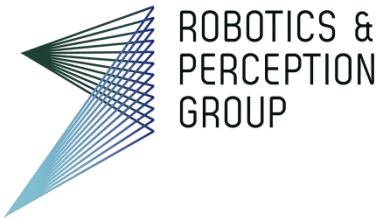


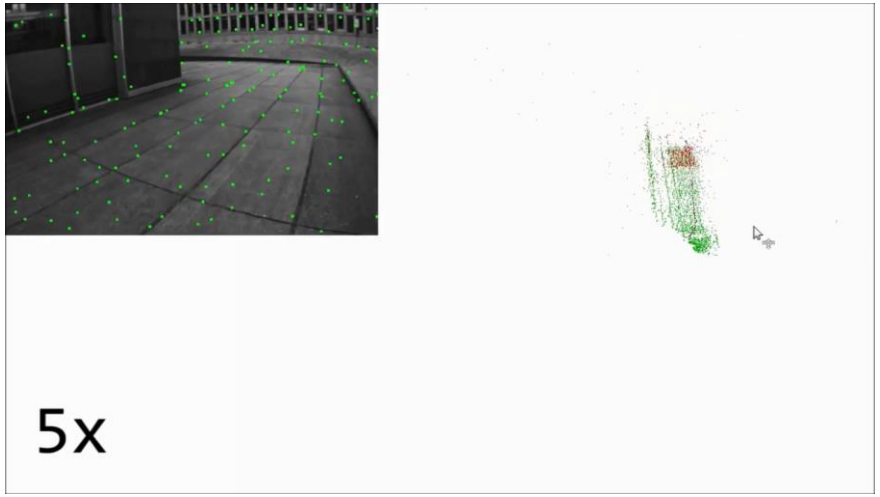
From Single-Agent to Decentralized Multi-Agent SLAM

Titus Cieslewski and Davide Scaramuzza

Our Research Areas

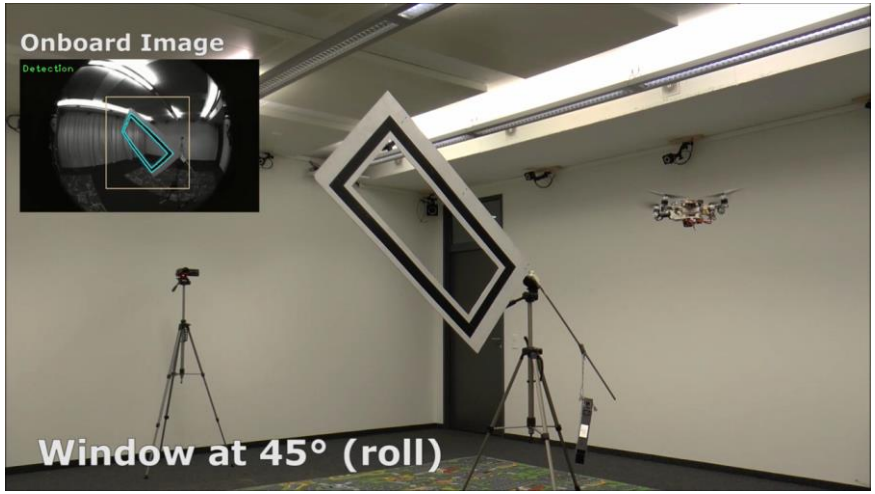
Visual-Inertial State Estimation (SVO)

[IJCV'11, PAMI'13, RSS'15, TRO'16]



Vision-based Navigation of Flying Robots

[AURO'12, RAM'14, JFR'15]

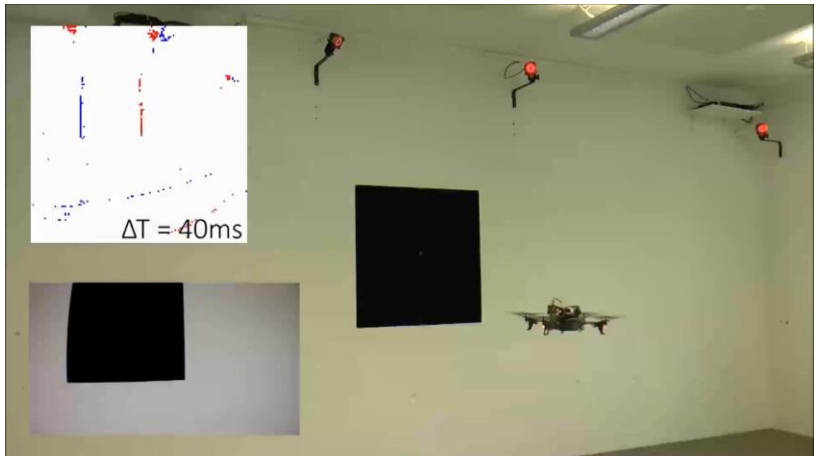


Deep Learning for End-to-End Navigation

[RAL'16]

Event-based Vision for Aggressive Flight

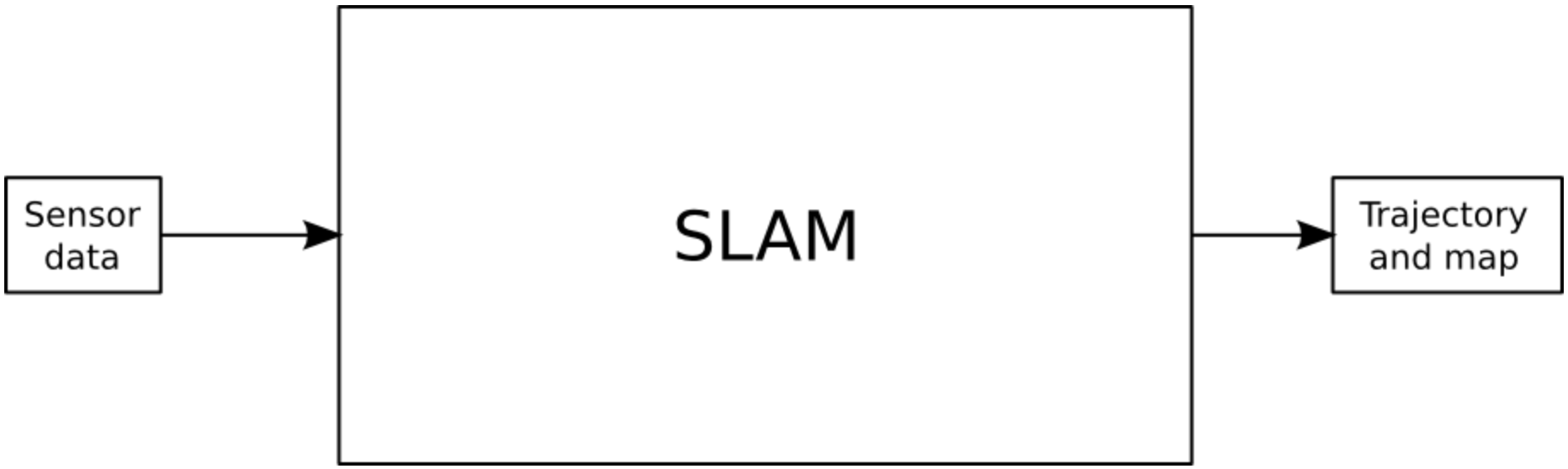
[IROS'3, ICRA'14, RSS'15]



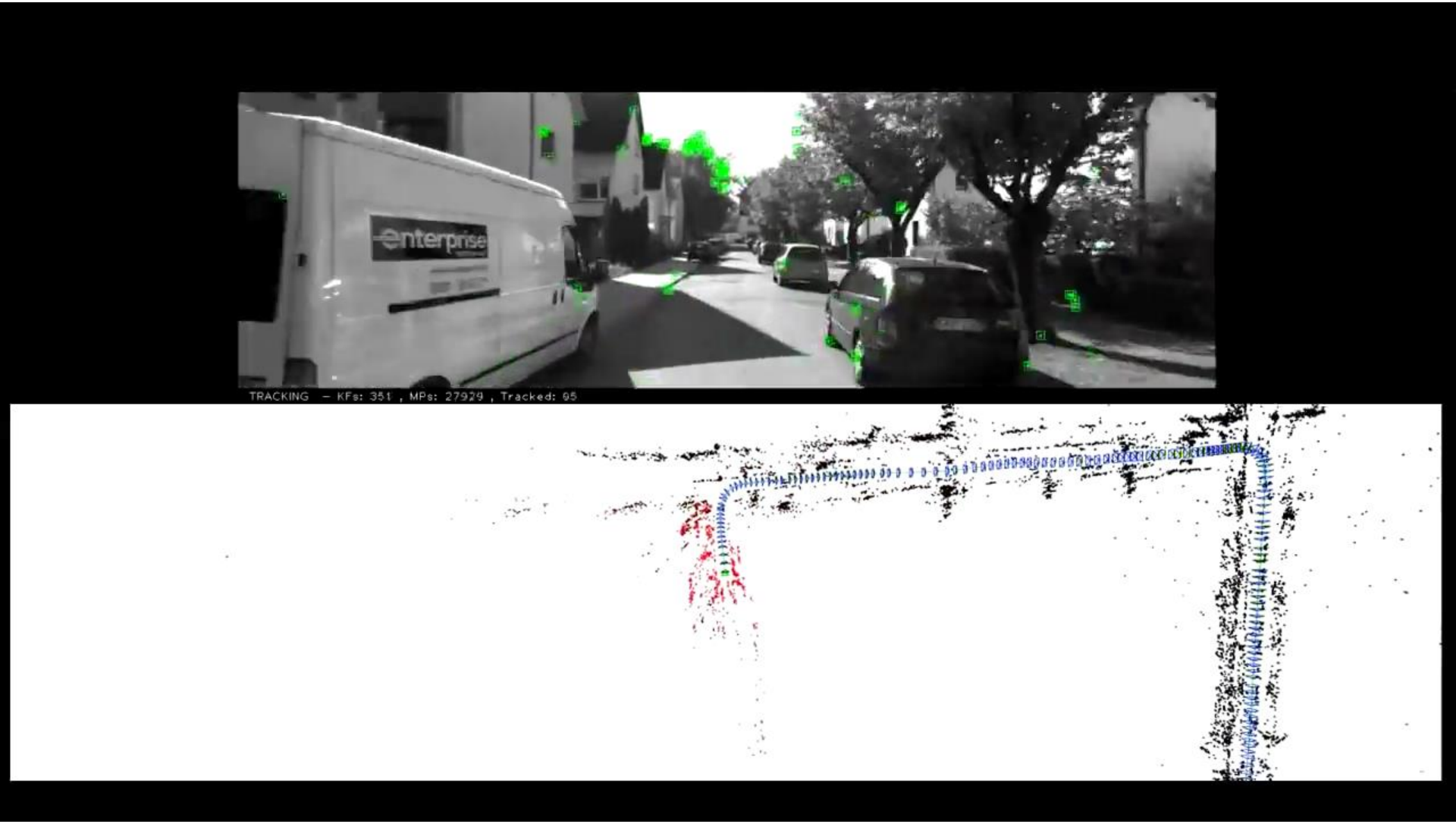
Outline

- From single-robot SLAM to **centralized** multi-robot SLAM
  - [Forster 2013]
- **Decentralized** multi-robot SLAM: **Place Recognition**
  - [Cieslewski 2017]
- Decentralized collaboration with **version control**
  - [Cieslewski 2015]

From single-robot to multi-robot SLAM



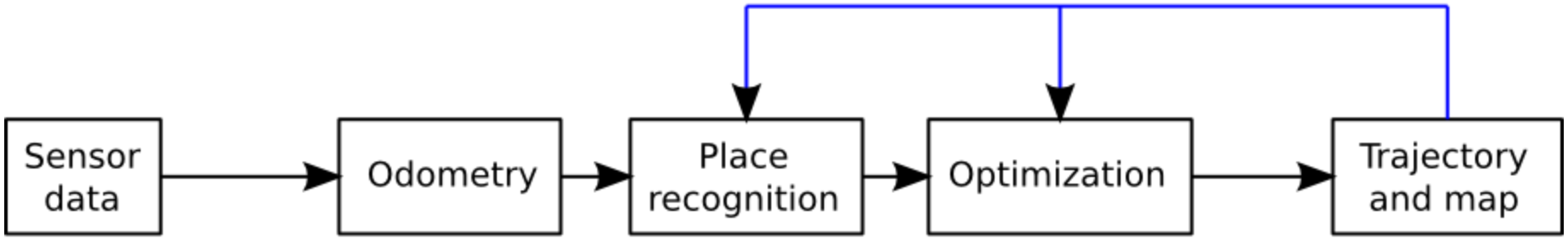
Single-robot SLAM



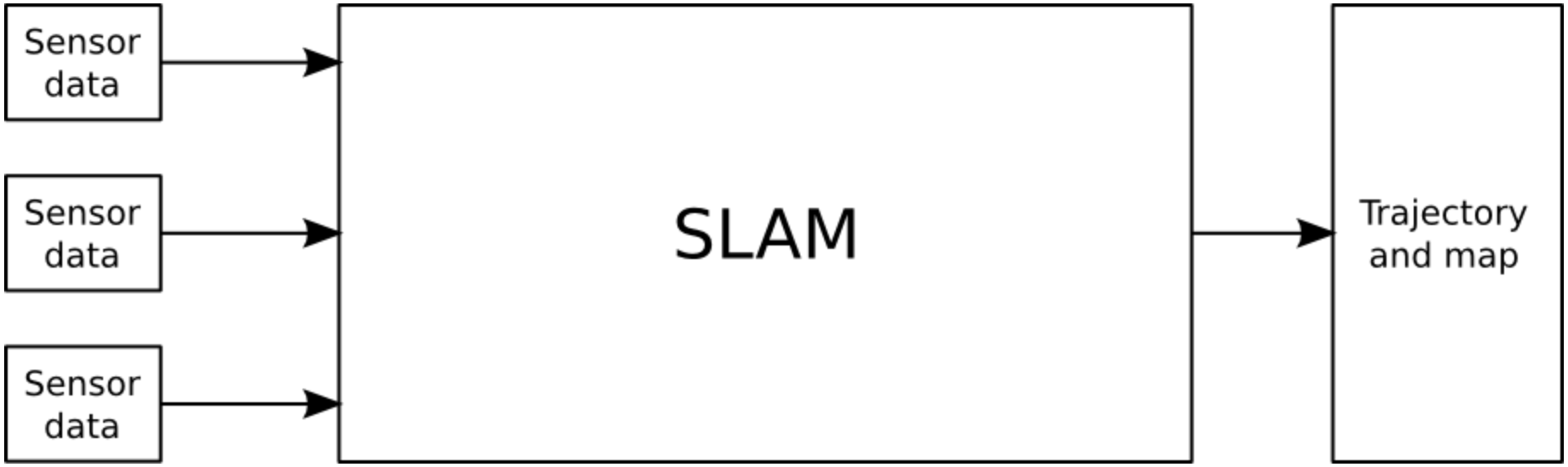
[Mur-Artal 2015 ORB-SLAM]

