3D Mapping and Autonomous Navigation of Legged Robots

UDRC Themed Meeting on Autonomous Systems

Wednesday November 24th, 2021

UNIVERSITY OF OXFORD

OXFORD ROBOTICS INSTITUTE

DYNAMIC ROBOT SYSTEMS GROUP

Building Blocks for Autonomy

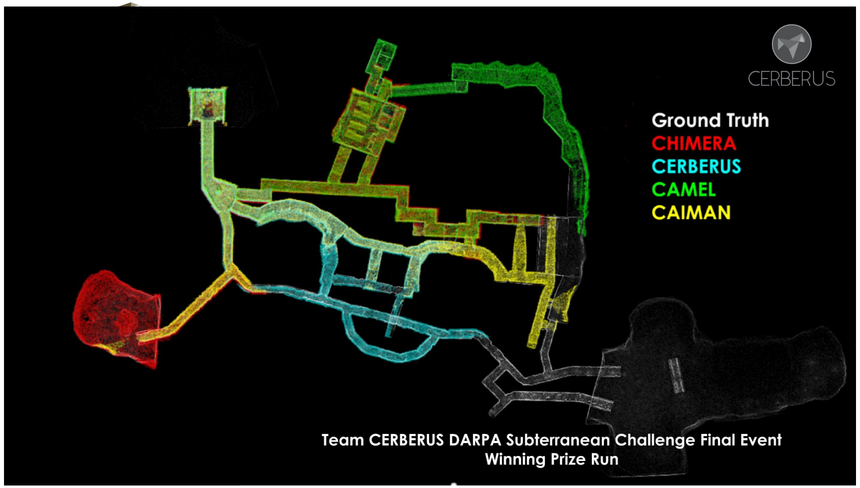
- Odometry
- Local mapping
- Locomotion
- Simultaneous Localisation and Mapping (SLAM)
- Safe path planning

What makes an environment extreme?

- Uneven, slippery, unstable, terrain
- Difficult communication
- Scarce or missing illumination
- Ill-constrained geometries (long tunnels)



DARPA Subterranean Challenge



University of Nevada, Reno · ETH zürich · SNC SIERRA NEVADA CORPORATION · Berkeley UNIVERSITY OF CALIFORNIA · FLYABILITY · NTNU Norwegian University of Science and Technology · UNIVERSITY OF OXFORD

Odometry

State Definition

UNIVERSITY OF OXFORD

Orientation Position Linear Velocity Biases

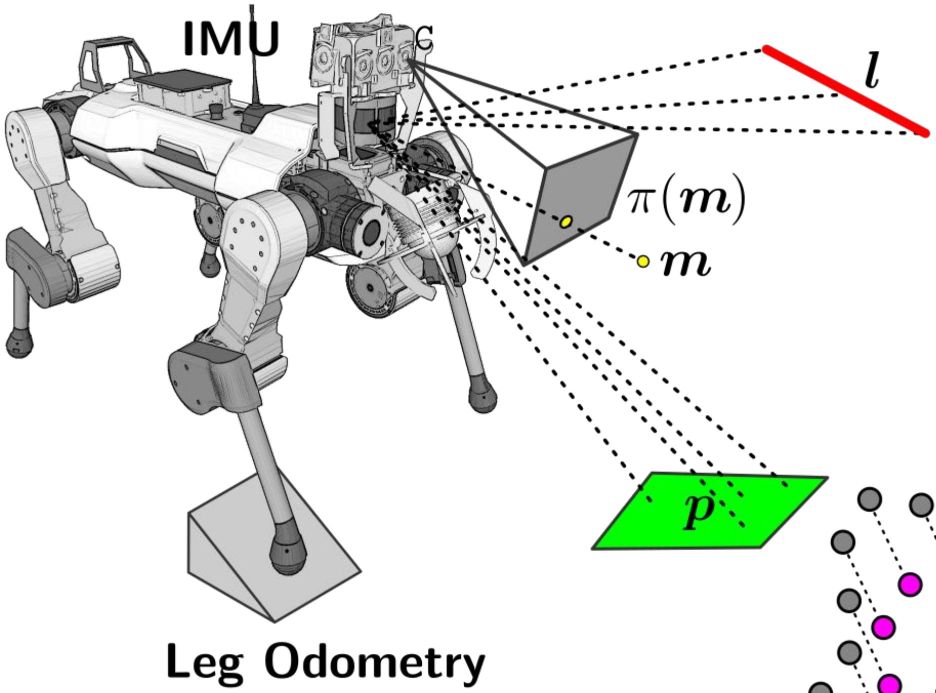
$$x_i \triangleq [\mathbf{R}_i, \mathbf{p}_i, \mathbf{v}_i, \mathbf{b}_i]$$

IMU - Gyroscope IMU - Accelerometer Velocity - Linear Velocity - Angular

$$\mathbf{b}_i = [\mathbf{b}_i^g \ \mathbf{b}_i^a, \ \mathbf{b}_i^\omega, \ \mathbf{b}_i^v] \in \mathbb{R}^{12}$$

Wisth *et al.* ‘Preintegrated Velocity Bias Estimation to Overcome Contact Nonlinearities in Legged Robot Odometry’

