Towards Autonomous Planetary Exploration
Collaborative Multi-Robot Localization and Mapping in GPS-denied Environments

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Scenarios for Heterogeneous Multi-Robot Teams

In Space: Planetary Exploration

On Earth: Search & Rescue Missions
The Lightweight Rover Unit (LRU) for Planetary Exploration


-A. Wedler et al., “First Results of the ROBEX Analogue Mission Campaign: Robotic Deployment of Seismic Networks for Future Lunar Missions”, in International Astronautical Congress (IAC), 2017
Heterogeneous Multi-Robot Teams for Autonomous Exploration
Mapping with two Rovers
Navigation for Multi-Robot Teams in Previously Unknown Environments

1. Real-time Local State Estimation & Obstacle Avoidance

- Local Reference Filter
- Terrain Classification

2. Online Global Localization and Mapping (6D-SLAM)

- Exchange of Submaps
- Multi-Robot Graph

How to combine these Methods?

⇒ **Novel graph topology** for decoupled integration of filter estimates
⇒ **Intra- and inter-robot loop closures** by matching submaps
⇒ Integration into **modular software architecture**
Local Reference Filter

- **Extended Kalman Filter (EKF)** for real-time state estimation
  - System state: \( x = (p_i^T, v_i^T, q_i^T, b_a^T, b_\omega^T) \in \mathbb{R}^{16} \)
  - Error state: \( \delta = (\delta p_i^T, \delta v_i^T, \delta q_i^T, \delta b_a^T, \delta b_\omega^T) \in \mathbb{R}^{15} \)
  - Time-delay compensation for visual odometry (VO) measurements
  - Locally drift-free estimation through VO keyframes

- **Switch frame of reference** into current robot pose
  - Reset pose uncertainty estimates to zero
  - Transform other filter state variables into new frame of reference

- **Benefits of frame switches:**
  - Reset unbounded covariances for unobservable states
    - Long-term numerical stability
    - No violation of small-angle approximations for error-state filter
  - Improved integration of filter estimates into SLAM graph

[Spinoff: Roboception GmbH]

3D Submap Creation and Matching

- **Creation of Submaps**
  Local aggregation of dense 3D data
  \[ \Rightarrow \text{Distributed computation} \]
  \[ \Rightarrow \text{Low bandwidth requirements for exchange} \]

- **Submap Matching**
  Estimation of transformation between submaps
  - Initial Alignment:
    - Keypoint selection: Obstacle classification
    - Feature matching: CSHOT (local geometry and texture)
  - Refinement: Iterative Closest Point (ICP)

  \[ \Rightarrow \text{Inter- and Intra-Robot Loop Closures} \]
Multi-Robot Graph Topology for Sequential Odometry Measurements

[Diagram showing multi-robot localization and mapping in GPS-denied environments]

[M. J. Schuster et al., “Multi-Robot 6D Graph SLAM Connecting Decoupled Local Reference Filters”, IROS, 2015]
Multi-Robot Graph Topology for Sequential Odometry Measurements

[M. J. Schuster et al., “Multi-Robot 6D Graph SLAM Connecting Decoupled Local Reference Filters”, IROS, 2015]
Multi-Robot Graph Topology for Sequential Odometry Measurements

[M. J. Schuster et al., “Multi-Robot 6D Graph SLAM Connecting Decoupled Local Reference Filters”, IROS, 2015]
New Multi-Robot Graph Topology for Local Reference Filter Estimates

[M. J. Schuster et al., “Multi-Robot 6D Graph SLAM Connecting Decoupled Local Reference Filters”, IROS, 2015]
Incremental Multi-Robot Graph SLAM

- **SLAM Front-End (Data Association)**
  - Loosely coupled integration of filter estimates according to their independence assumptions
  - No knowledge about filter-internal states required
  - Aggregation of high-frequency measurements
  - **Small graph:** Fast optimization steps

- **SLAM Back-End (Graph Optimization)**
  - Incremental non-linear optimization (least-squares)

\[
f(\Theta) = \prod_i f_i(\Theta_i)\]

\[
\arg\min_\Theta (-\log f(\Theta)) = \arg\min_\Theta \frac{1}{2} \sum_i \| h_i(\Theta_i) - z_i \|^2_{\Sigma_i}
\]

- **Robust cost function** for outlier suppression (Cauchy)
Mapping with two Rovers

- Area: 57m x 53m
- SLAM-Graph: 105 Nodes, 143 Factors
SpaceBotCamp 2015

- National Robotics Challenge
- Moon-like Scenario
- Area: 13m x 18m

Autonomous Exploration

- **Goal selection** according to expected information gain
- **Active loop closing**: Trade-off between exploration of unknown areas and exploitation of known information
- Consideration of **match effect**, impact of a loop closure, as well as match likelihood and match costs

[H. Lehner et al., “Exploration with Active Loop Closing: A Trade-off between Exploration Efficiency and Map Quality”, in IROS, 2017]
Autonomous Exploration
Autonomous Exploration
Long-Range Navigation & Multi-Robot Exploration Experiments

- ROBEX Project (2012 – 2017)
- Moon-analogue environment on Mt. Etna

[A. Wedler et al., “First Results of the ROBEX Analogue Mission Campaign: Robotic Deployment of Seismic Networks for Future Lunar Missions”, in International Astronautical Congress (IAC), 2017]
ROBEX: Multi-Robot Exploration Experiment on Mt. Etna
Future Work and Outlook

- ARCHES Project (2018 – 2021)
- Heterogeneous teams of robots
- Long-term and large-scale localization and mapping
References


