Tightly-coupled Radar-LiDAR fusion for Robust Odometry

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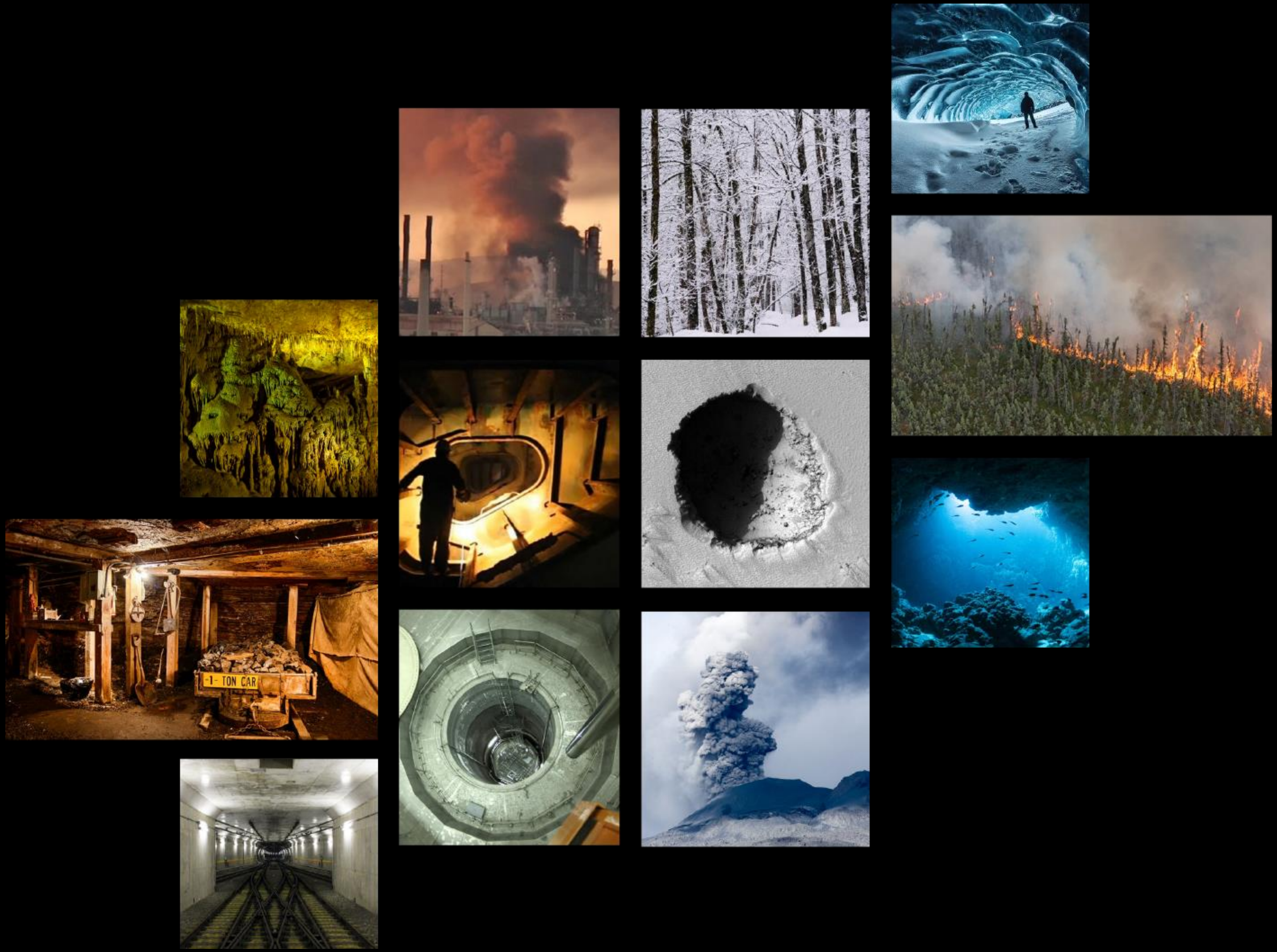
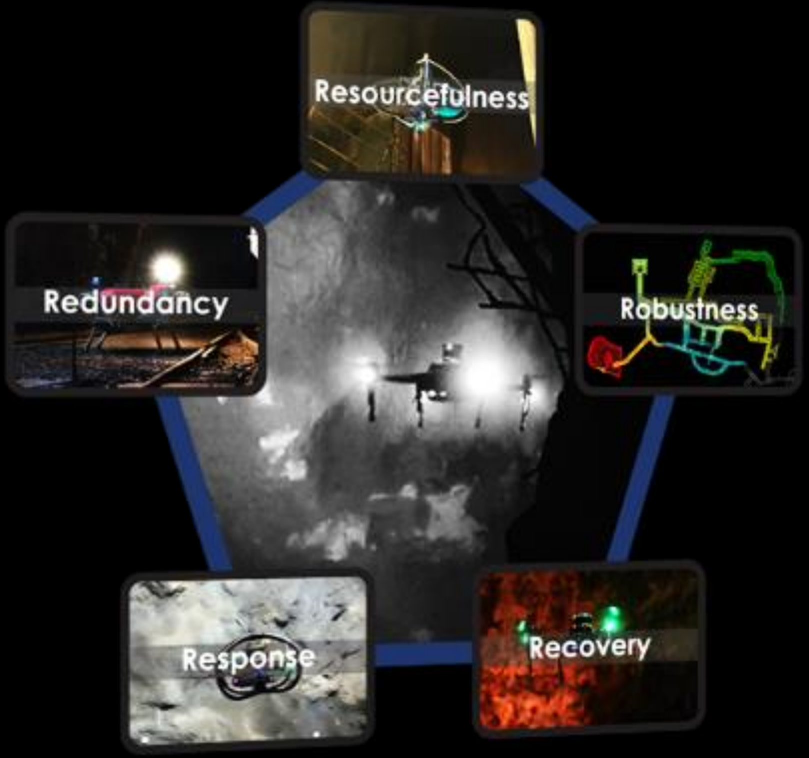
Resilient Autonomy **Anywhere**