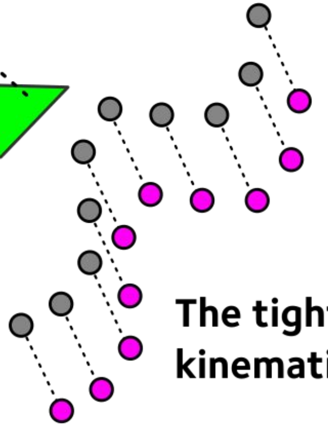
Proposed Approach



VILENS

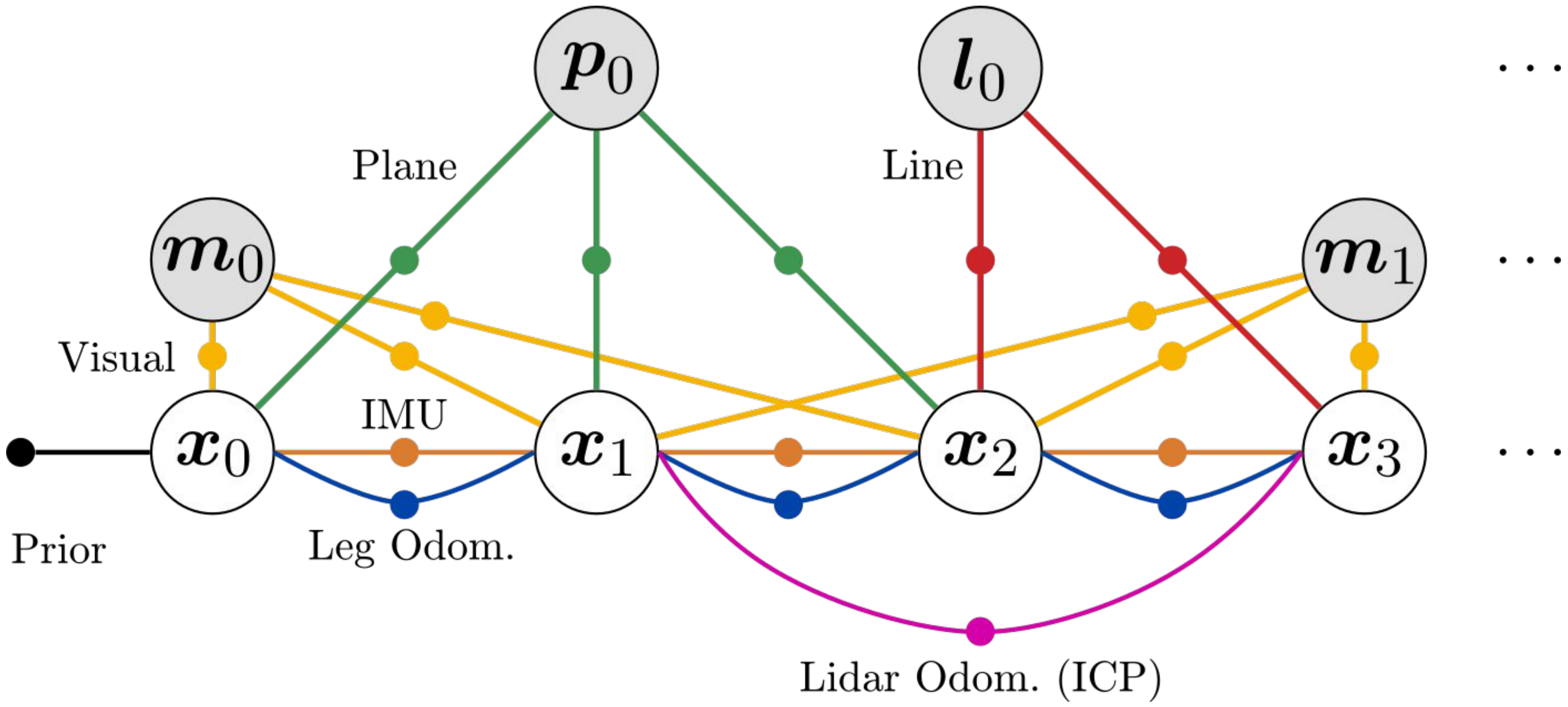
Factor graph framework fusing:

- IMU
- Visual features
- Lidar features (planes & lines)
- Leg Odometry
- ICP registration (optional)



The tight fusion of all sensor modalities allows for kinematic and inertial biases to be estimated online