Single-robot SLAM components

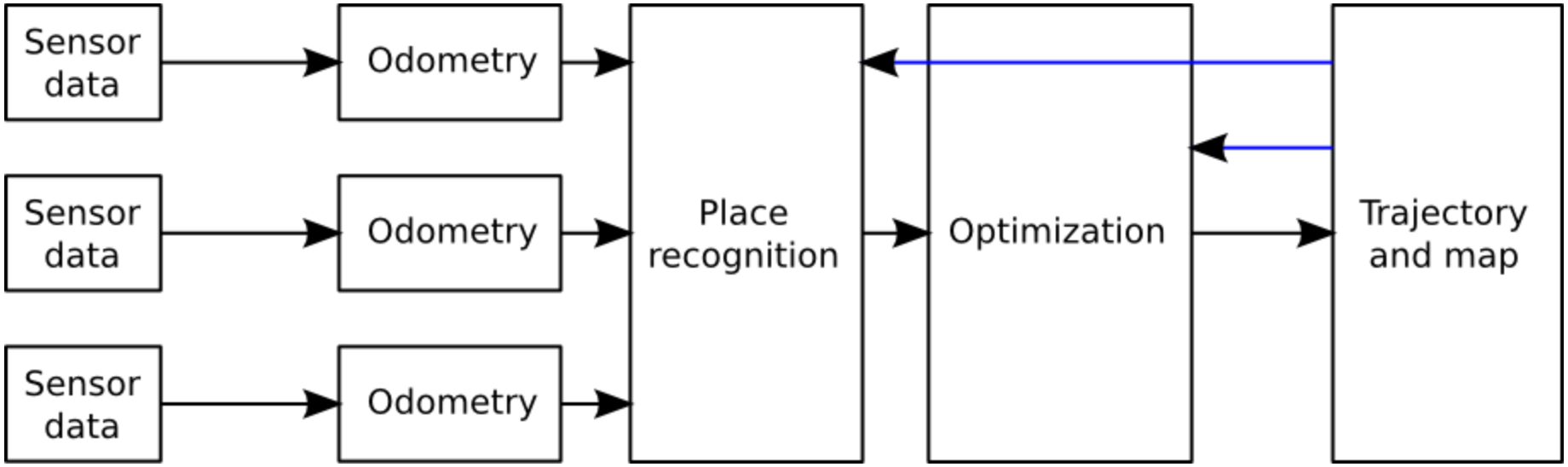
- Our focus is on **visual / visual-inertial** SLAM

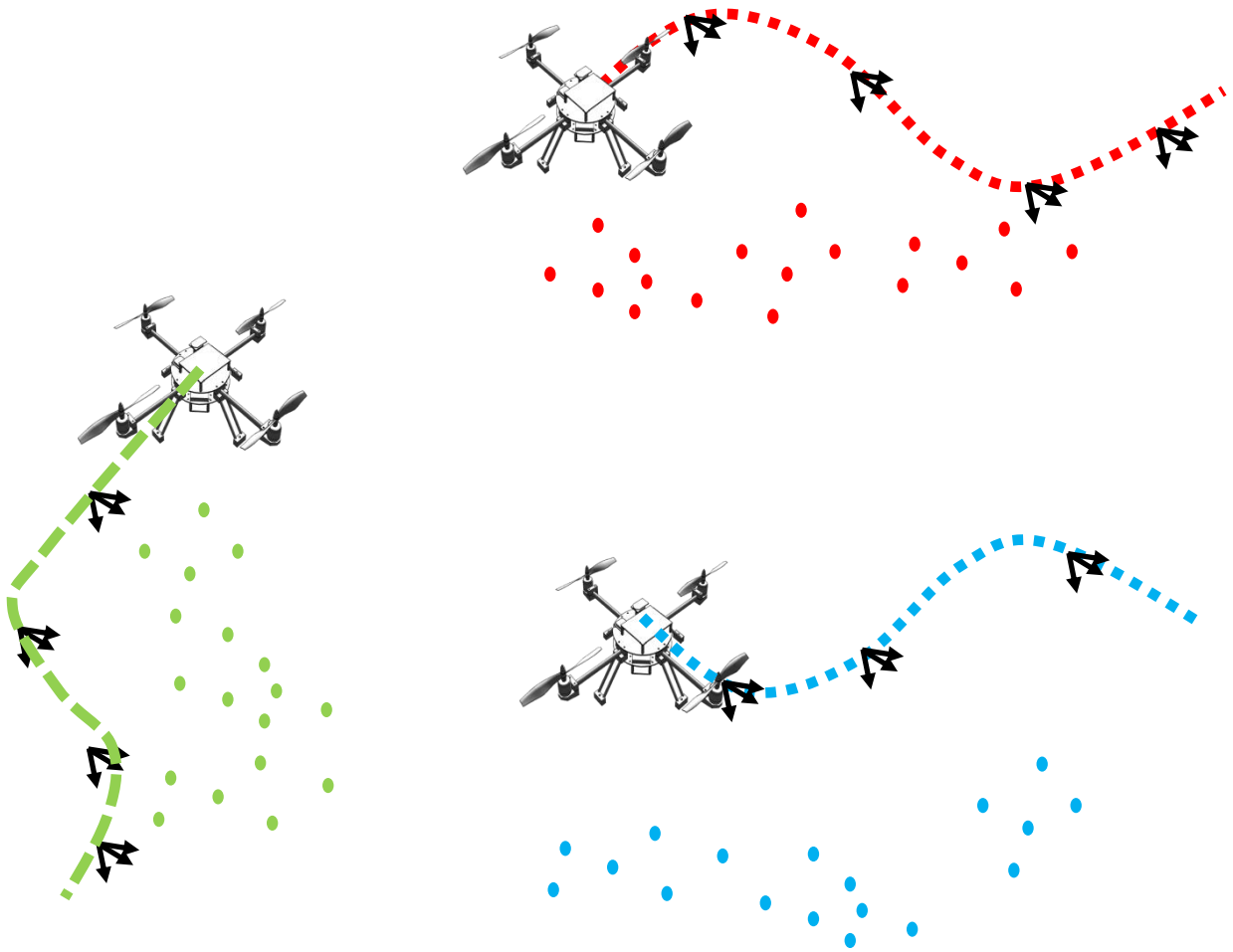


Multi-robot SLAM

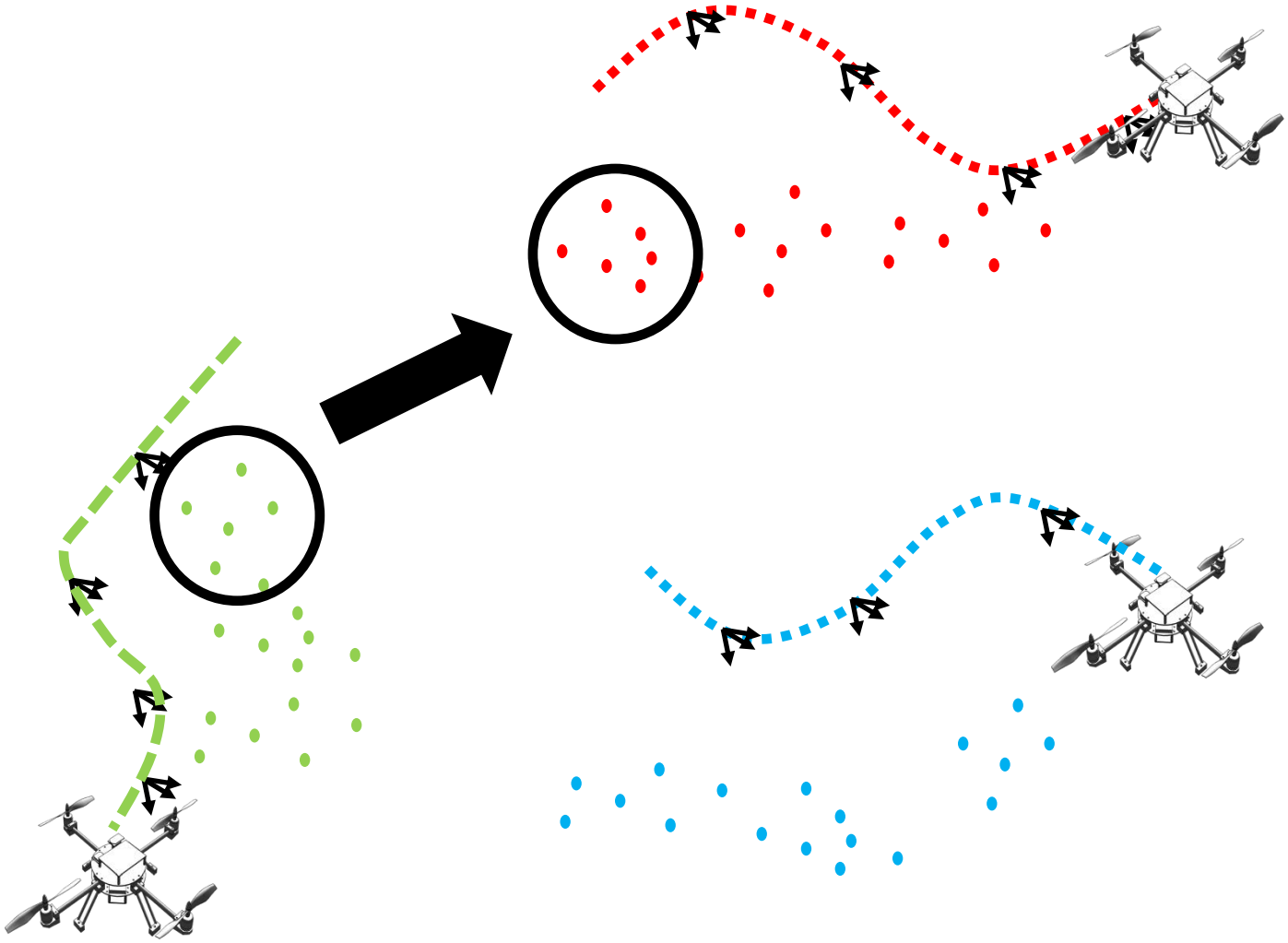


Centralized multi-robot SLAM





C. Forster, S. Lynen, L. Kneip, D. Scaramuzza: *Collaborative Monocular SLAM with Multiple Micro Aerial Vehicles* **IROS 2013**



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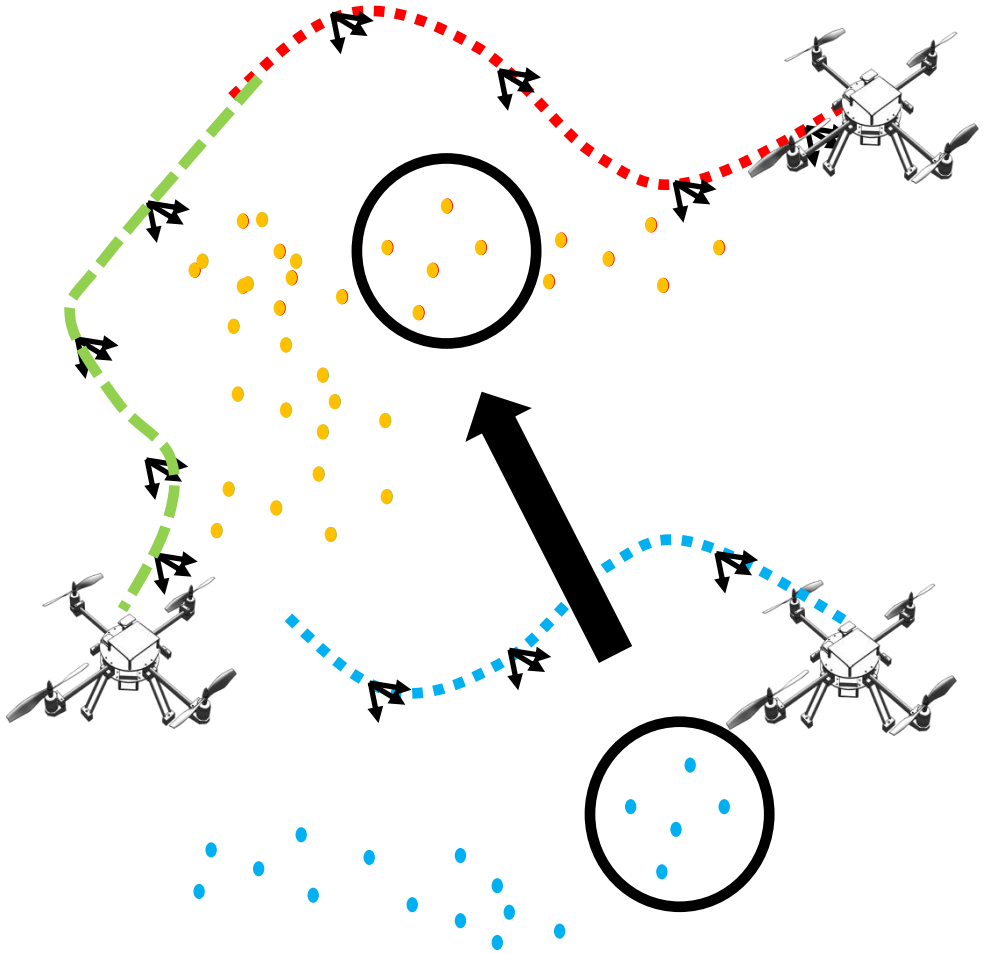

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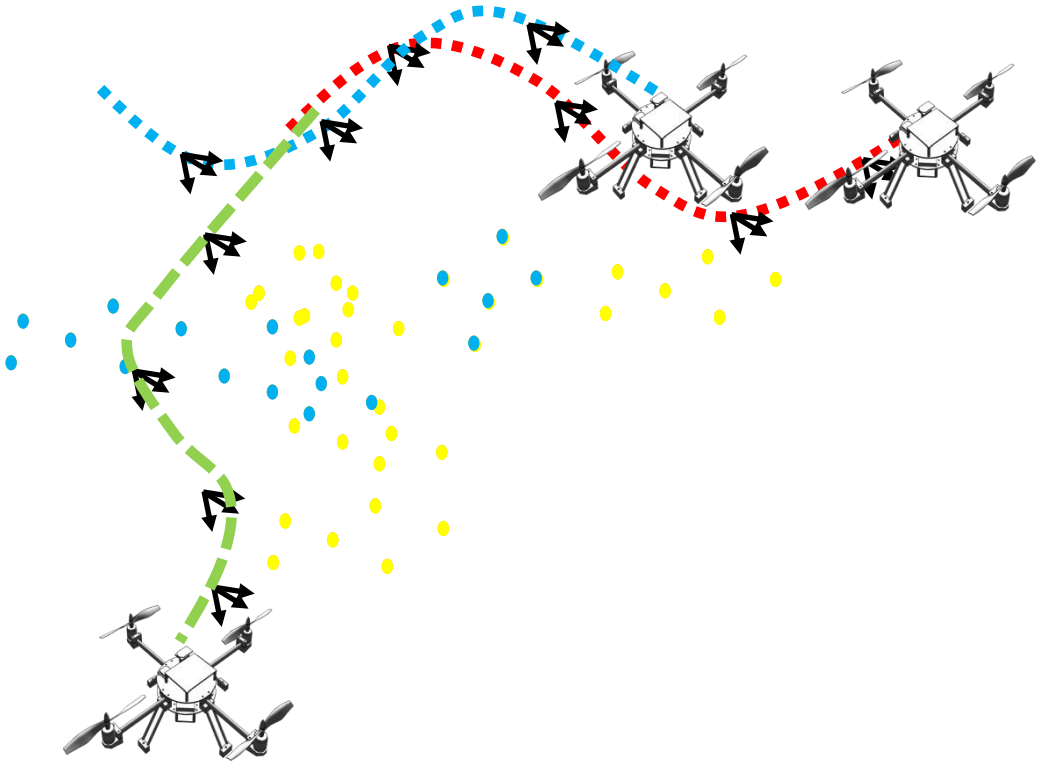

