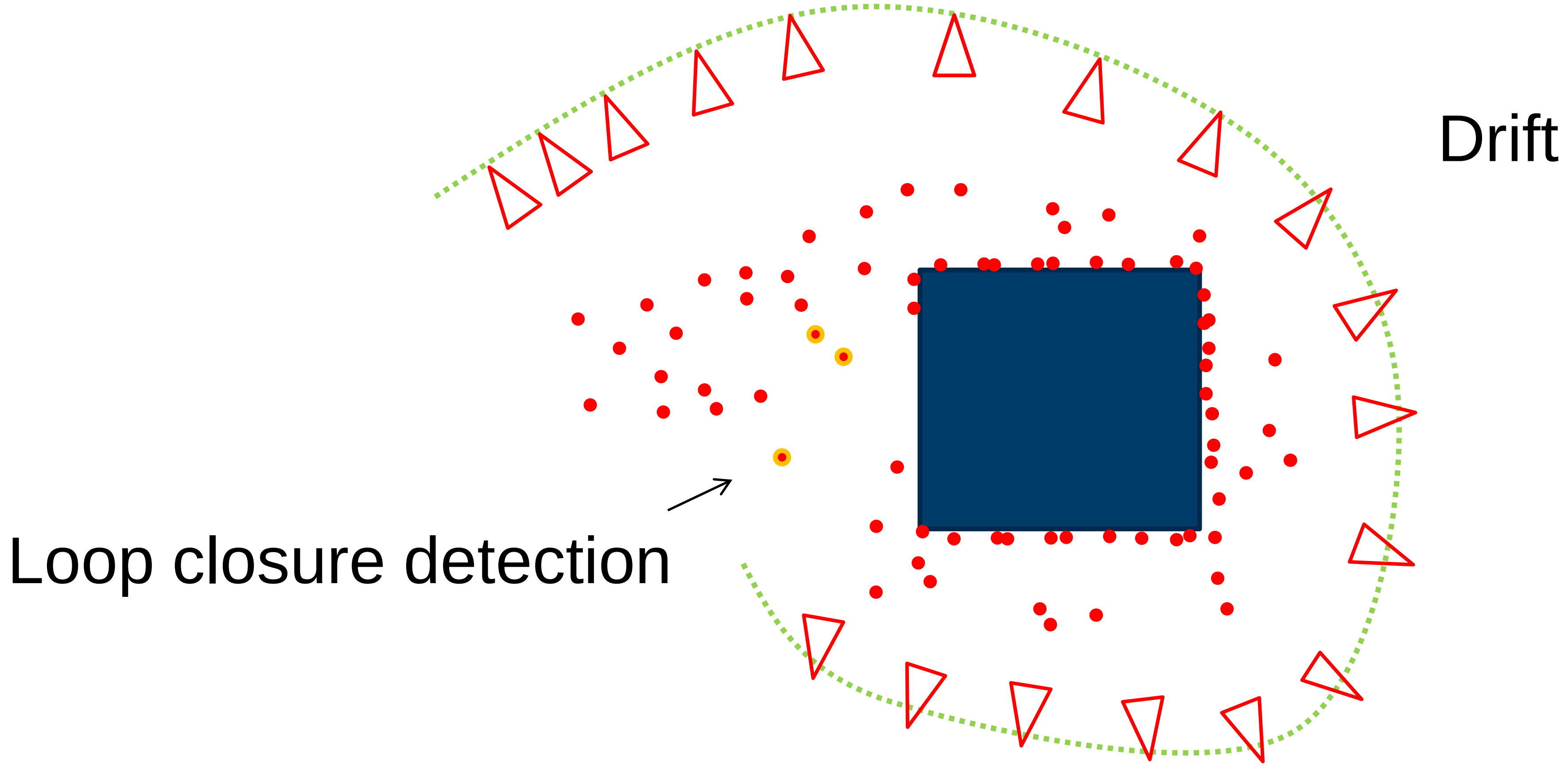