Factor Graph Formulation

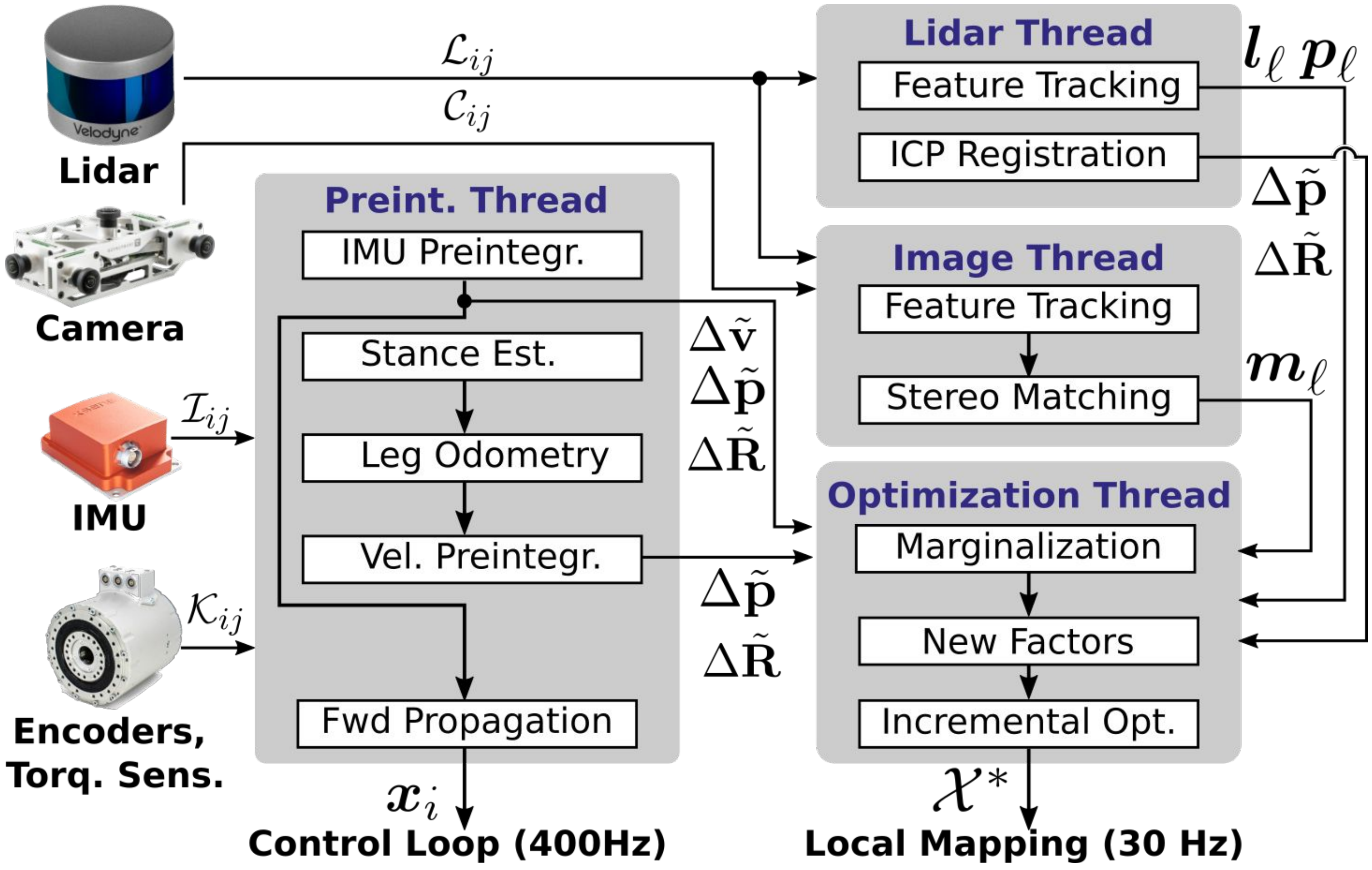


$$\mathcal{X}_k^* = \arg\min_{\mathcal{X}_k} \|\mathbf{r}_0\|^2_{\Sigma_0} + \sum_{i\in \mathsf{K}_k} \left(\|\mathbf{r}_{\mathcal{I}_{ij}}\|^2_{\Sigma_{\mathcal{I}_{ij}}} + \sum_{\ell\in \mathsf{P}_i} \|\mathbf{r}_{\boldsymbol{x}_i,\boldsymbol{p}_\ell}\|^2_{\Sigma_{\boldsymbol{x}_i,\boldsymbol{p}_\ell}} + \sum_{\ell\in \mathsf{L}_i} \|\mathbf{r}_{\boldsymbol{x}_i,\boldsymbol{l}_\ell}\|^2_{\Sigma_{\boldsymbol{x}_i,\boldsymbol{l}_\ell}} + \sum_{\ell\in \mathsf{M}_i} \|\mathbf{r}_{\boldsymbol{x}_i,\boldsymbol{m}_\ell}\|^2_{\Sigma_{\boldsymbol{x}_i,\boldsymbol{m}_\ell}} + \|\mathbf{r}_{\mathcal{L}_i}\|^2_{\Sigma_{\mathcal{L}_i}} + \|\mathbf{r}_{\mathcal{K}_{ij}}\|^2_{\Sigma_{\mathcal{K}_{ij}}} \right)$$

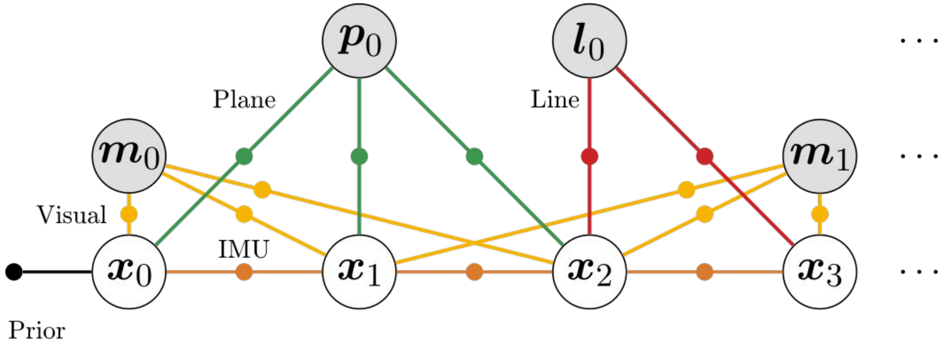
Prior | IMU | Planes | Lines | Points | Lidar | Leg Odom.