Resilience: To *preserve the existence of functionality* and retain performance against unexpected adverse conditions, and unknown, unmodelled disturbances or other phenomena.

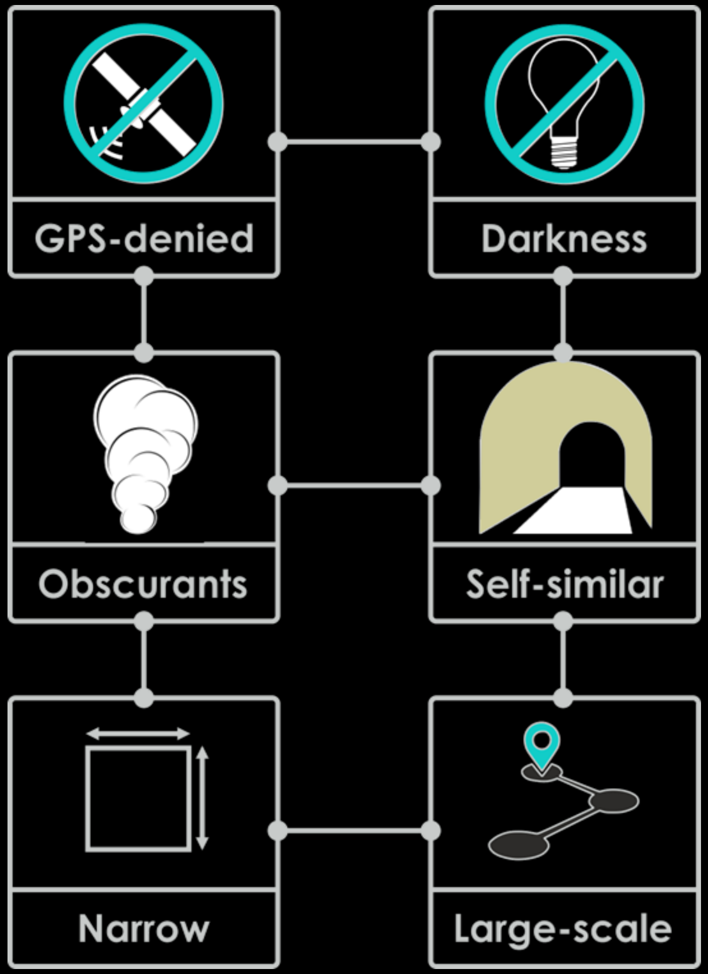


Autonomy through Degradation

- **Penetrate and overcome conditions of degradation & austerity leading to high-risk operations**
  - **Perceptually:**
    - Self-similarity
    - Lack of visual texture
    - Obscurants such as smoke or dust