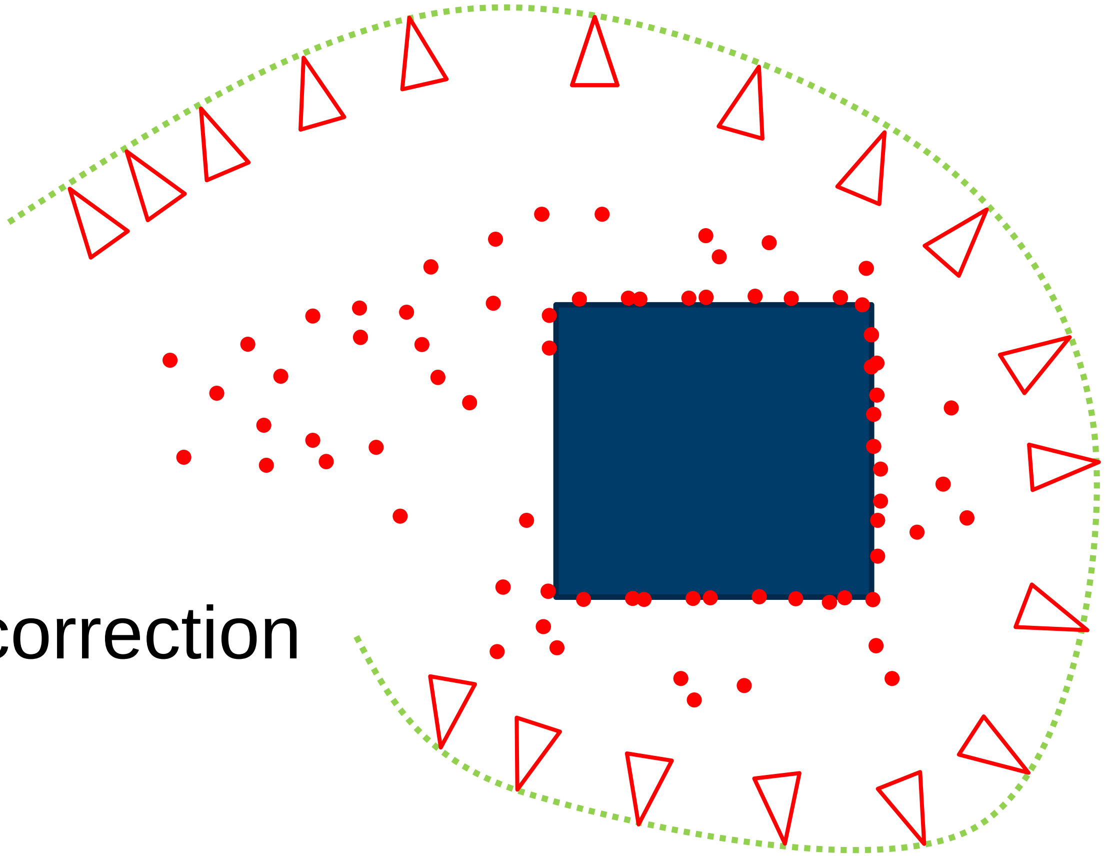