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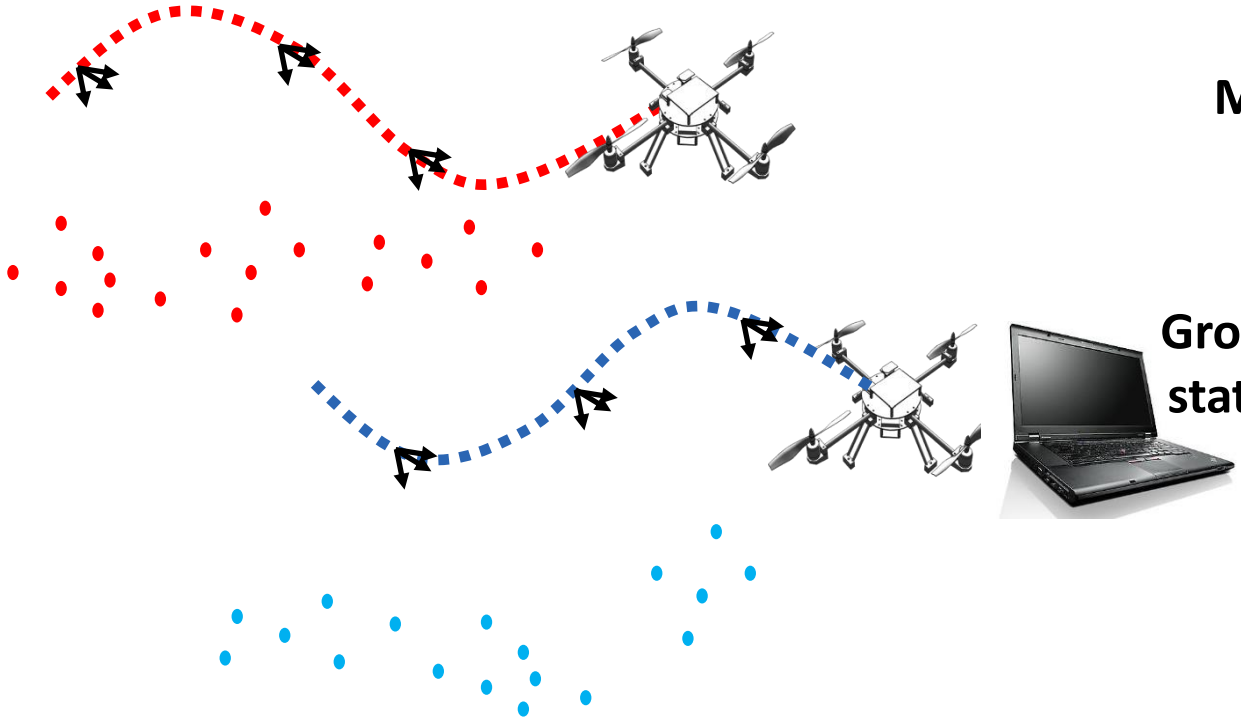
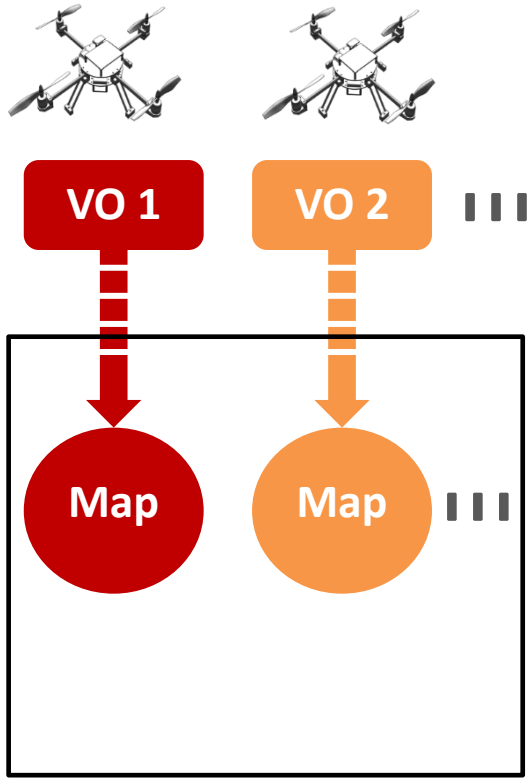
System Overview





Distributed processing:

- **Each MAV** runs an **onboard visual odometry** and **streams point features and relative poses** (1 Mbit/s instead of 90 Mbit/s for full frames at 30 Hz)

- The **ground station** computes local maps for each MAV, detects overlaps, and **merges different maps into global map**

C. Forster, S. Lynen, L. Kneip, D. Scaramuzza: *Collaborative Monocular SLAM with Multiple Micro Aerial Vehicles* **IROS 2013**

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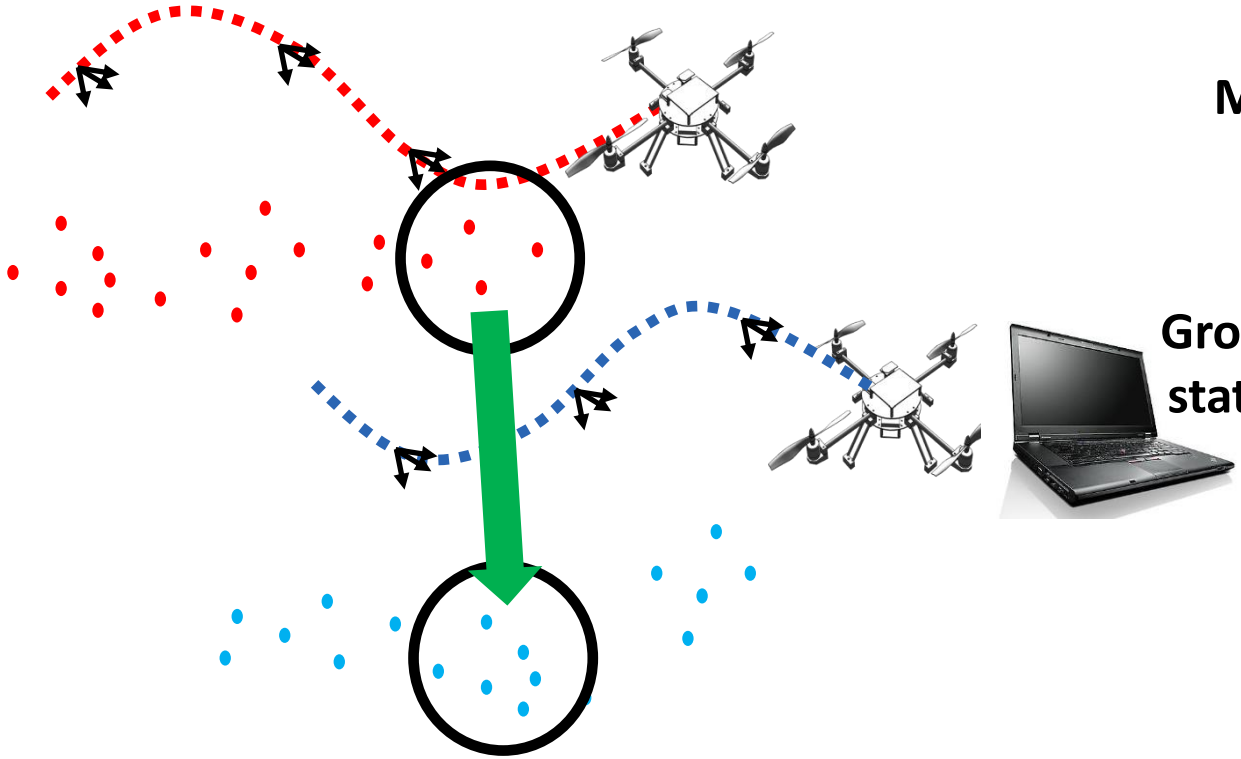

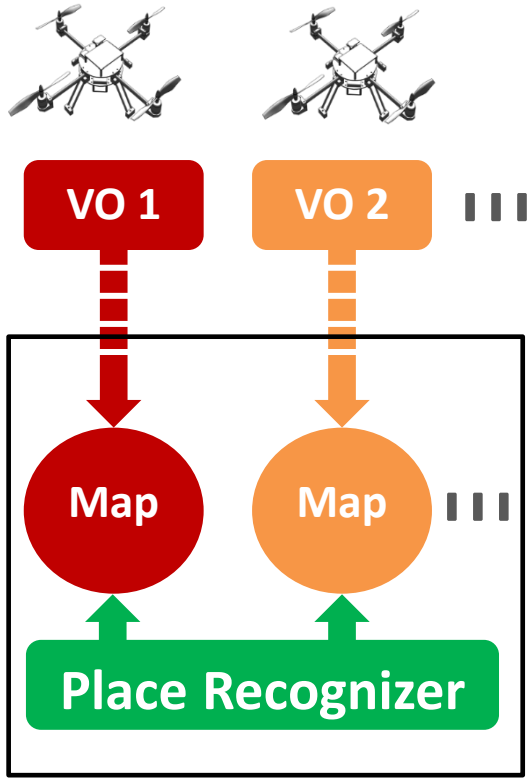

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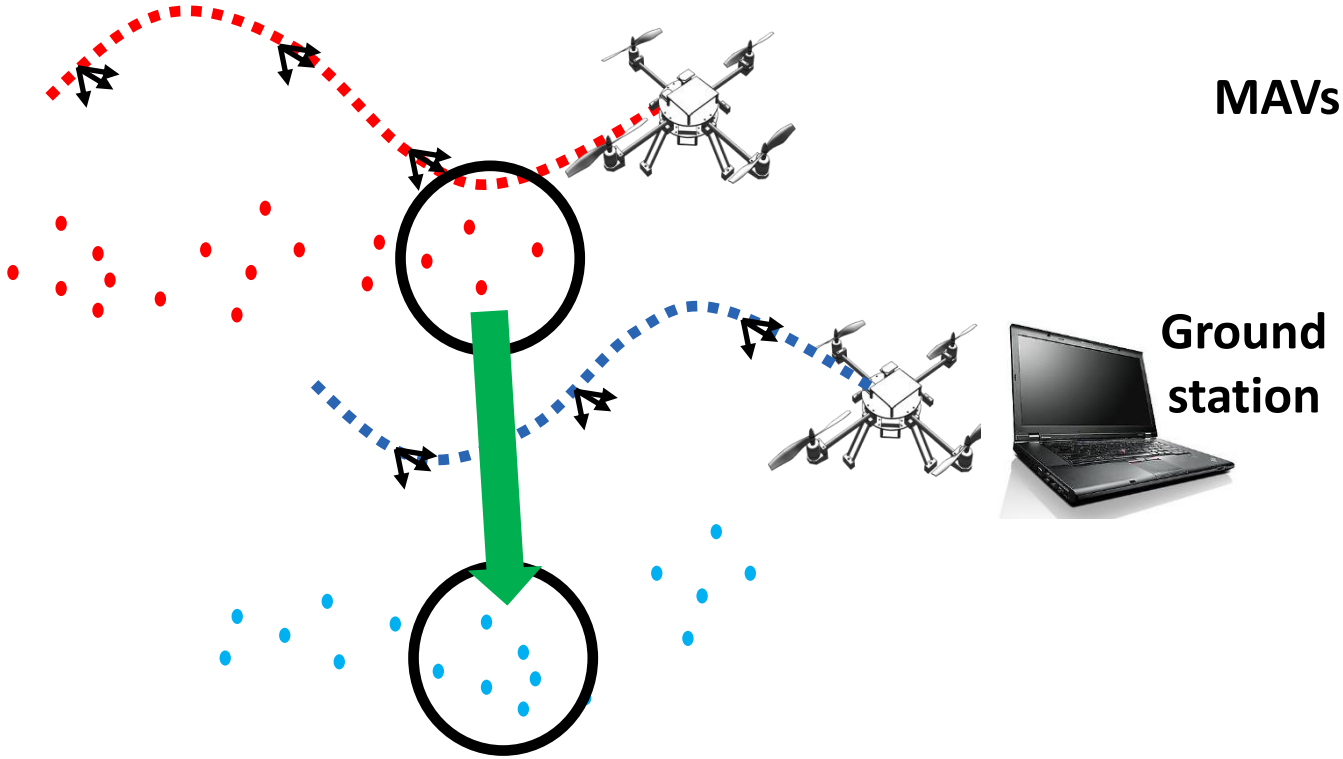