    Multiple but not all simultaneously
  - **Geometrically:**
    - Large in scale
    - Narrow in cross section
    - Obstacle-filled

    Potentially all simultaneously
  - **Unknown/aleatoric sources of risk:**
    - Unaccounted and unmodelled factors leading to module/system failures (e.g., map failure)
- Deliver resilient robot pose and map estimation, alongside scene reasoning



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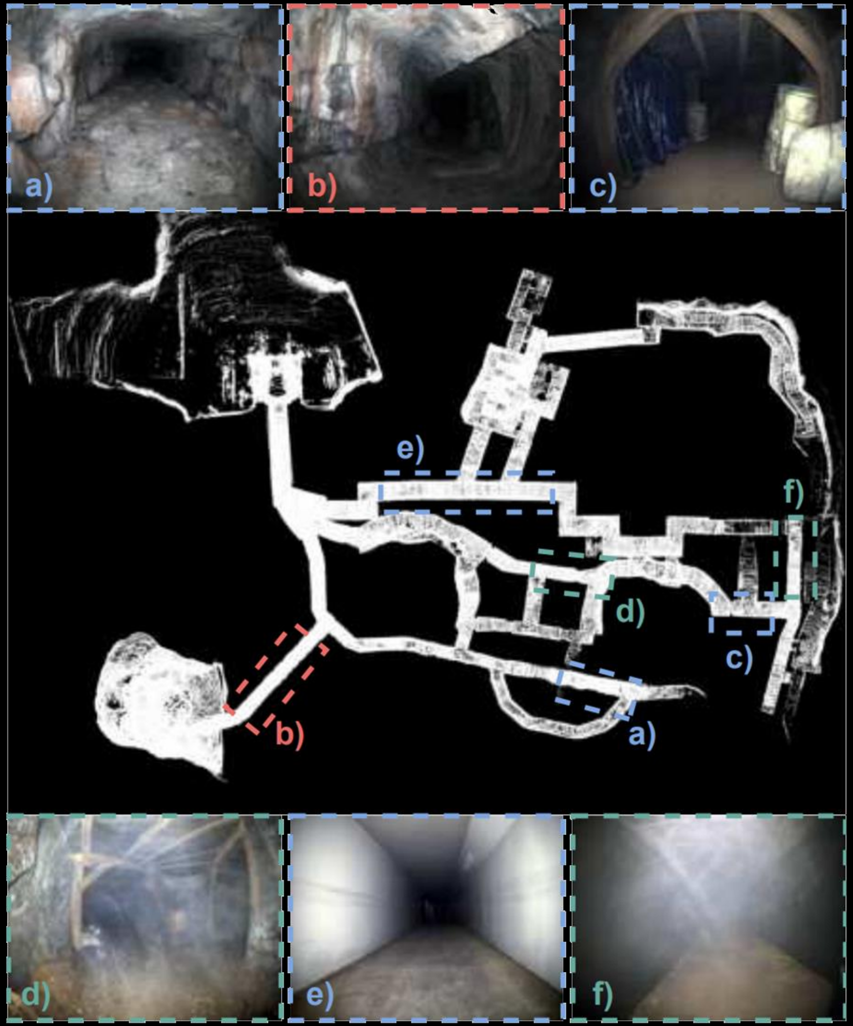
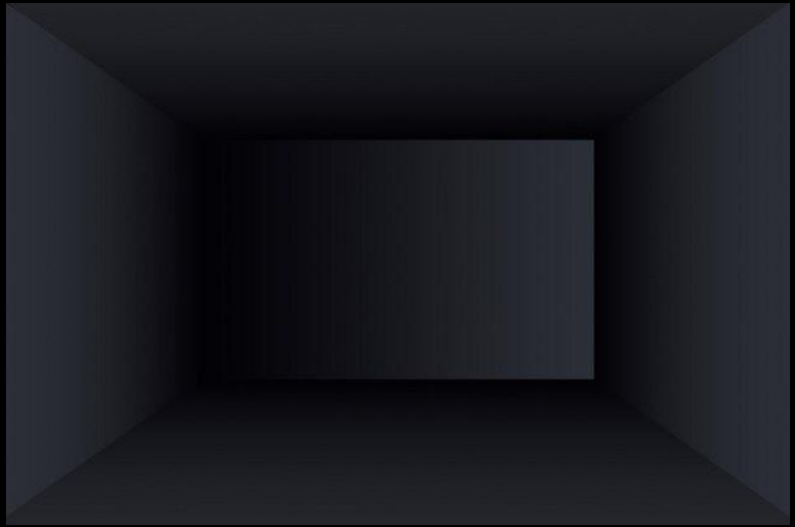