Monocular Visual SLAM

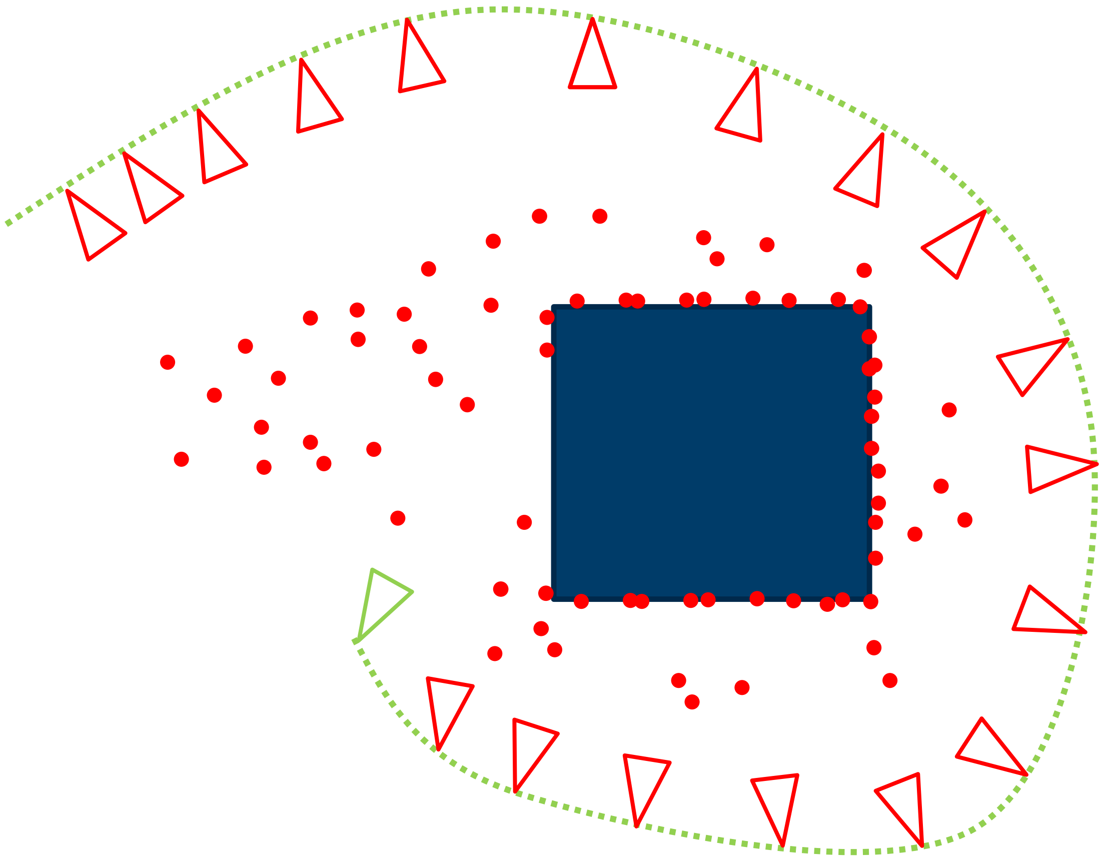


Monocular Visual SLAM

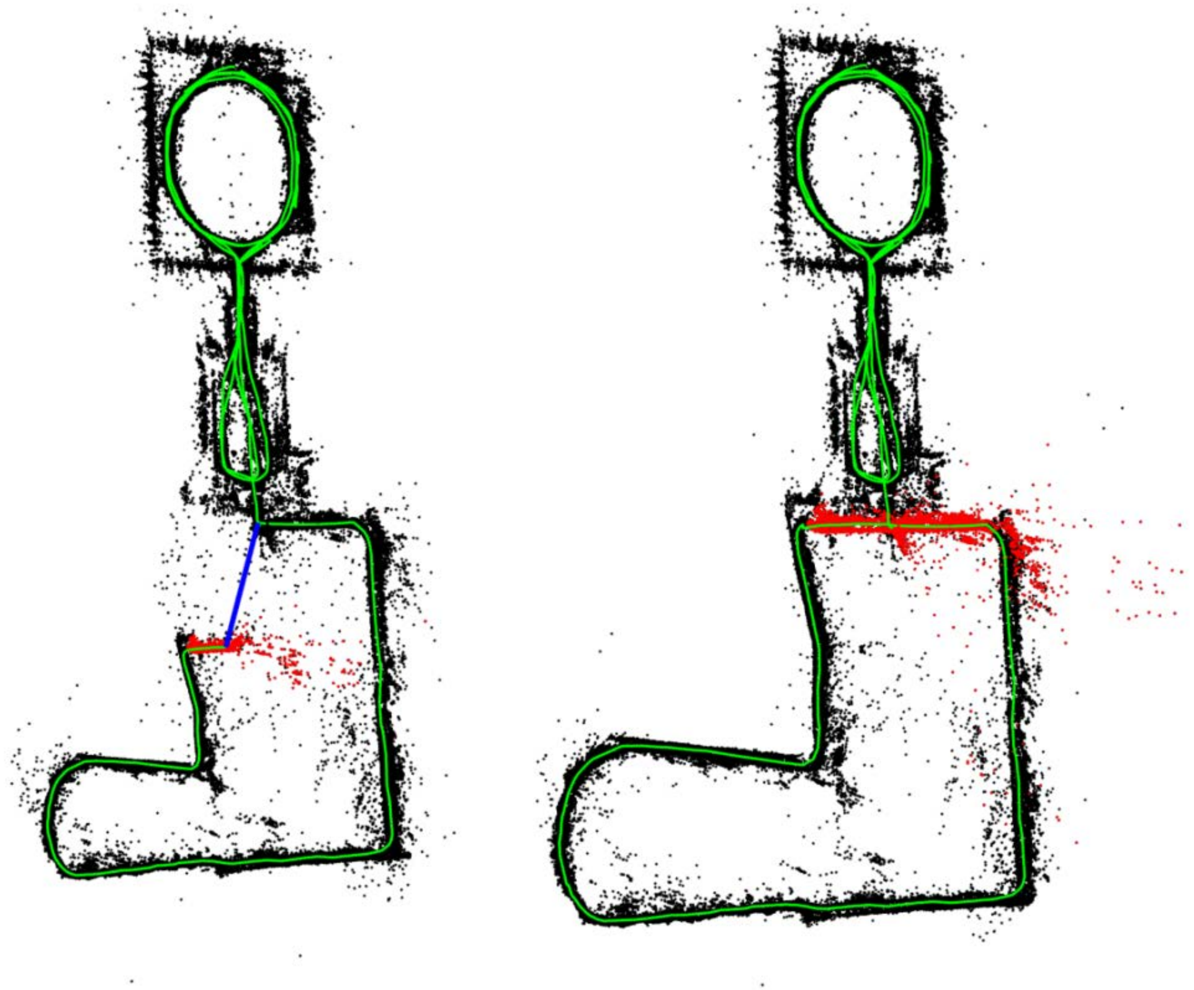


Loop closure correction

Monocular Visual SLAM