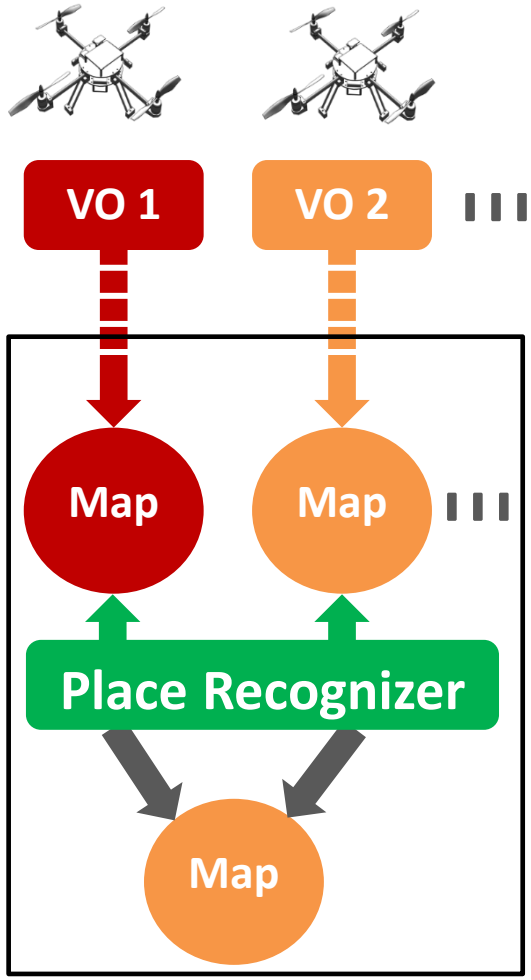

Ground station

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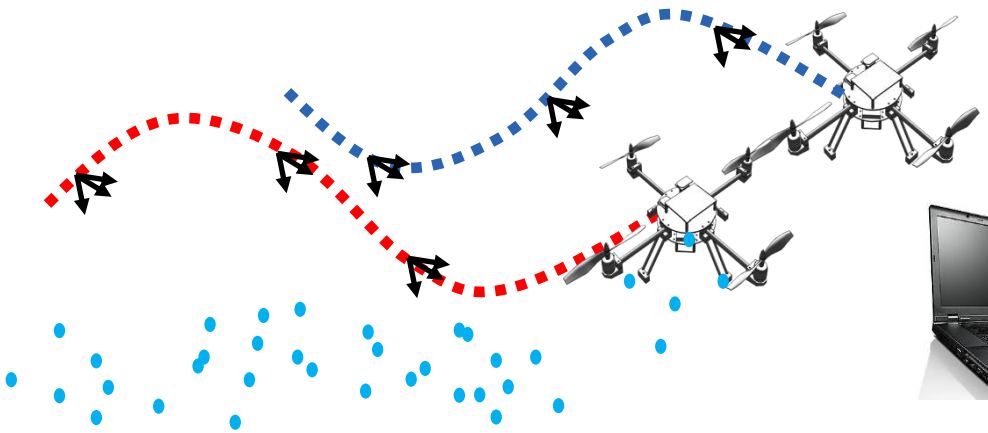
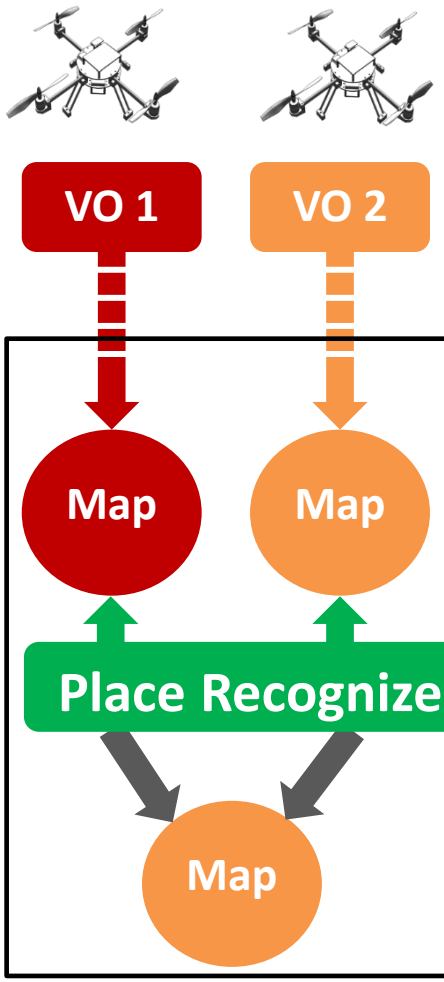


Ground station



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Mapping on the Groundstation

MAV

R, t

MAVs

VO 1

Map

Ground station

Groundstation

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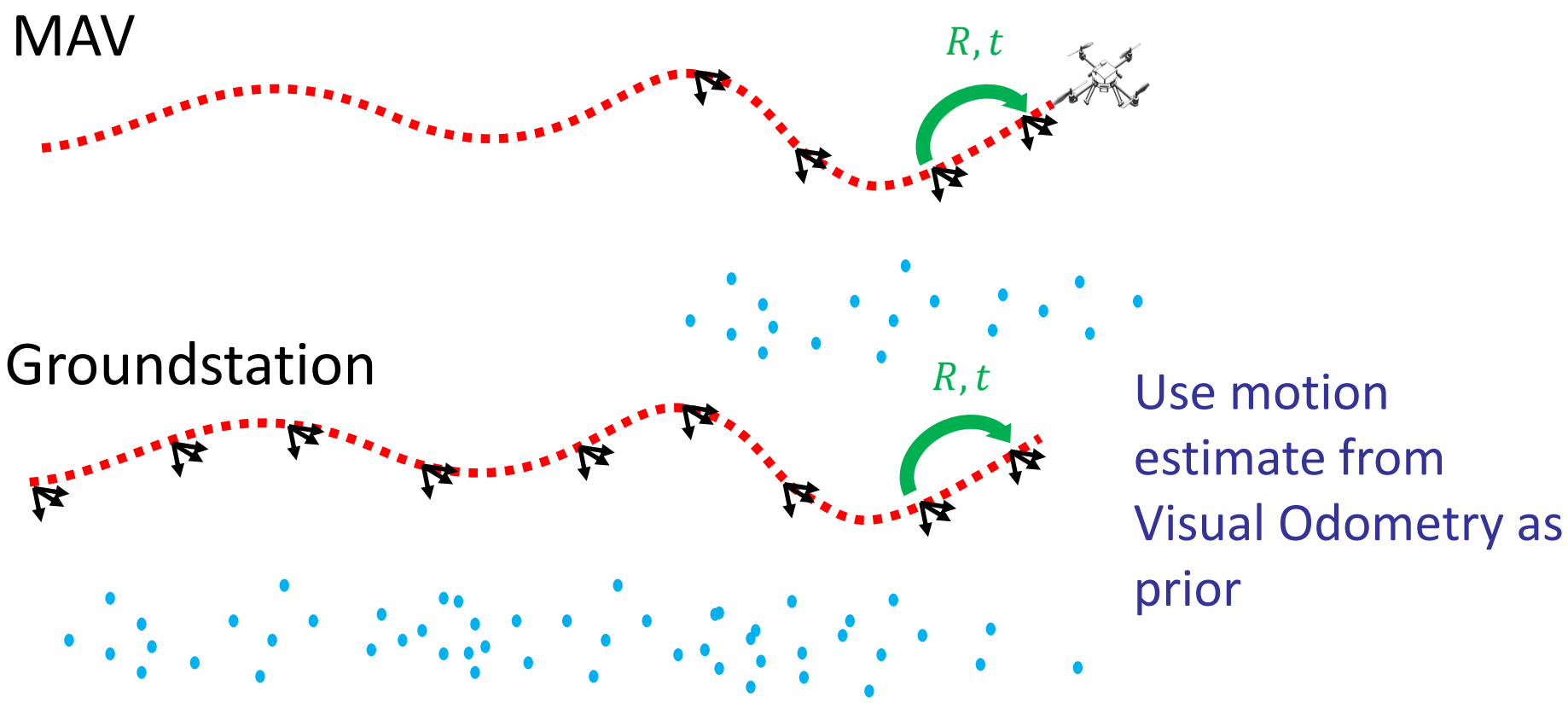

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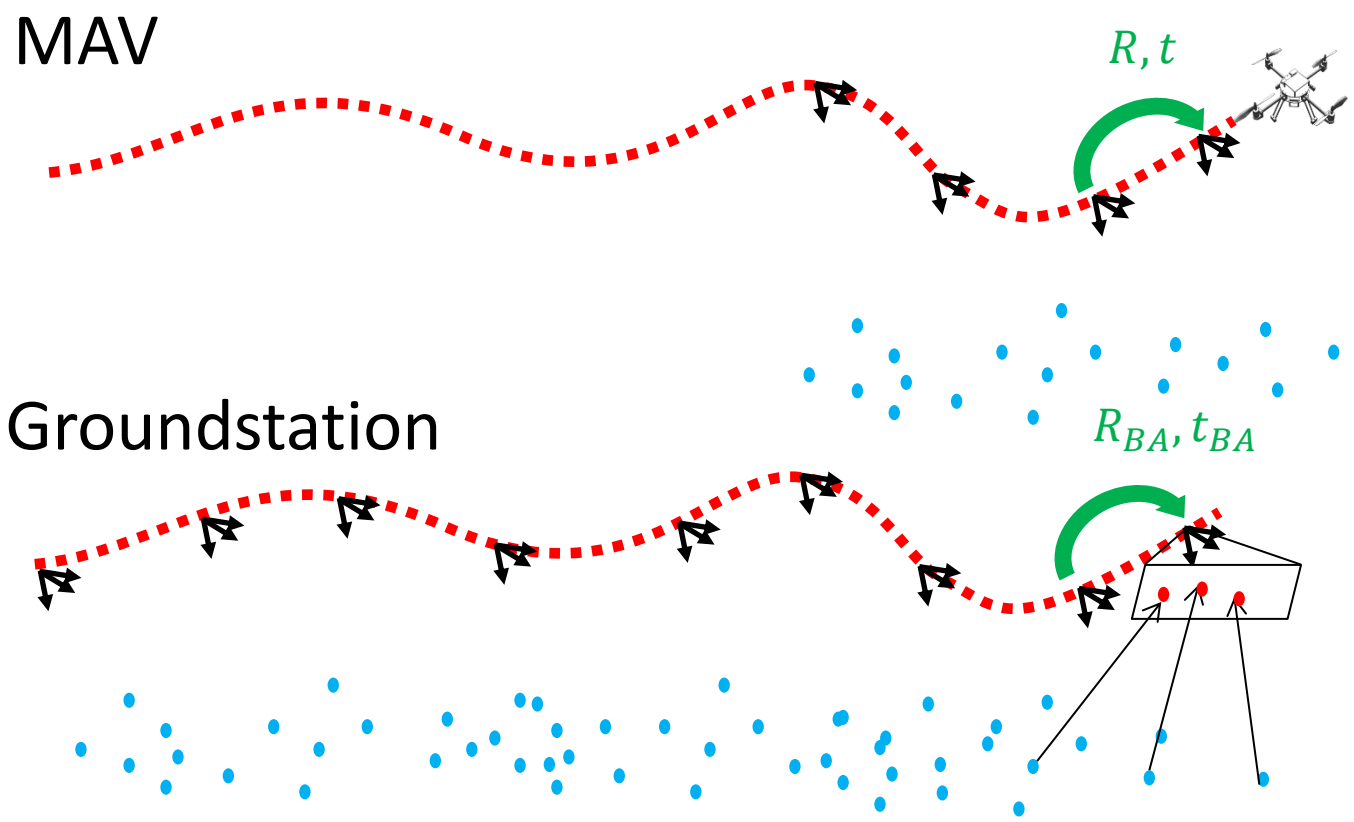
Mapping on the Groundstation



Refine pose w.r.t map
with Bundle Adjustment

$$C(\mathbf{x}) = \frac{1}{2} \sum_i \mathbf{e}_i(\mathbf{x})^T \, \mathbf{W}_i \, \mathbf{e}_i(\mathbf{x})$$

$$\hat{\mathbf{x}}^{LS} = \text{argmin}_{\mathbf{x}} \; C(\mathbf{x}),$$

g2o [Kümmerle et al., ICRA'11]

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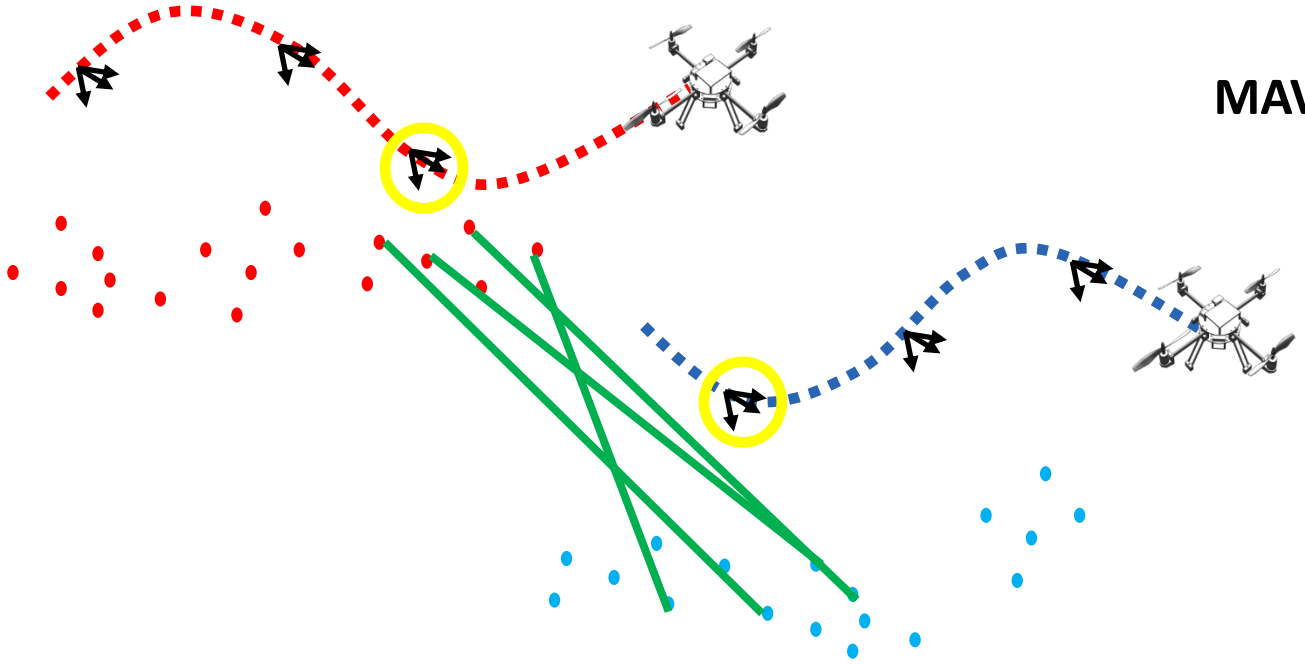
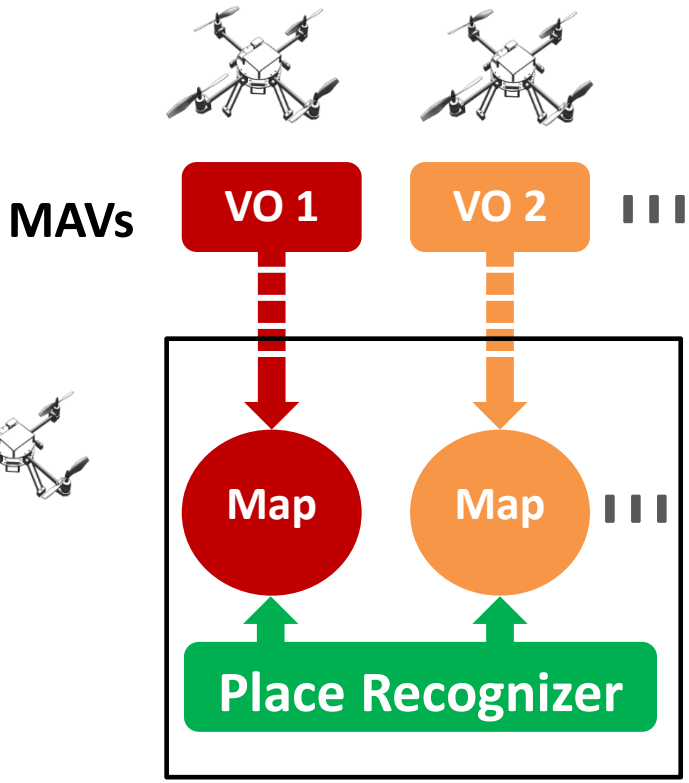
Place Recognition