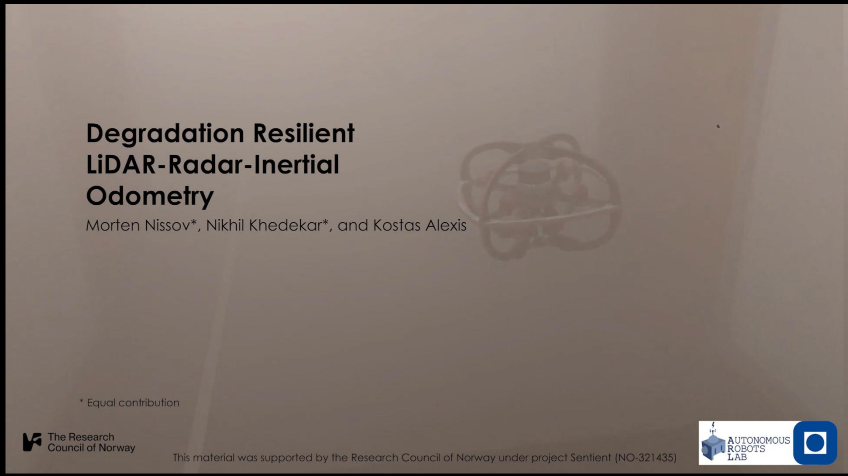
Perceptually degraded conditions

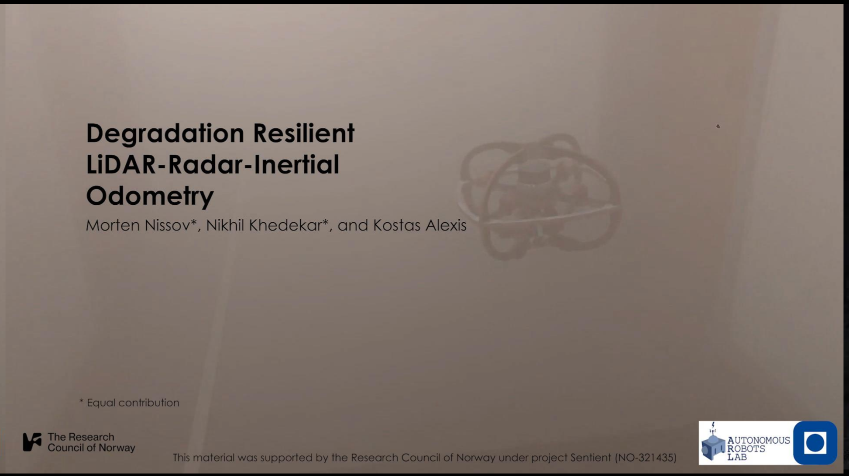
Obscurants

Self-similarity

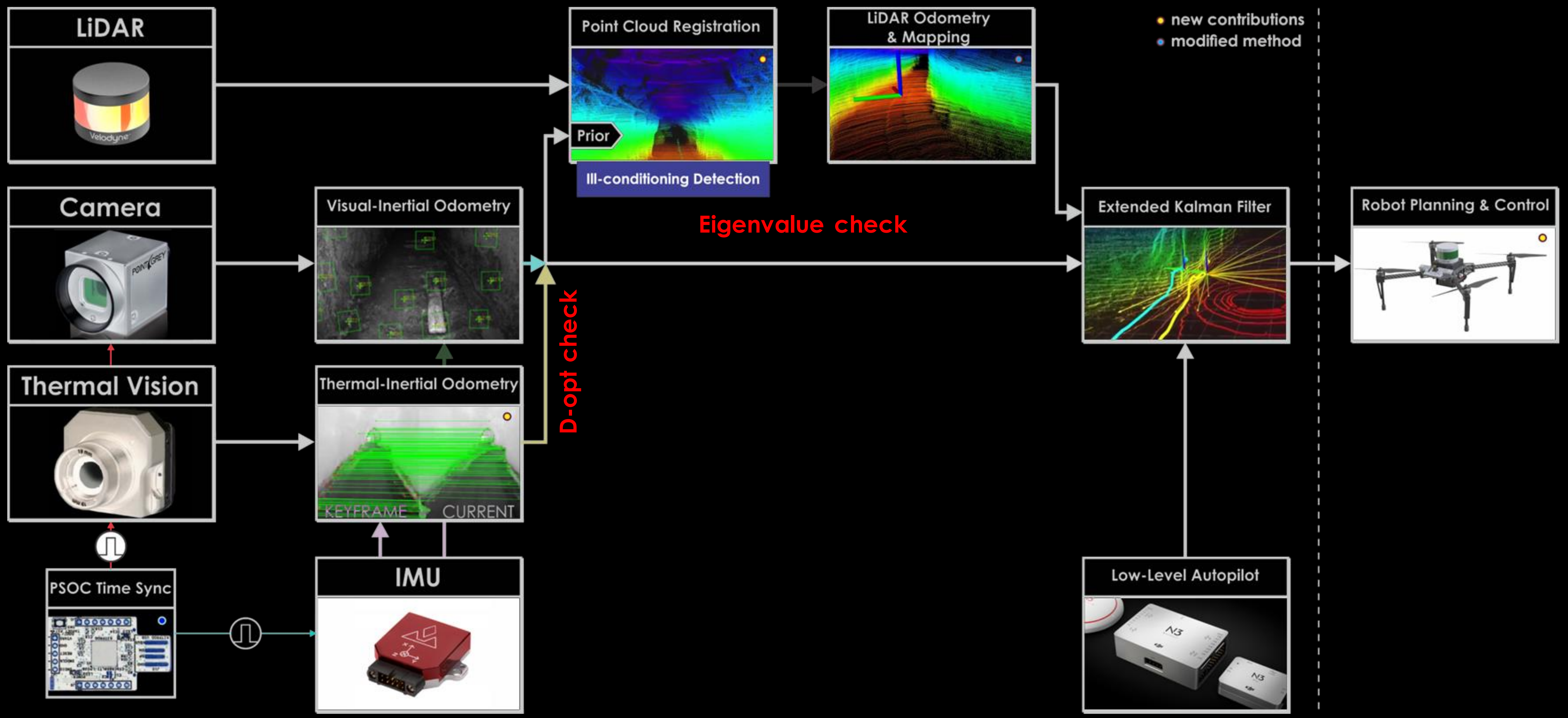


Weak visual texture

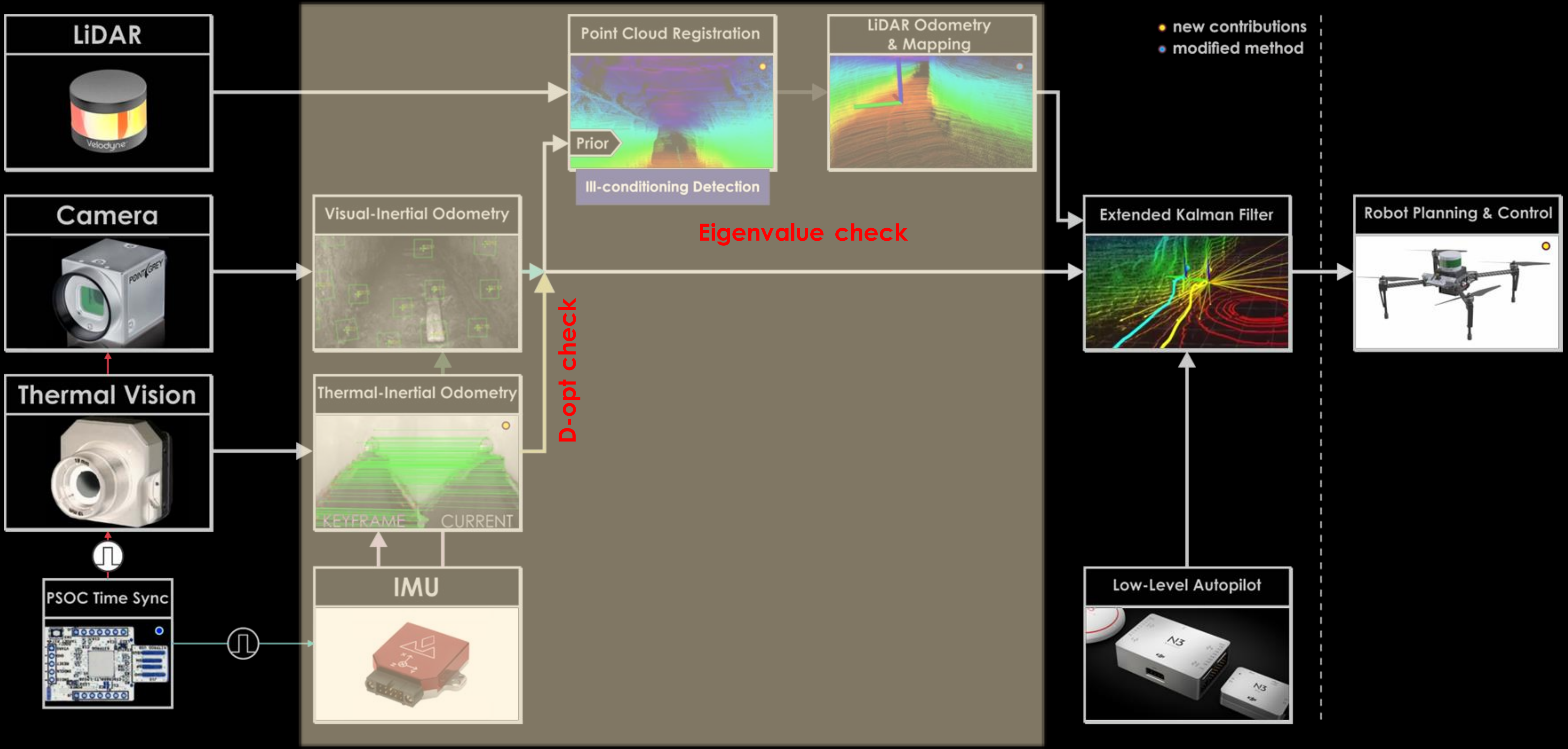




Multi-modal Loosely-coupled SLAM



Multi-modal Loosely-coupled SLAM



Handling degeneracy

- **Detection:**
  - Point cloud Registration: Threshold eigenvalues of the approximate Hessian of the Jacobian of the nonlinear optimization

$$J^T J \delta \mathbf{x} = -J^T r$$

  - Visual(Thermal)-inertial Odometry: Threshold the D-Optimality metric

$$D_{\text{opt}} = \exp(\log(\det(\Sigma)^{1/l}))$$

- **Handling:**
  - Retain successful degrees of freedom from LiDAR localization and mapping and replace those degenerate from VIO.
  - Disregard VIO if its D-opt value exceeds threshold.

Complementary Multi-Modal Sensor Fusion for Resilient Robot Pose Estimation in Subterranean Environments