Visual SLAM vs visual odometry



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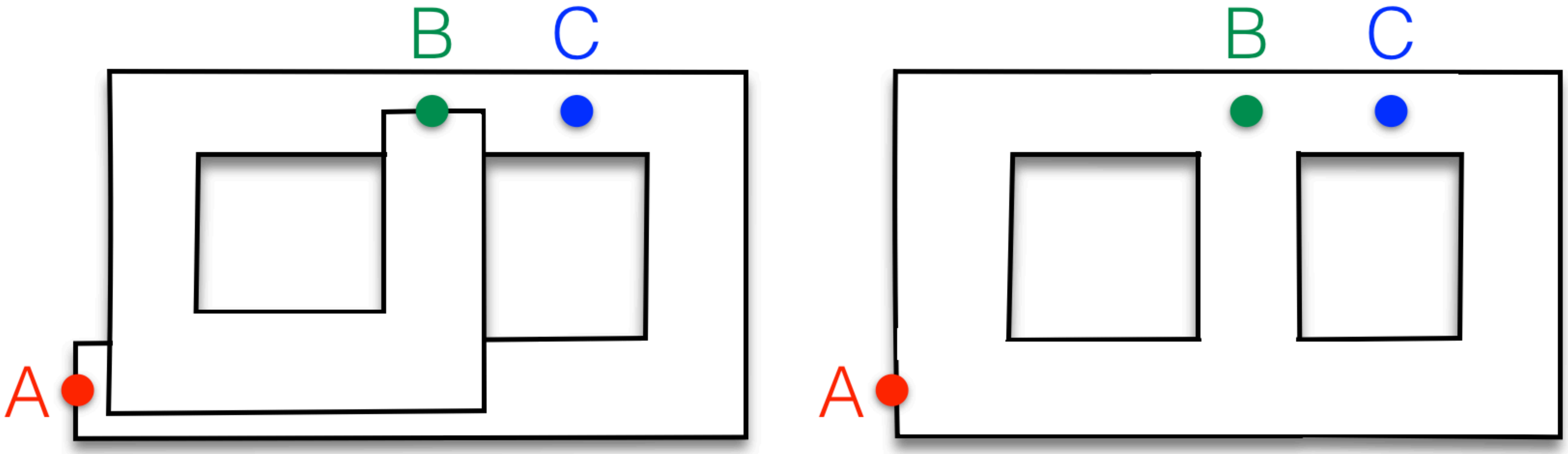
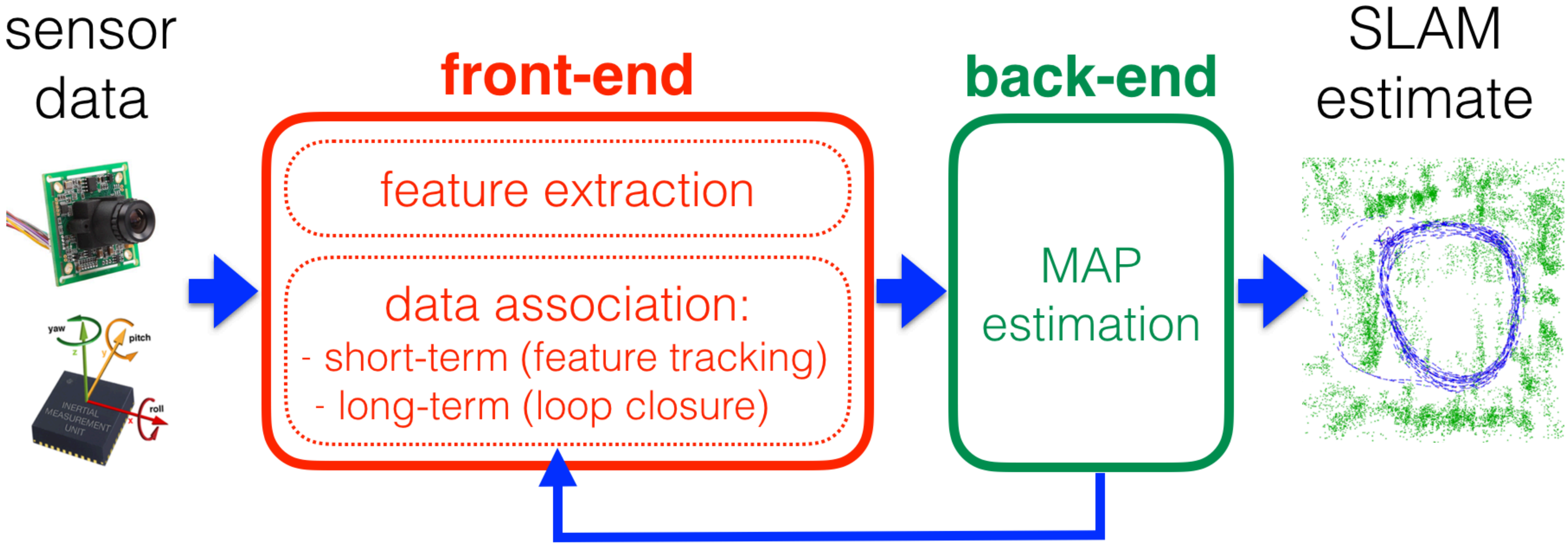
Visual SLAM vs visual odometry



Cadena, C., et al. (2016). Past, Present, and Future of Simultaneous Localization and Mapping:
Toward the Robust-Perception Age. *IEEE Transactions on Robotics*, *32*(6), 1309–1332