System Overview

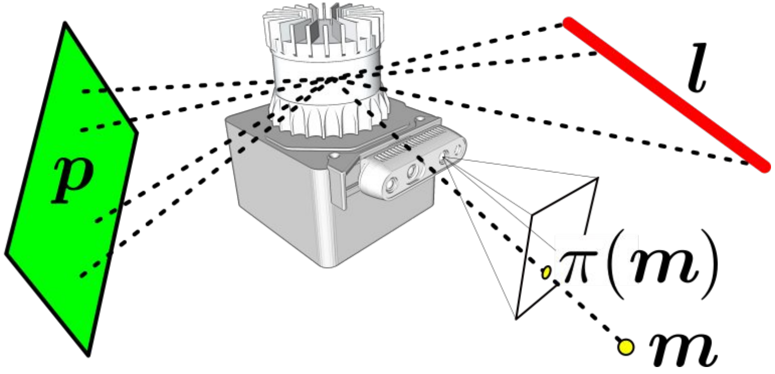
UNIVERSITY OF OXFORD



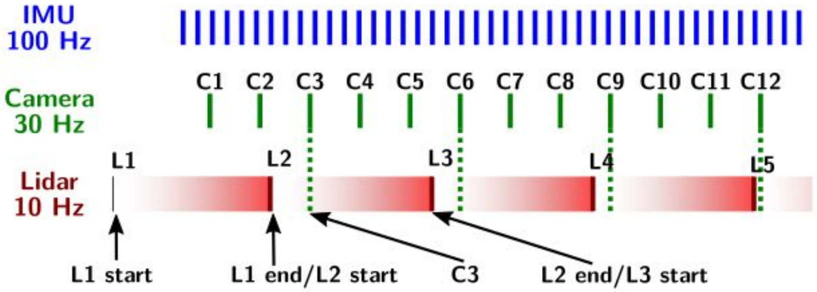
Key features



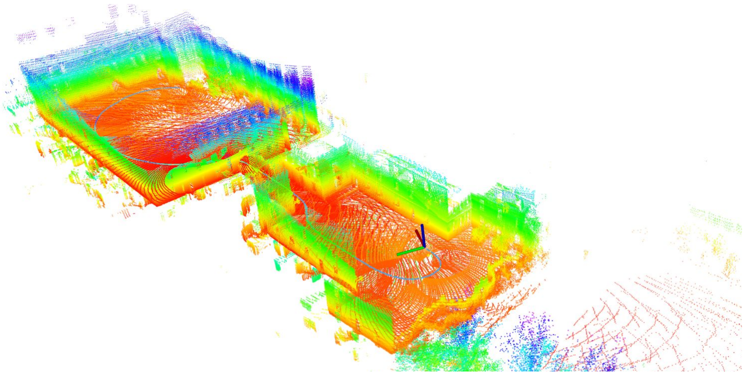
Multi-sensor fusion via factor graphs



Unified tracking and optimization



Novel lidar-camera synchronization



Extensive field experiments

Technical motivation

UNIVERSITY OF OXFORD

Visual-inertial or lidar-inertial:

- Smoothing-based methods
- Fail in well-known scenarios
- Most lidar tracking is frame-to-frame

Lidar-visual-inertial:

- Filter-based or loosely coupled
- High computational requirements
- Hard-switching between modalities

Unified approach:

Directly detect and track landmarks from vision and lidar for multiple frames

✔ Joint optimization of all sensor modalities

✔ Lightweight, sparse approach

✔ Natural handling of degeneracy by partial constraints

Performance in Challenging Environments

VILENS outperforms LOAM[1] by 85% translation and 67% rotation

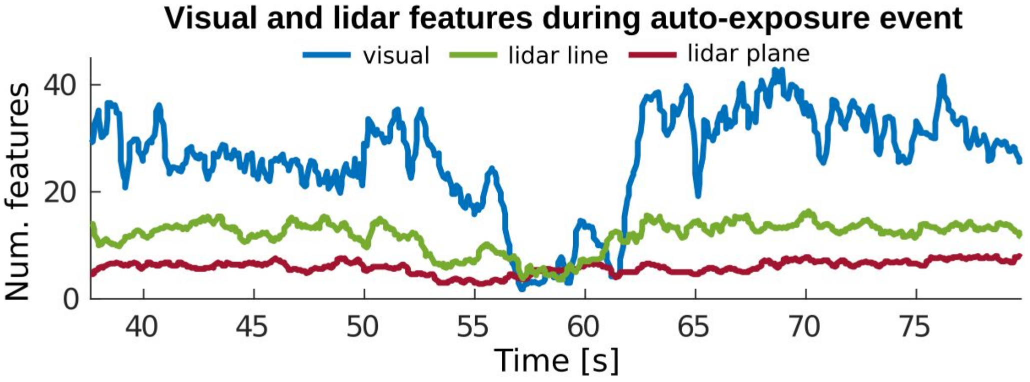
No loop closures
No mapping (in contrast to LOAM[1])

[1] Khattak et al. “Complementary Multi-Modal Sensor Fusion for Resilient Robot Pose Estimation in Subterranean Environments”, ICUAS, 2020.

Handling Degeneracy

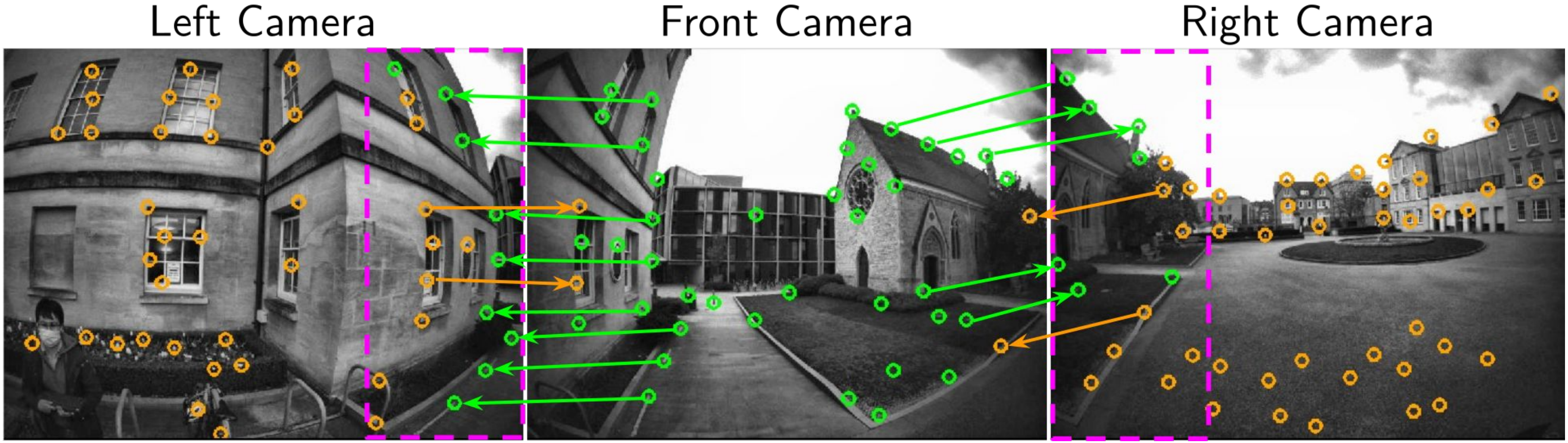
UNIVERSITY OF OXFORD

- Unified approach avoids hard switching and enables use of partial constraints.
- Visual degradation Example:
  - Auto-exposure event moving between sunlight and shade.
  - Other methods would detect a degenerate scenario and “hard switch” to remove visual measurements.