S. Khattak, H. Nguyen, F. Mascarich, T. Dang, K. Alexis

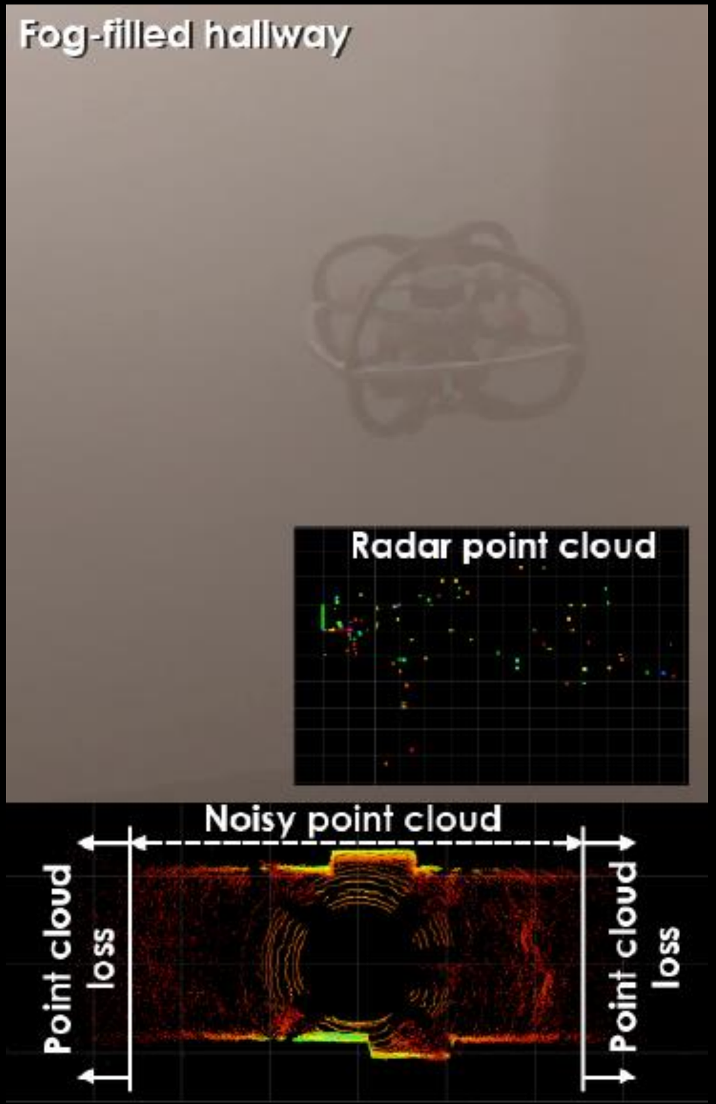
DARPA

AUTONOMOUS ROBOTS LAB

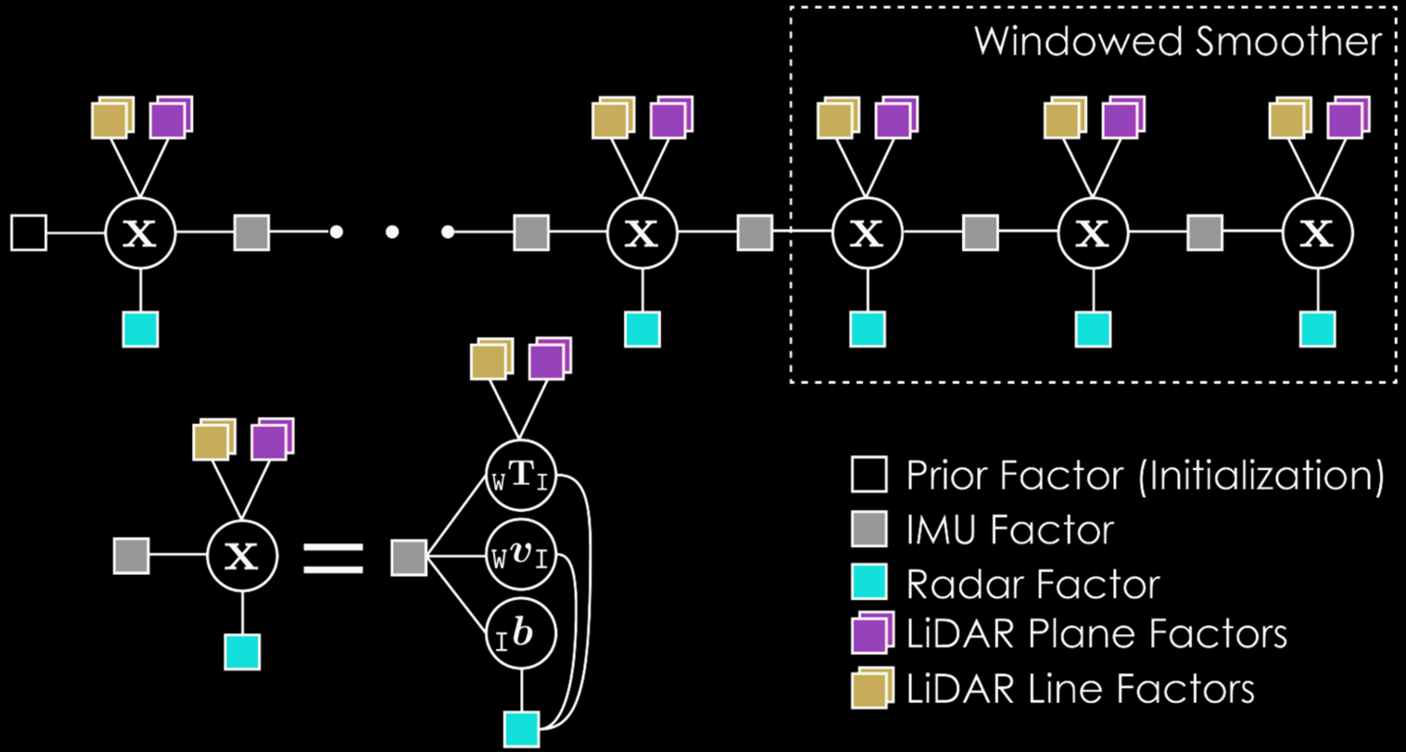
The research effort for the results depicted is sponsored by the Defense Advanced Research Projects Agency. The presented content and ideas are solely those of the authors.