Ground station

1. Appearance-based Detection

- Bag of Words image retrieval [Sivic et al., 2005]

2. Geometric Verification

- 3-point RANSAC for point-cloud alignment

3-point algorithm [Kneip & Scaramuzza,CVPR'11]

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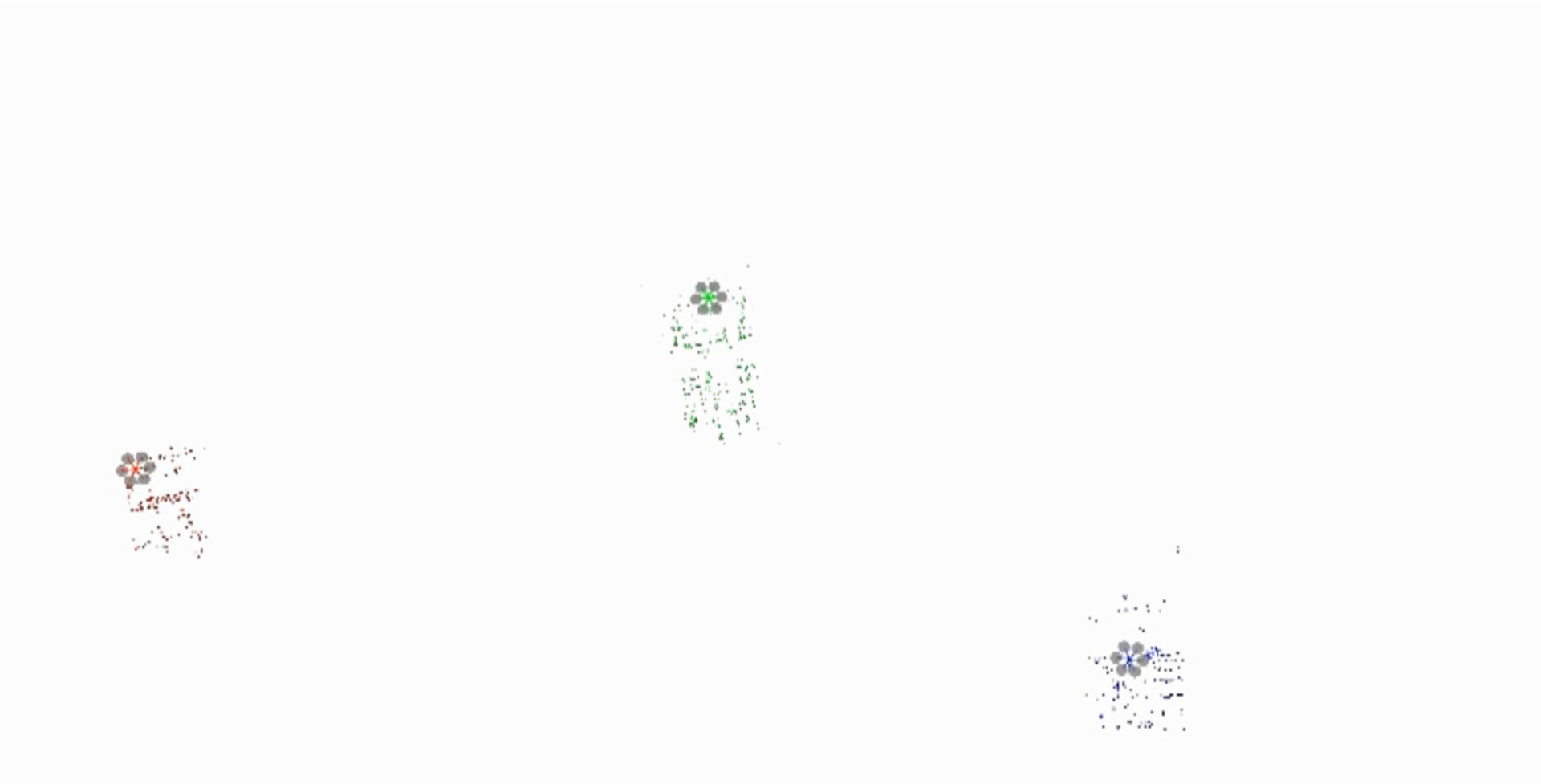
Map Merging (multiple robots)

Outdoor flight



C. Forster, S. Lynen, L. Kneip, D. Scaramuzza: *Collaborative Monocular SLAM with Multiple Micro Aerial Vehicles* **IROS 2013**

Summary: Centralized multi-robot SLAM

- Visual **odometry on-board** the individual robots
- **Ground station**
  - **Optimization** with bundle adjustment
  - Loop closure and map merging with bag-of-words **place recognition**
- At the heart of **active research**:
  - [Morrison 2016 MOARSLAM]
  - [Schmuck 2017 Multi]
  - …

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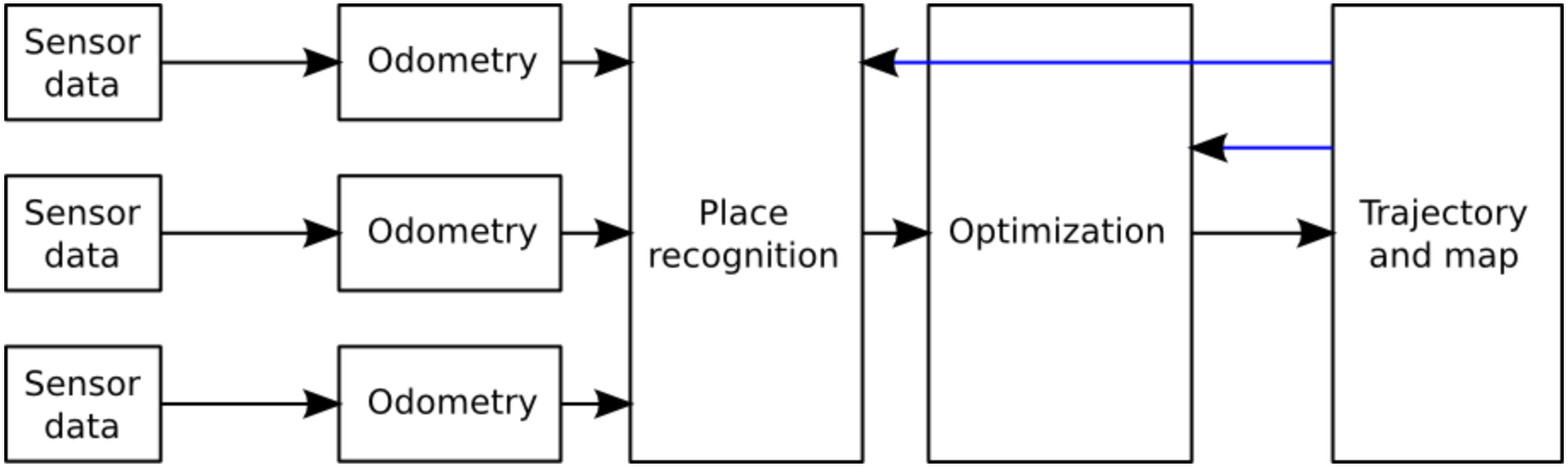
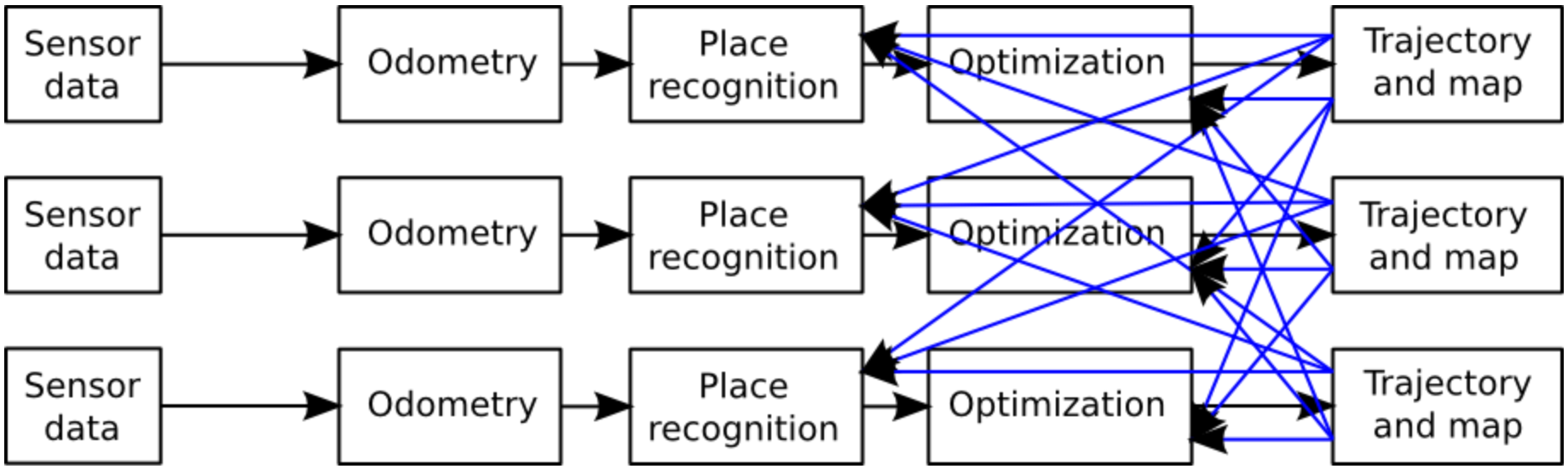
Decentralized multi-robot SLAM

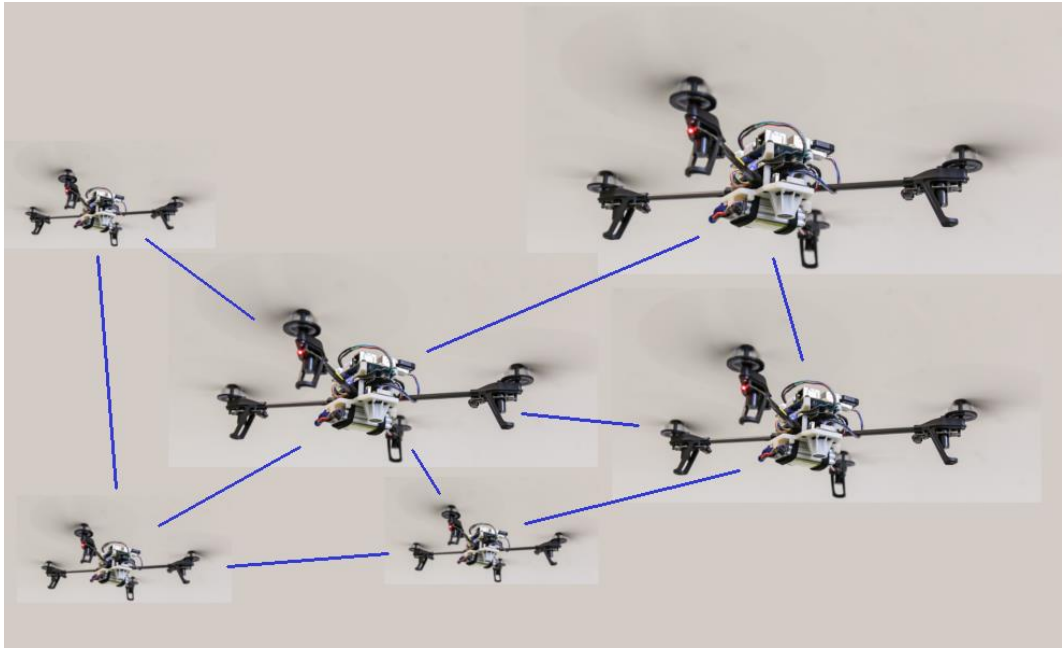


Decentralized multi-robot SLAM

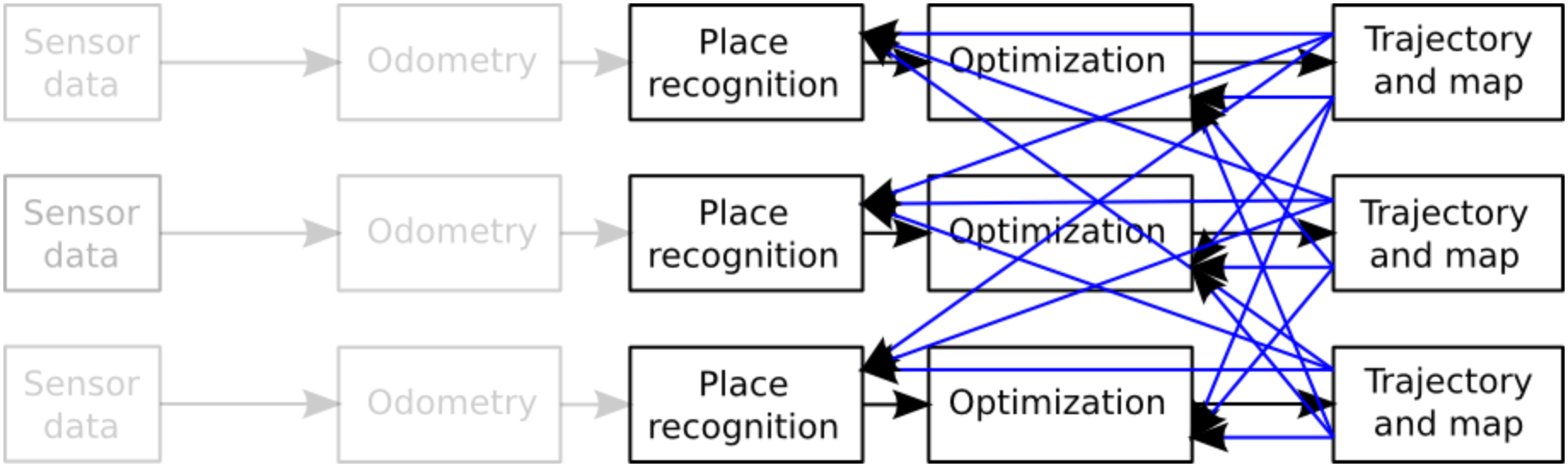


Why decentralize?