Multi-Camera Odometry

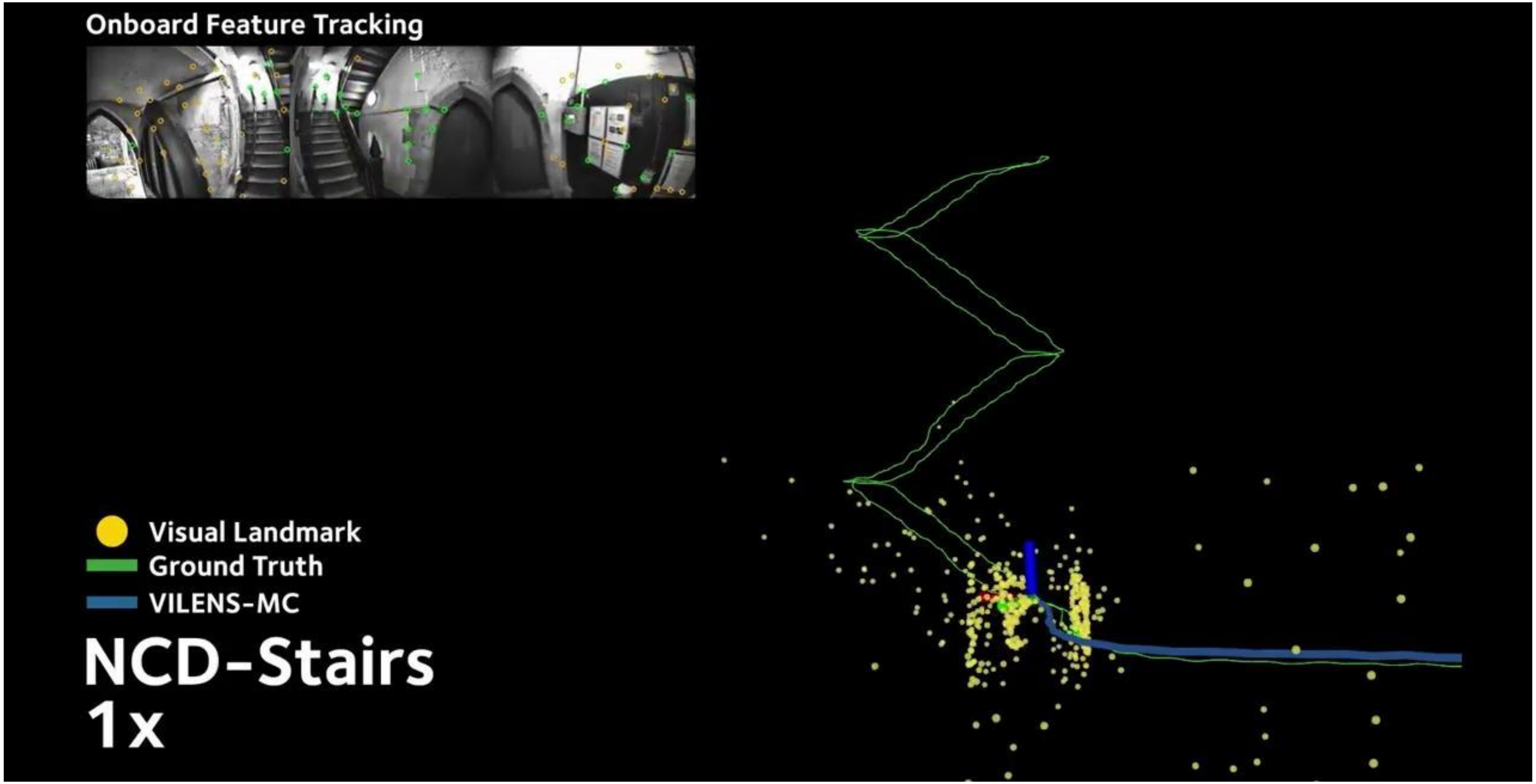
Cross Cam Feature Tracking (CCFT)



CCFT & SFS Example

Experiment: New College Stairs

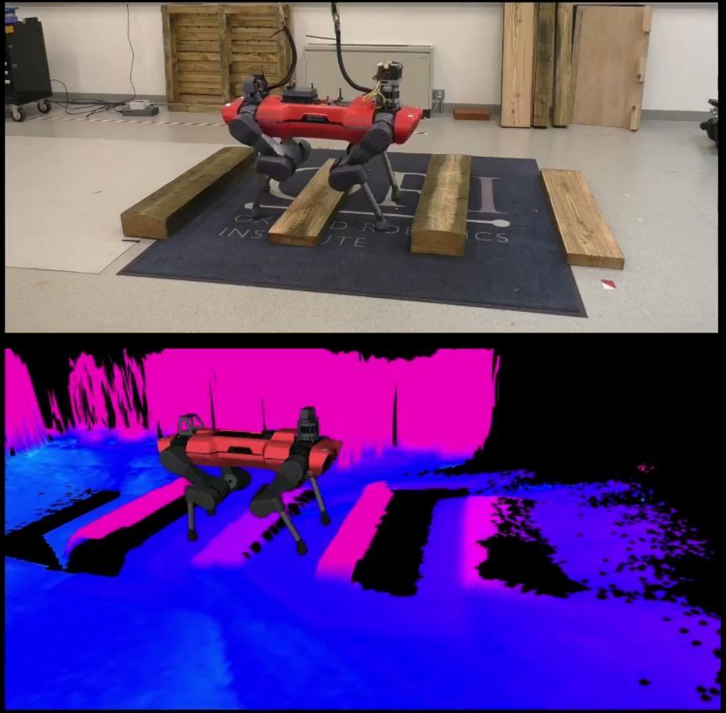
Key challenge: narrow space + texture less walls + door opening



ORB-Slam Comparison

Local mapping

Perceptive Controller* (RLOC)



* Gangapurwala et al., T-RO 2021(preprint)

SLAM

Solution Overview

Two subsystems:

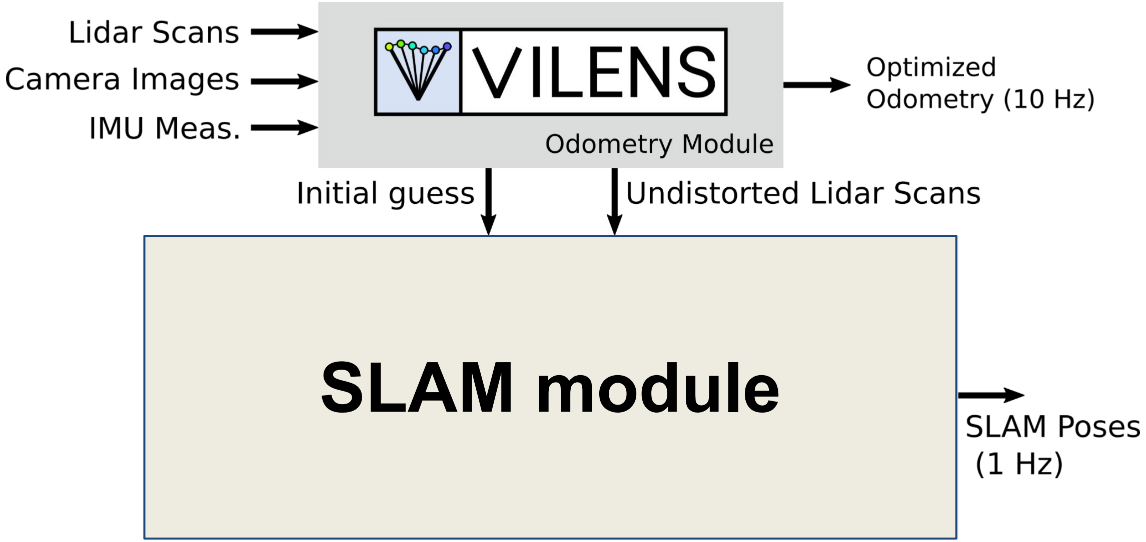
- VILENS odometry
- Global lidar SLAM

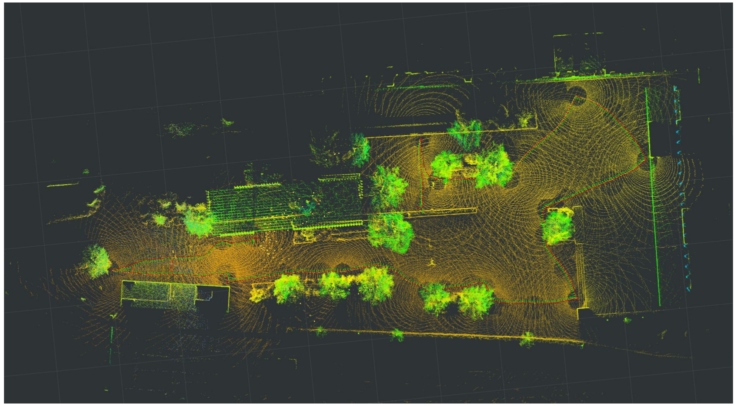
VILENS provides an initial guess for the SLAM module

The SLAM module "bends" the map when a loop closure is found

Computation Time:

- Processed in real-time using ROS





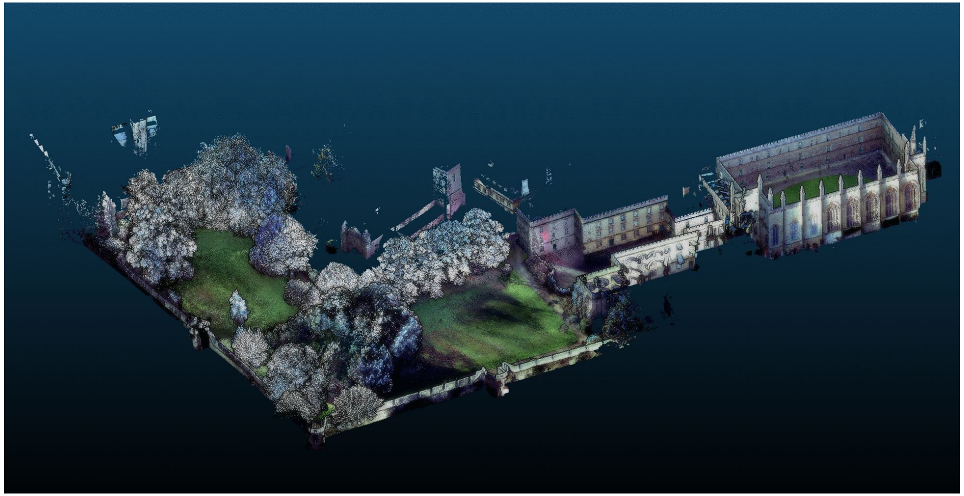
Pose Graph-based LIDAR SLAM

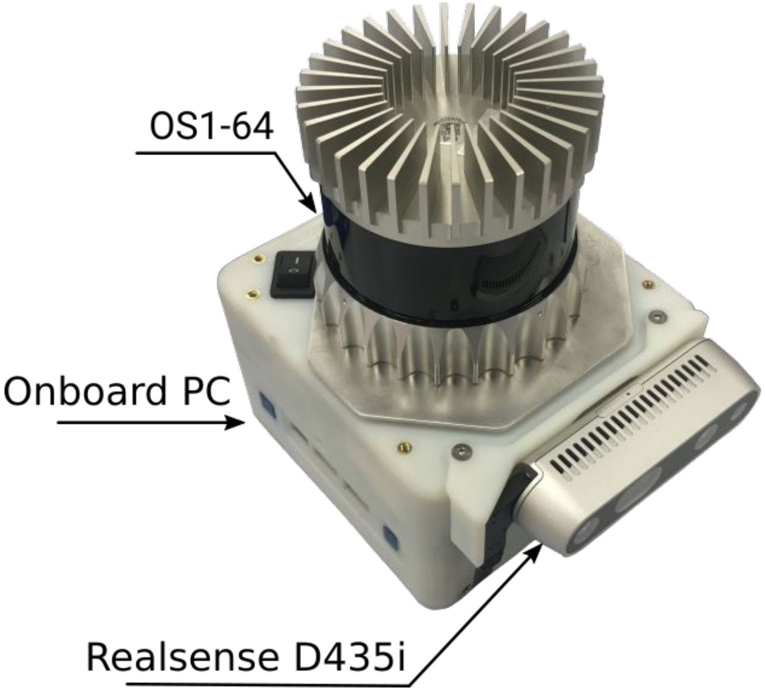
Approach: Keep map as a graph of places we've been, detect places, reshape map for consistency

Ramezani, Milad, Georgi Tinchev, Egor Iuganov, and Maurice Fallon. "Online LiDAR-SLAM for Legged Robots with Robust Registration and Deep-Learned Loop Closure," IEEE International Conference on Robotics and Automation (ICRA), 2020.