Components of SLAM



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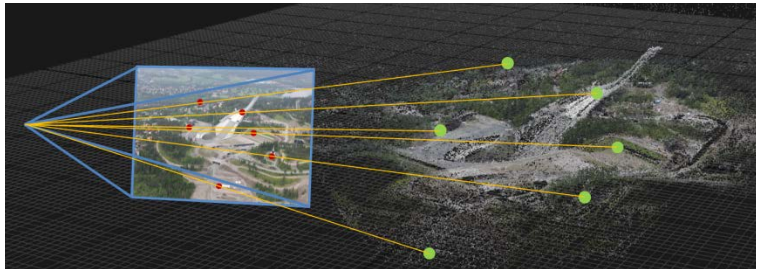
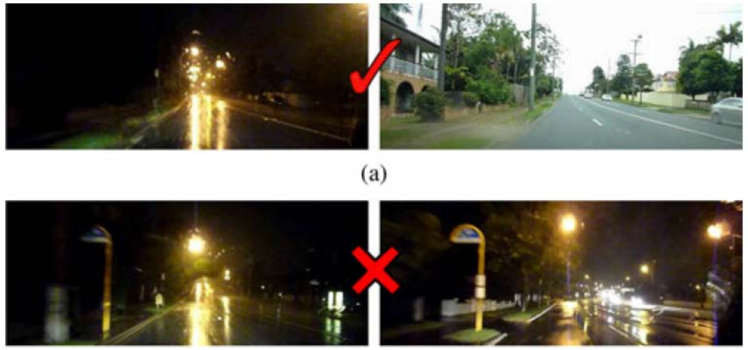
Components of VSLAM

- Short-term tracking
  - Pose estimation given the map
  - Keyframe proposals

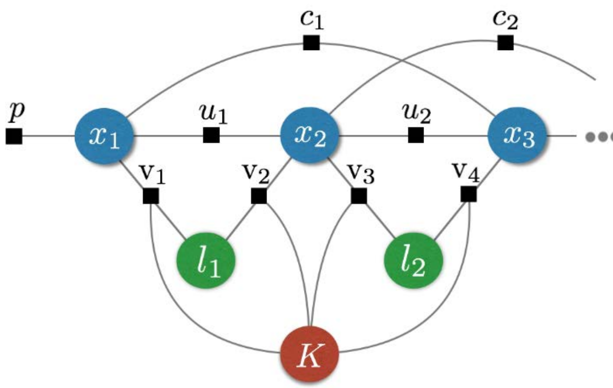
- Long-term tracking
  - Visual place recognition
  - Loop closure detection over keyframes