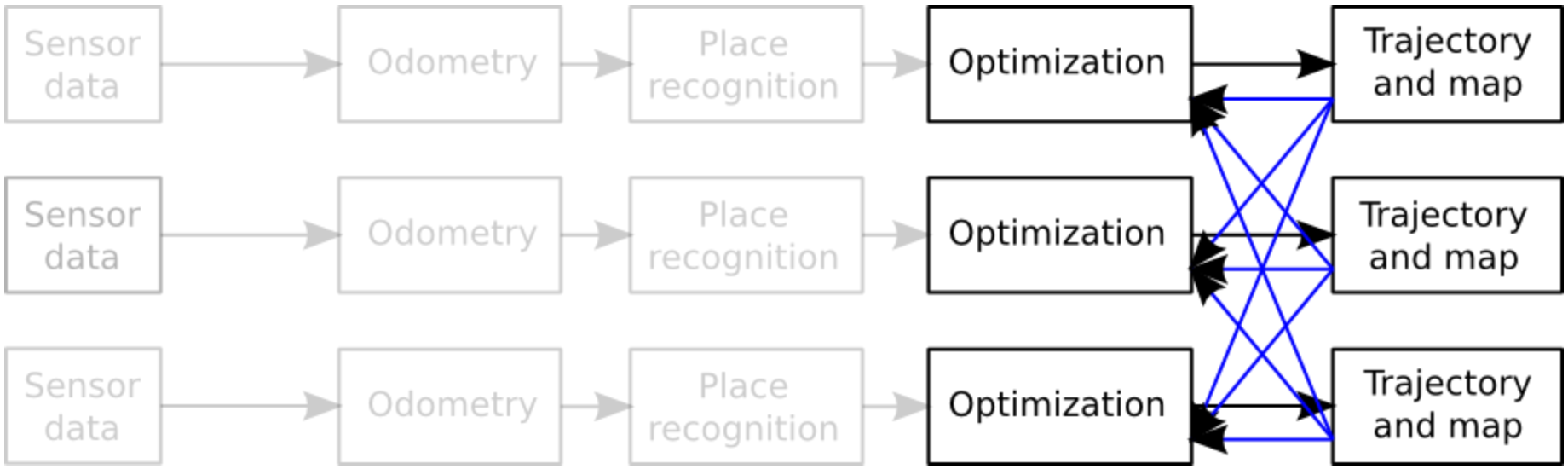
- Scalability
- More practical field deployment
- Robustness to failure
- Privacy / militaristic considerations



How to decentralize?

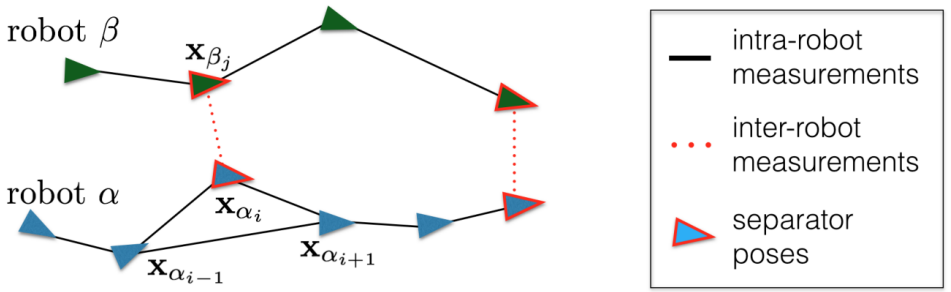


How to decentralize map optimization?



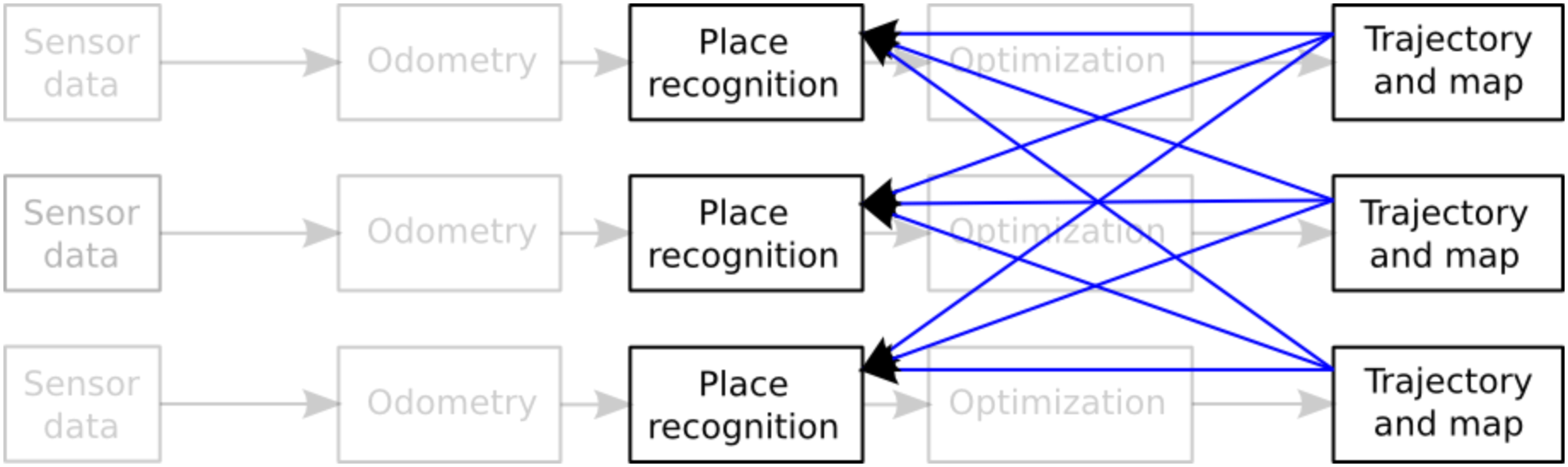
Decentralized trajectory optimization

- Filter- based: [Grime 1994 Data], [Roumeliotis 2002 Distributed], [Nettleton 2003 Decentralised], [Carlone 2010 Rao], [Leung 2011 Distributed]
- Graph- based: [Kim 2010 Multiple], [Cunningham 2010/2013 DDF], [Paull 2015 Communication], [Choudhary 2016 Distributed]
- Approach: Each robot optimizes its own map, **exchange of condensed / marginalized information**



From [Choudhary 2016 Distributed]

How to decentralize place recognition?



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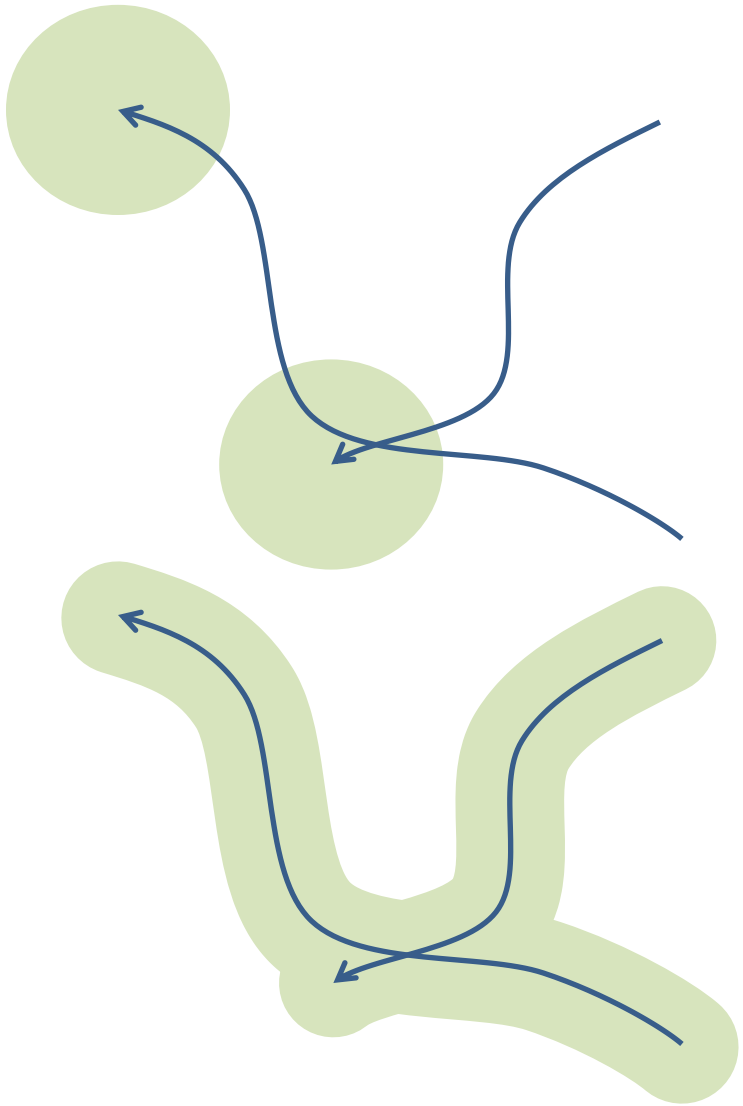
Place recognition from other robot's maps

- Relative localization with **visual place recognition** instead of direct observations
- Advantages
  - **More recall** → less redundancy e.g. in exploration
  - **No** special **hardware** needed
- Disadvantages
  - Relies on **connectivity**
  - More **bandwidth** required
  - Can be prone to **Perceptual Aliasing**



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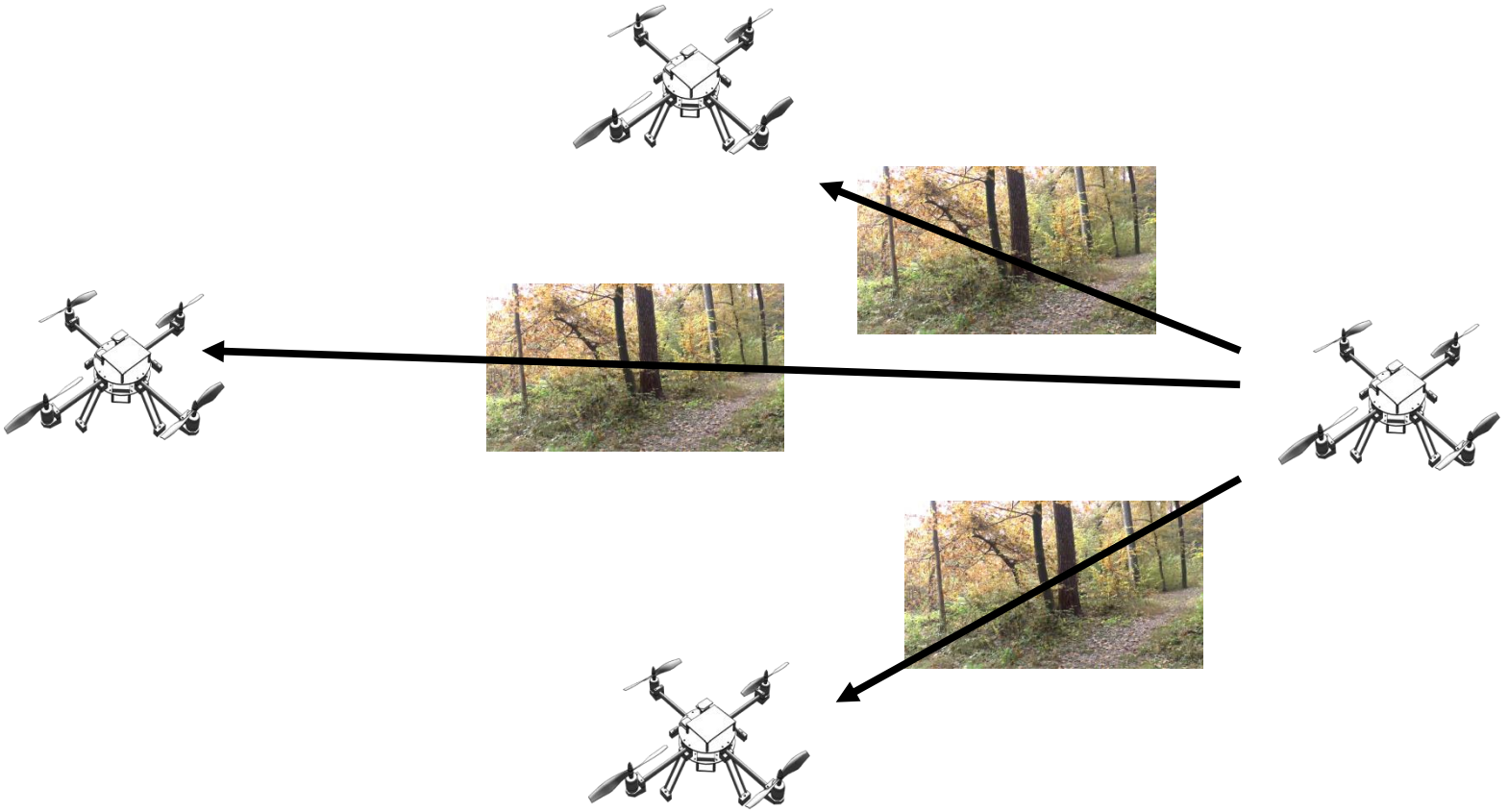
Decentralized visual PR: Query everyone?



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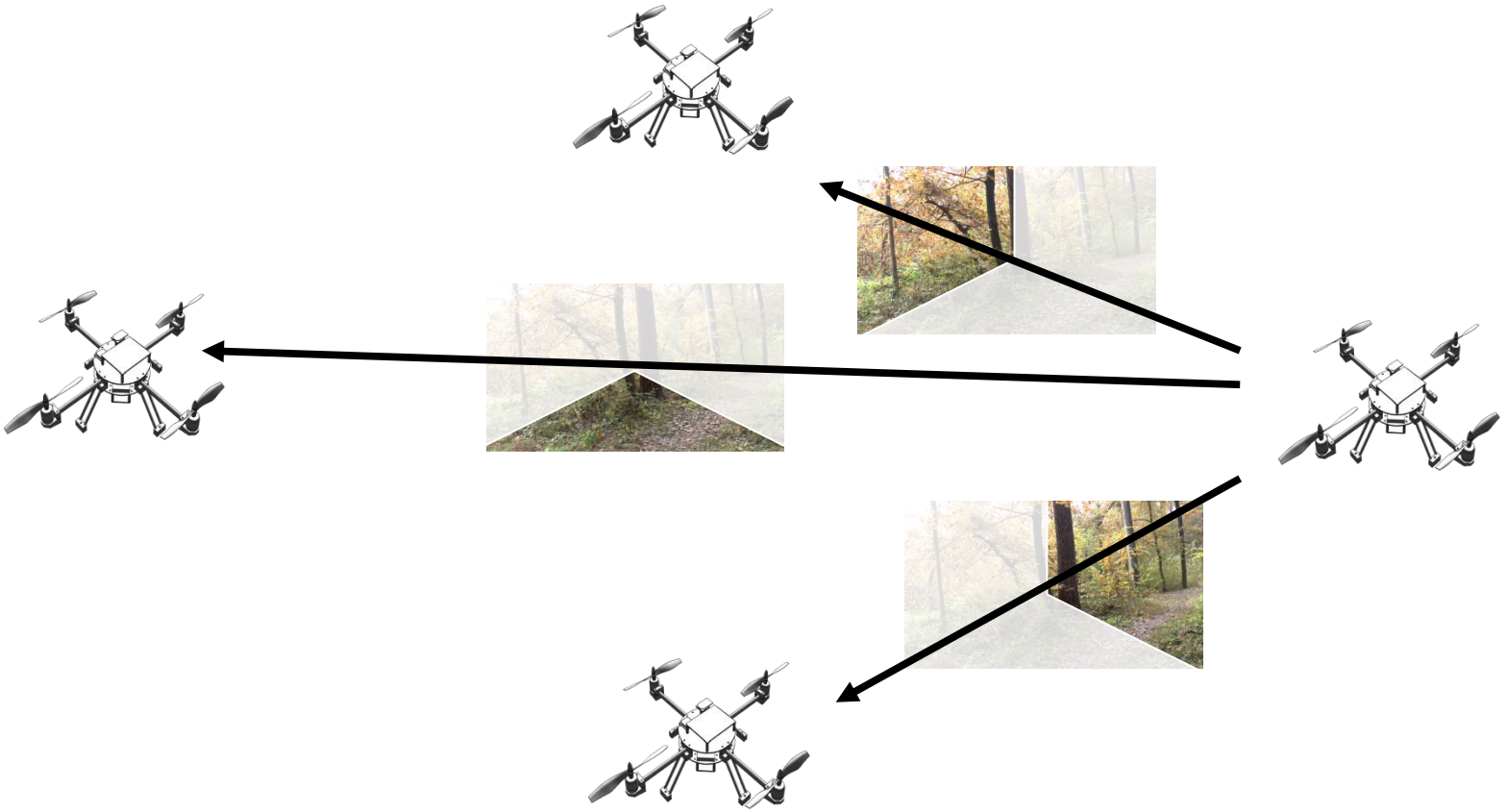
We can do better