A common sensor payload

- All computation performed onboard
- 360 Field of View Lidar
- One or more stereo cameras
- Battery powered
- Public dataset released at IROS 2020





ori-drs.github.io/newer-college-dataset/

M. Ramezani, Y. Wang, M. Camurri, D. Wisth, M. Mattamala and M. Fallon, **"The Newer College Dataset: Handheld LiDAR, Inertial and Vision with Ground Truth"** 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2020, pp. 4353-4360,

HILTI SLAM Challenge

UNIVERSITY OF OXFORD

- Best Academic Participant
- Real-Time solution (no long post-processing)
- No “overfitting” assumption
- Same configuration for all sequences

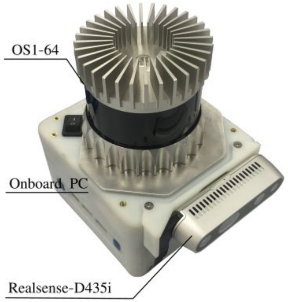
LEADERBOARD

Rank	Team Name		Score
1	Megvii	IROS Talk	461.0
2	Bosch CR - Advanced Autonomous Systems	IROS Talk	457.0
3	V&R Vision & Robotics GmbH		406.0
4	GeoSLAM		389.0
5	VILENS and SLAM, Oxford Robotics Institute	7000 USD	378.0
6	VIRAL SLAM, Nanyang Technological University, Singapore	2000 USD	346.0
7	CMU Doom		333.0
8	Maplab + OKVIS, ETHZ	1000 USD	288.0

- Ground truth from surveying station
- Point scoring based on error from each ground truth point (e.g. 10 points for error below 1 cm)

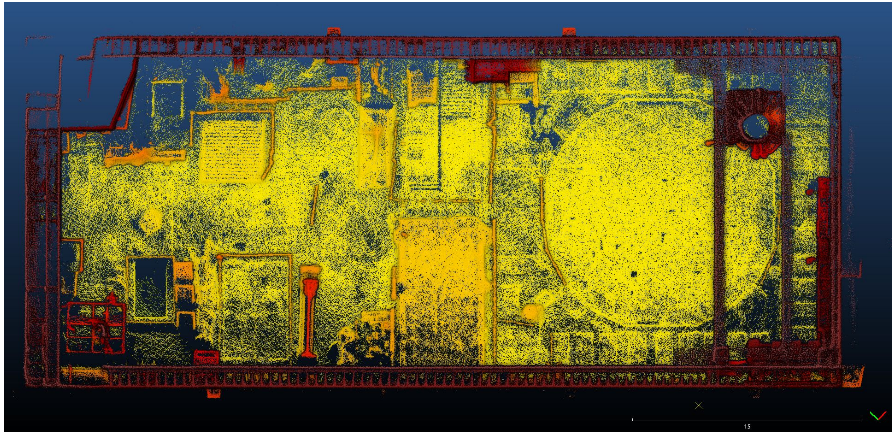
Chernobyl – Control Room for Reactor 4

Led by Prof. Tom Scott (Bristol). We provided mapping.
Spot batteries didn't arrive … all mapping done handheld instead



University of BRISTOL

Chernobyl – Reactor Hall 3



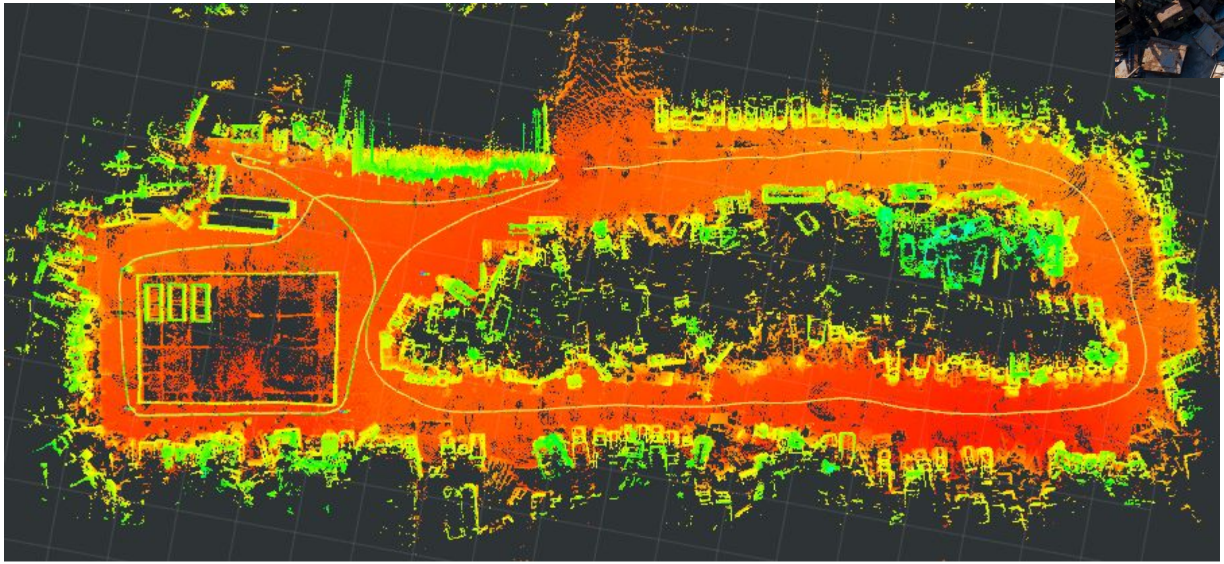
Presentation by Prof. Tom Scott: https://tinyurl.com/chernobyl-bristol
Video on Chernobyl Youtube Challenge: https://www.youtube.com/chernobylnpp