- Mapping
  - Building and optimizing the map over keyframes
  - Data fusion



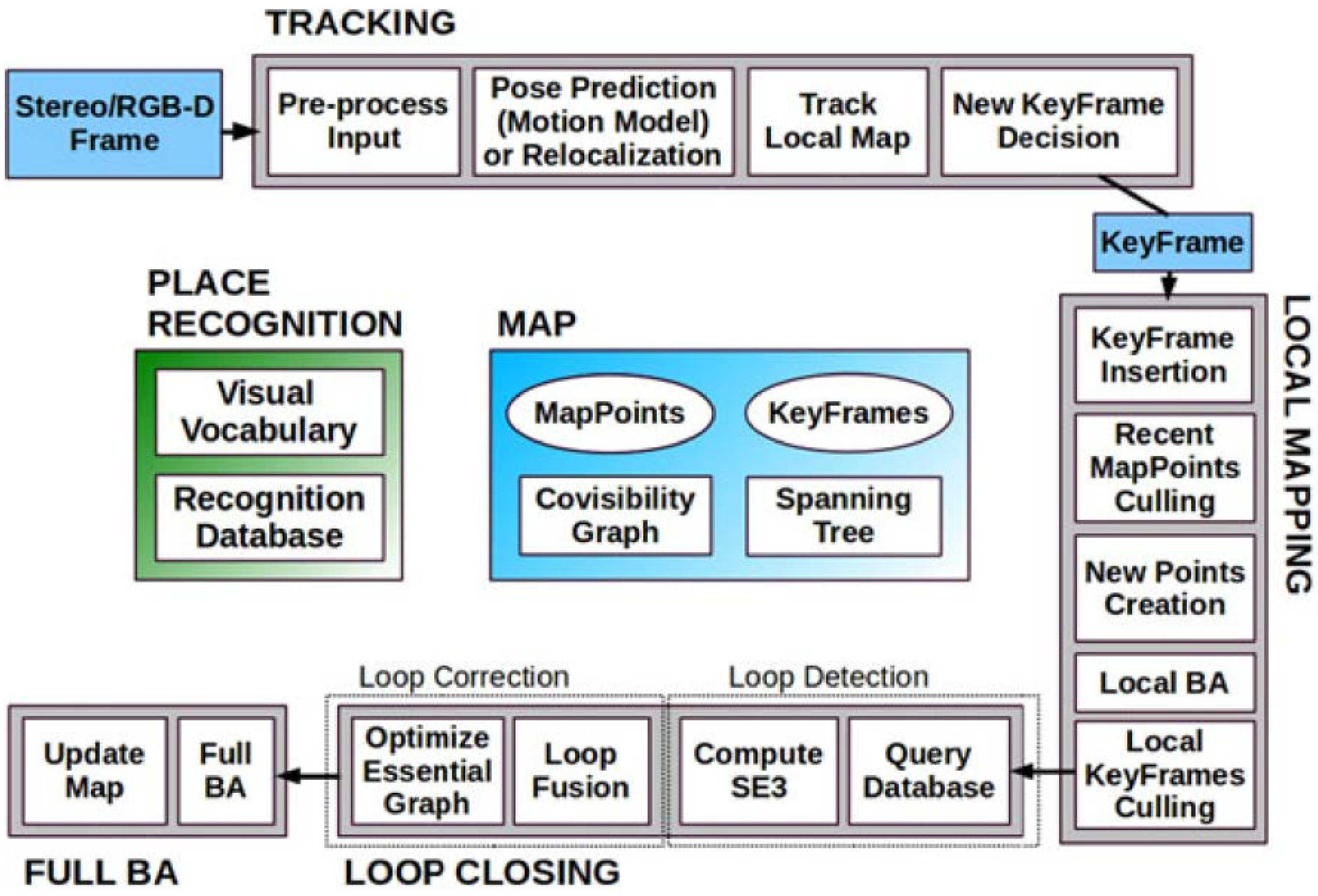


Lowry, S. et al. (2016). Visual Place Recognition: A Survey. IEEE Transactions on Robotics, 32(1), 1–19.



Cadena, C., et al. (2016). Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. *IEEE Transactions on Robotics*, *32*(6), 1309–1332

Example: ORB-SLAM 2



R. Mur-Artal and J. D. Tardos, "ORB-SLAM2: An Open-Source SLAM System for Monocular, Stereo, and RGB-D Cameras," *IEEE Trans. Robot.*, pp. 1–8, 2017.

Supplementary material

- “Parallel Tracking and Mapping for Small AR Workspaces”,
  Klein and Murray,
  In Proc. International Symposium on Mixed and Augmented Reality (ISMAR'07, Nara), 2007
  https://www.robots.ox.ac.uk/~vgg/rg/papers/klein_murray__2007__ptam.pdf

- “Past, Present, and Future of Simultaneous Localization And Mapping: Towards the Robust-Perception Age”,
  Cadena et al., IEEE Transactions on Robotics 32 (6) pp 1309-1332, 2016
  https://arxiv.org/abs/1606.05830

- “Visual Place Recognition: A Survey“,
  Lowry, S. et al., IEEE Transactions on Robotics, 32 (1), pp 1–19, 2016
  https://ieeexplore.ieee.org/document/7339473