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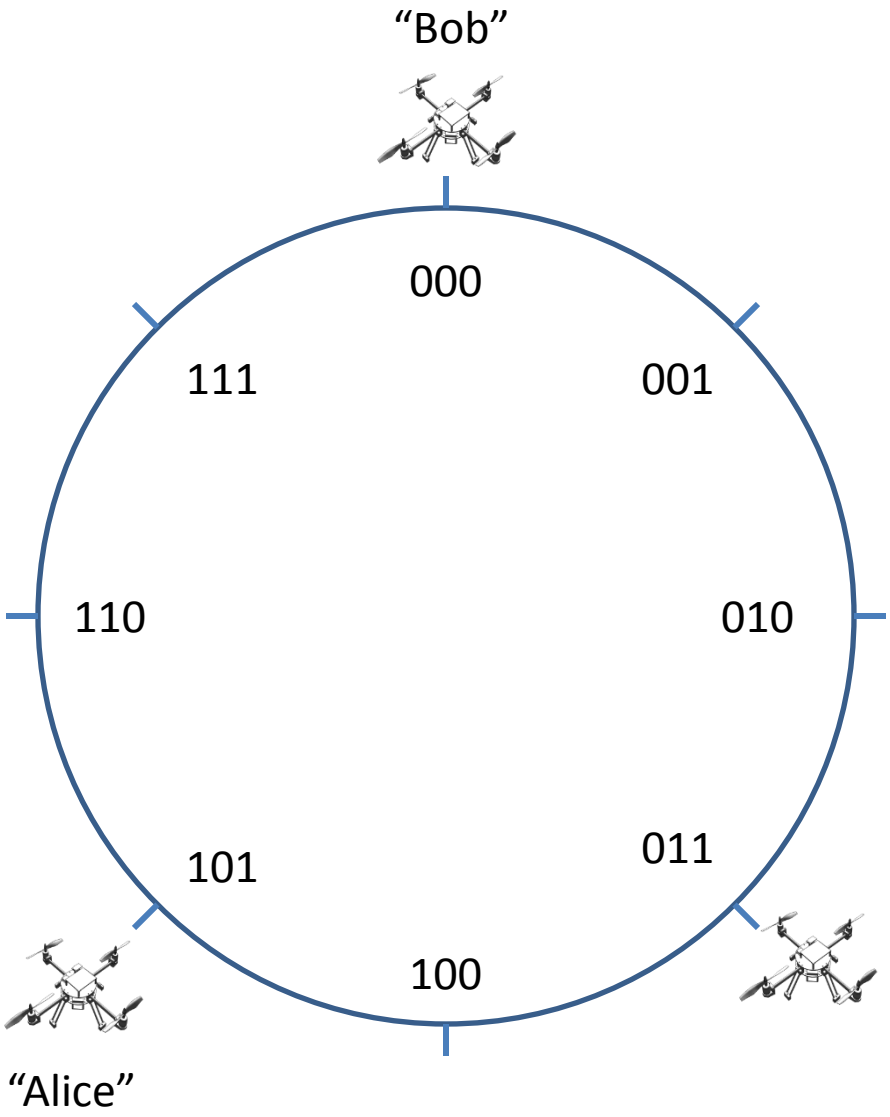
Distributed Hash Tables (DHTs)

- Developed by the distributed computing community in the early 2000s (e.g. [Stoica 2001])
- Efficient **Key-Value lookup** in a **distributed** map
- Key insight: **Deterministic assignment** of keys to peers: Report new data to and query only one peer



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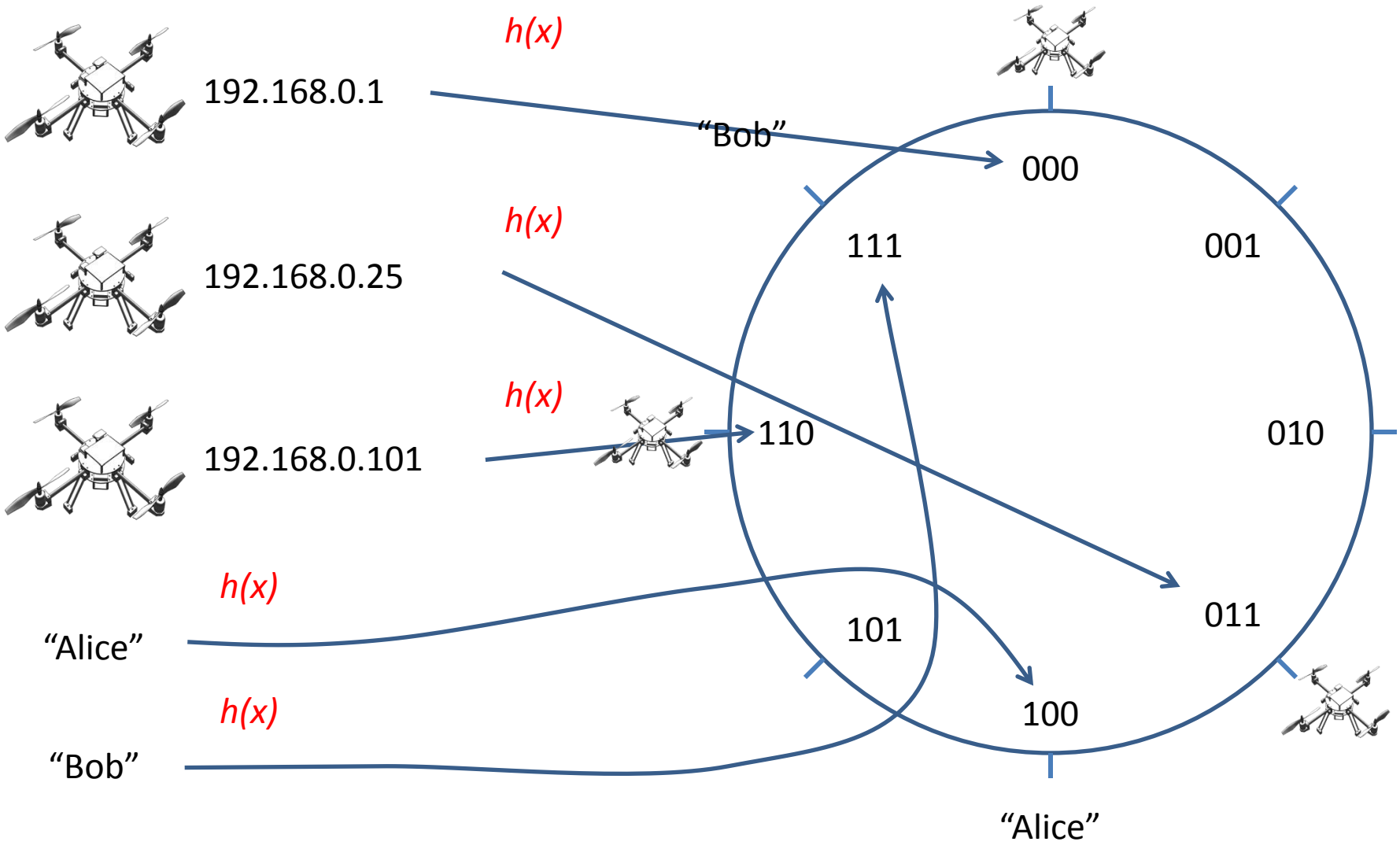

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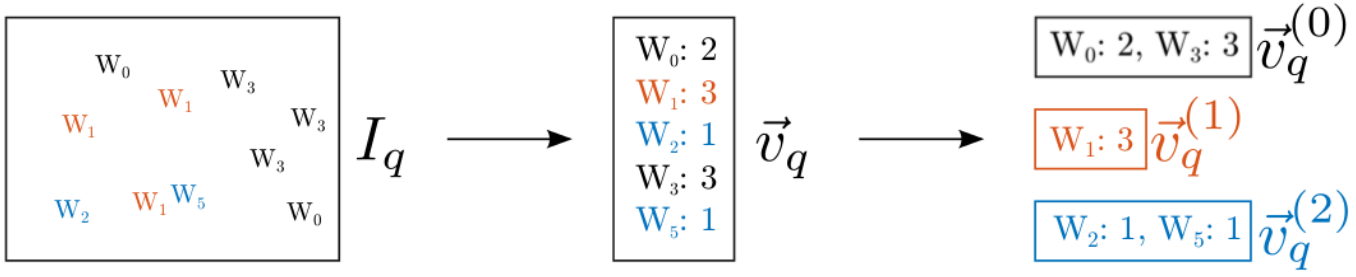
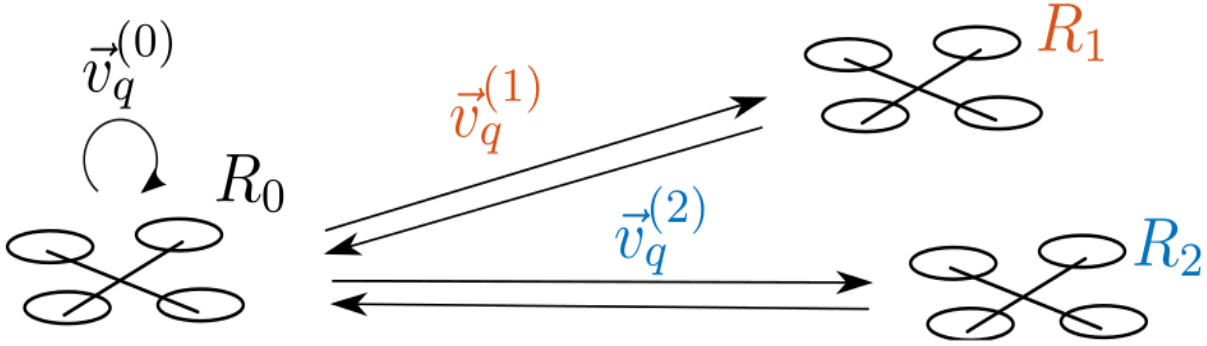
Distributed Bag-of-Word Place Recognition

- Deterministically **assign Visual Words** to Robots using a DHT!
- A **place query** is now **split** into several partial queries



- Send partial queries to the different robots.



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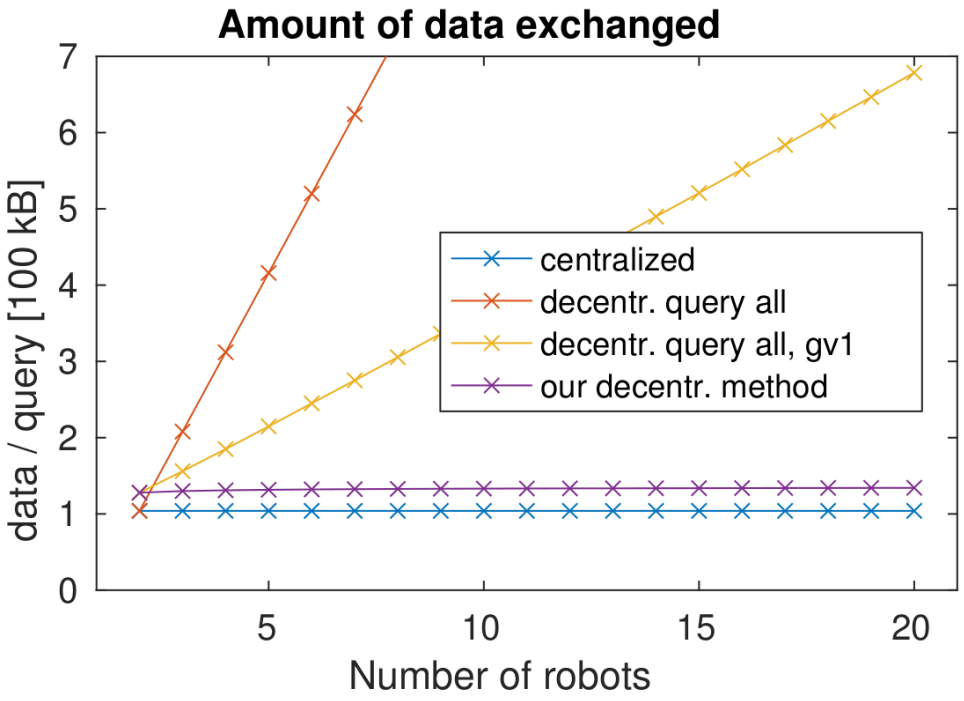
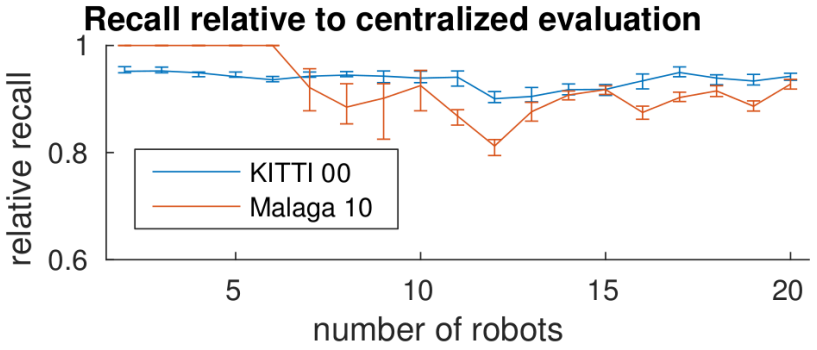
Results

- The amount of **data** exchanged is **significantly reduced**
- In the paper, we discuss consequences in different **network types**
- Because of a **simplification in aggregation**, recall is slightly affected





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What about full image descriptors?