Chernobyl – Buriakivka Vehicle Graveyard

UNIVERSITY OF OXFORD

Storage location for vehicles used in 1986 emergency efforts including the German Joker robot

Bristol are looking at longitudinal radiation monitoring and localization of radiation sources

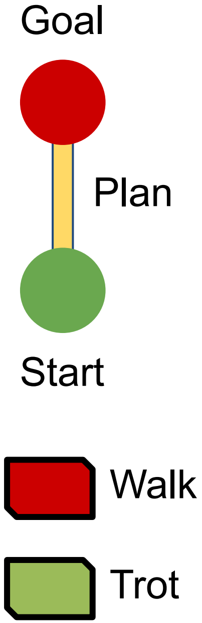


Safe Path Following

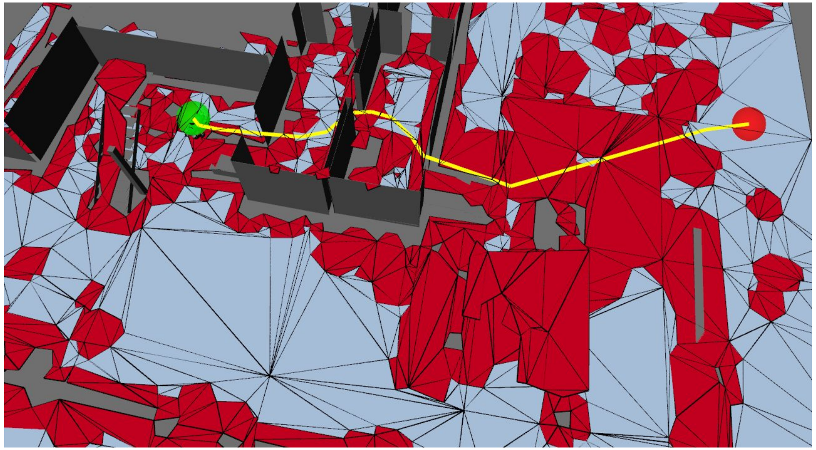
Navigation and Planning

UNIVERSITY OF OXFORD

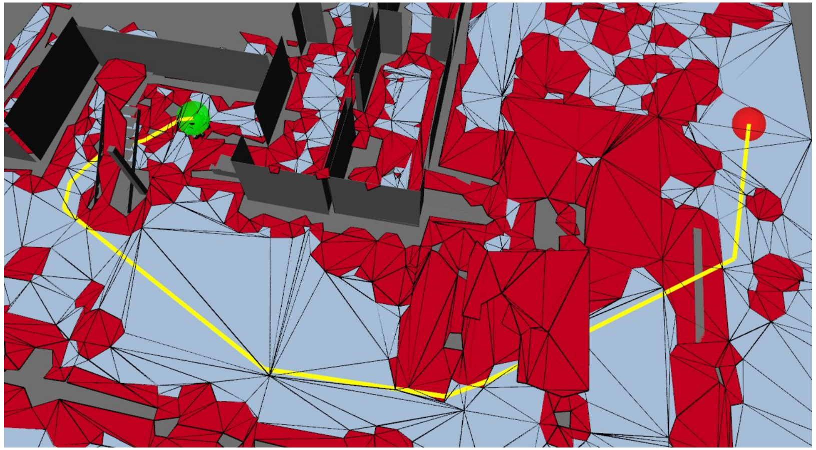
- The mesh is obtained automatically from a point cloud of the environment
- The planner assigns a gait (walk/trot) to each mesh region and...
- … minimizes the total time/energy to goal



Shorter path but slower (walks most of the time)



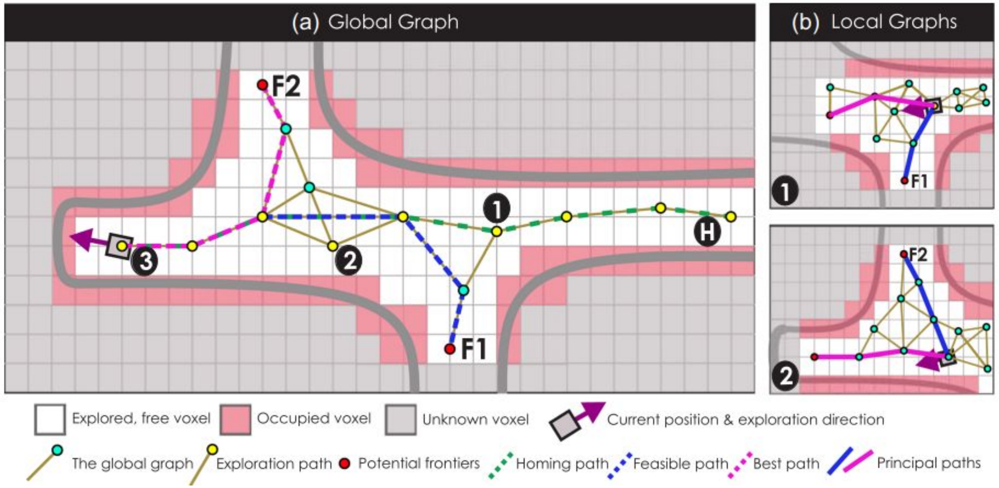
Longer path but faster



Multi-controller multi-objective locomotion planning for legged robots.
Brandao, Havoutis, Fallon, RAL 2020

Local graphs finds path through free space

Global graph:
- Manages exploration frontiers
- Decides on promising corridors
- Considers mission time budget



Safe Visual Teach & Repeat

mcamurri@robots.ox.ac.uk

ori.ox.ac.uk/labs/drs