- Preliminary work: https://arxiv.org/abs/1705.10739
- Using **NetVLAD** [Arandjelović 2016]
- Simpler: Not visual words, but **clusters of full image descriptors** assigned to robots

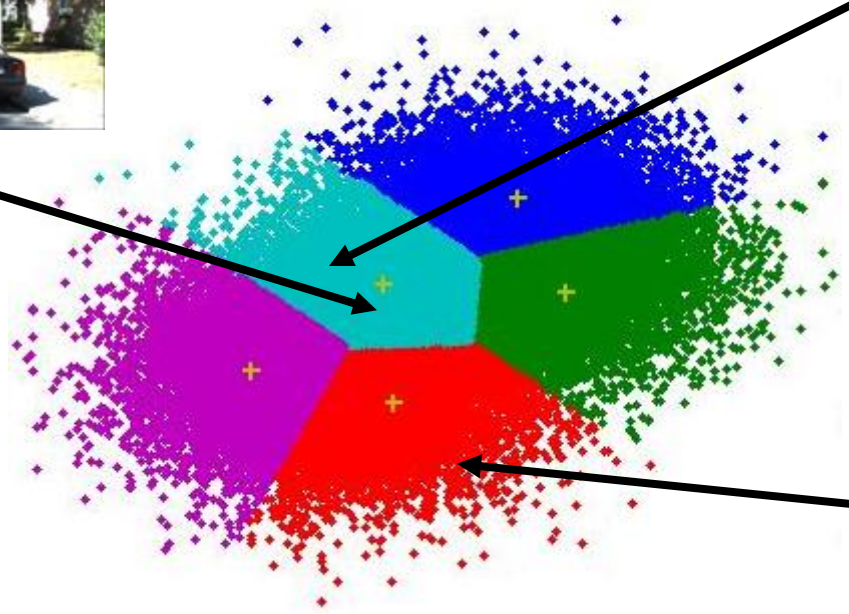
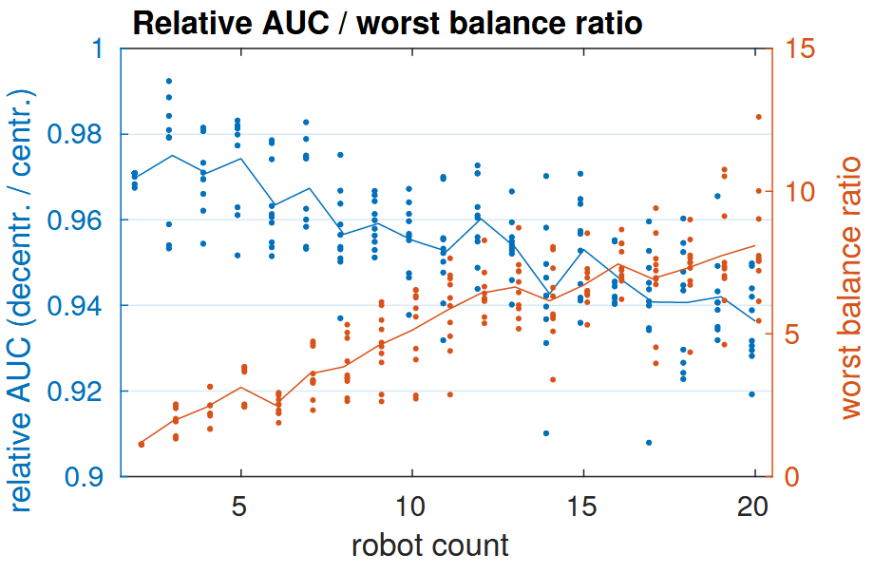


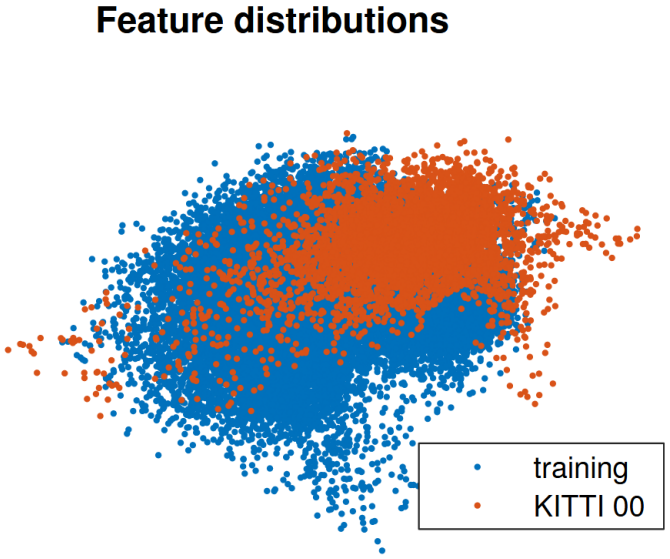
Image source: Yi Cao, Mathworks file exchange

T. Cieslewski, D. Scaramuzza: *Efficient Decentralized Visual Place Recognition From Full-Image Descriptors* **Arxiv 2017**

Full image descriptors: Preliminary results

- Performance relative to centralized place recognition similar to the Bag-of-Words approach
- Much **smaller queries** (0.5 VS 16kB) and **better absolute performance** with our Bag-of-Words implementation
- However: **Bad load balancing**: Inherent difference between training and testing distribution.

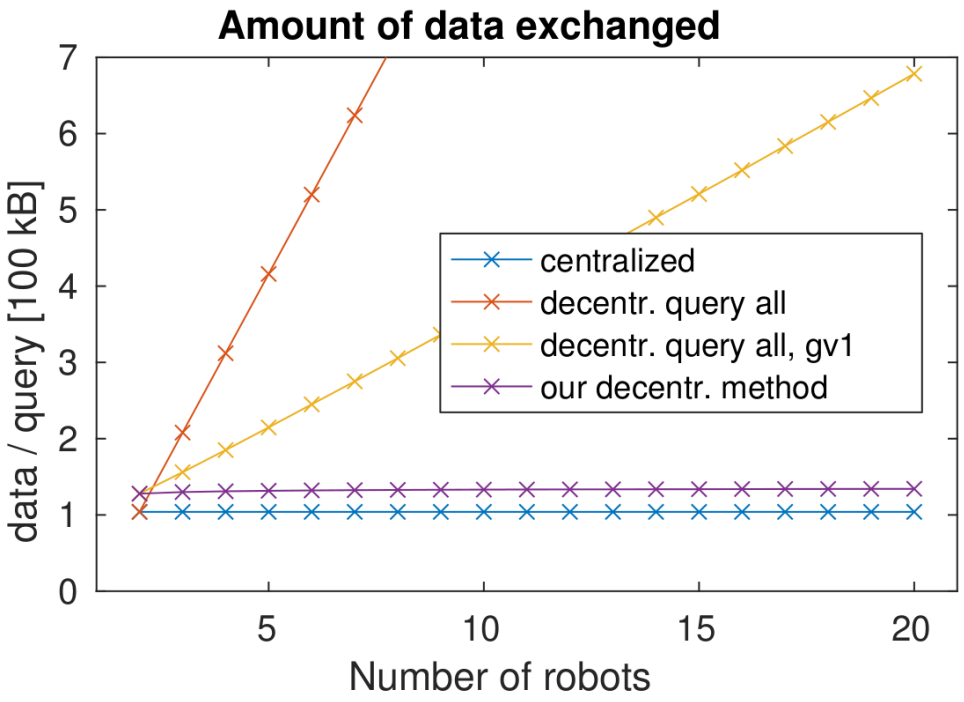


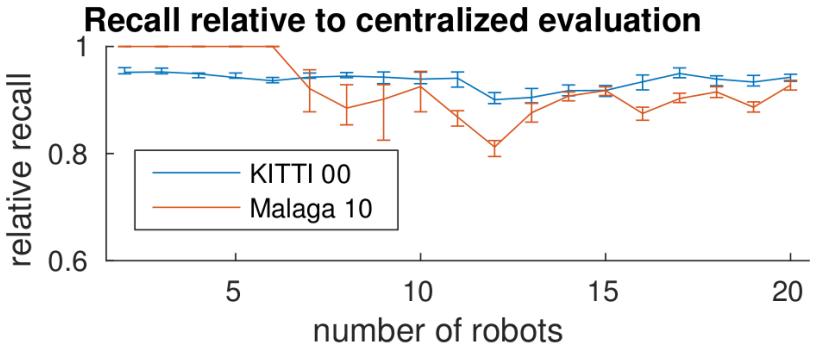


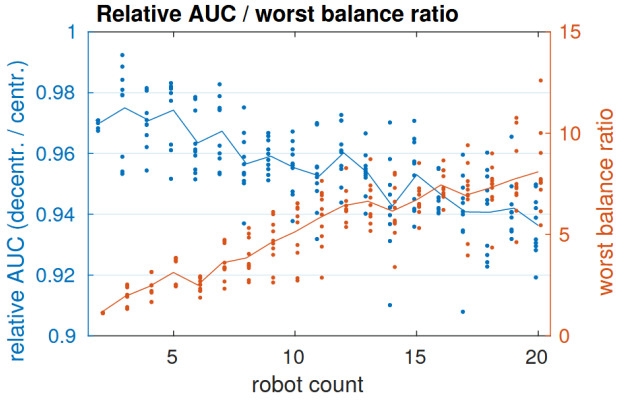
T. Cieslewski, D. Scaramuzza: *Efficient Decentralized Visual Place Recognition From Full-Image Descriptors* **Arxiv 2017**

Summary: Decentralized Place Recognition

- Place recognition **from other robot's maps**
- Up to **n-fold bandwidth reduction** VS querying all robots
- Based on Bag-of-Words or full image descriptors







T. Cieslewski, D. Scaramuzza: *Efficient Decentralized Visual Place Recognition Using a Distributed Inverted Index* **RA-L 2017**

T. Cieslewski, D. Scaramuzza: *Efficient Decentralized Visual Place Recognition From Full-Image Descriptors* **Arxiv 2017**

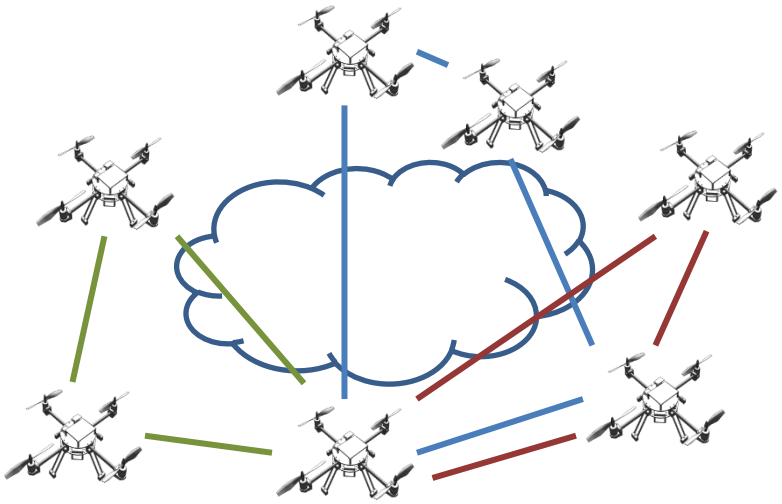
Decentralized collaboration

- SLAM is not the only multi-robot task
- Can we make a **general framework** for multi-robot collaboration?
- **Shared state** with different levels of ownership
- How do humans collaborate on a shared state?
  - **Version control**

T. Cieslewski, S. Lynen, M. Dymczyk, S. Magnenat, R. Siegwart: *Map API-scalable decentralized map building for robots* **ICRA 2015**

Decentralized version control for robots

- Like typical version control:
  - Optimistic Concurrency Control (**checkout/commit**)
  - **Conflict** handling (rule-based)
- Unlike typical version control:
  - **Partial participation** in the distributed state
  - Fully **decentralized**
  - Changes are implicitly **pushed**
  - Deals with **time delays**
- More features:
  - Decentralized **lookup**



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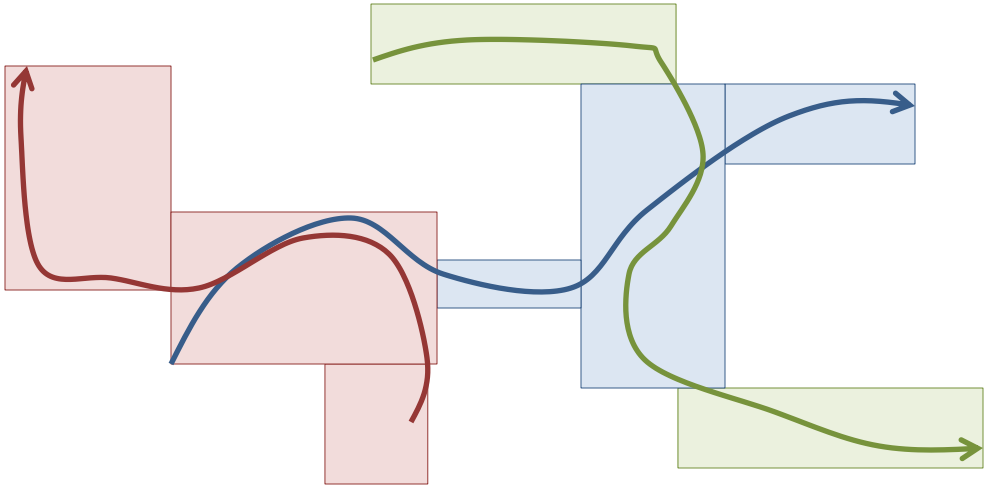
T. Cieslewski, S. Lynen, M. Dymczyk, S. Magnenat, R. Siegwart: *Map API-scalable decentralized map building for robots* **ICRA 2015**

Why we developed it

- We originally wanted to use it in decentralized multi-session **SLAM**
- Problem: Constraints propagate through the **entire graph**
- Map API better suited for **locally restricted** tasks



T. Cieslewski, S. Lynen, M. Dymczyk, S. Magnenat, R. Siegwart: *Map API-scalable decentralized map building for robots* **ICRA 2015**

Do you see a use case?

- Decentralized version control for **your** robot teams
- C++
- We **open source** it!
- https://github.com/ethz-asl/map_api

```
MAP_API_REVISION_PROTOBUF(proto::DataType);
enum Fields { kField };

map_api::TableDescriptor descriptor;
descriptor.setName("my_table");
descriptor.addField<proto::DataType>(kField);
map_api::NetTable* my_table = map_api::↩
    NetTableManager::addTable(descriptor);

my_table->getChunk(chunk_id);  // Assumed given.
map_api::Transaction transaction;
map_api::Revision revision = transaction.getById(↩
    my_table, item_id);  // Assumed given.
proto::DataType data;
revision.get(kField, &data);
data.set_some_subvalue(data.some_subvalue() + 1);
revision.set(kField, data);
transaction.update(my_table, revision);
if (transaction.commit()) {
  LOG(INFO) << "Commit succeeded!";
}
```

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Summary

- Overview of **multi-robot SLAM**
  - How a **centralized** system works
  - Centralized VS **Decentralized**
- Decentralized **Place Recognition**
  - Recognize **from maps** for higher recall
  - A **DHT-based** method for **less bandwidth**
- Decentralized **general collaboration framework**
  - **Version control** for robots.
  - Available as **open-source** code!