Tightly-coupled LiDAR-Radar-Inertial fusion

- **Motivation:**
  - In self-similar and obscurants-filled environments, LiDAR faces significant limitations.
    - Threshold-based detection, which can be environment dependent
  - Experience from SubT indicated that dense smoke-filled environments render both LiDAR and vision degraded, while certain types of smoke render LWIR degraded.
    - Thermal vision is not a viable solution for all obscurants.
  - Radar represents a viable and versatile alternative.
- **Contribution:**
  - **Tightly-coupled LiDAR-Radar-Inertial fusion** for odometry
  - Factors for **direct integration of LiDAR features** in the graph with a global map
  - Factor for integration of **radar velocity** in a factor graph for inertial navigation



Tightly-coupled LiDAR-Radar-Inertial fusion

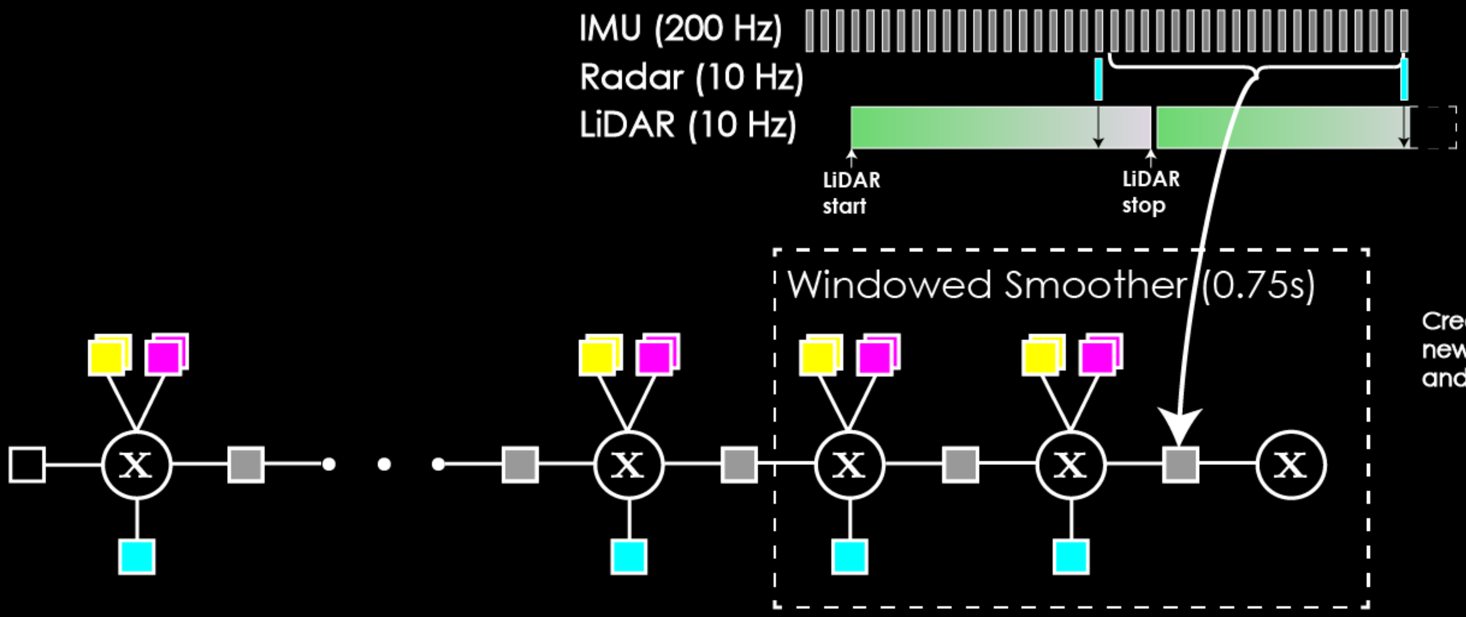


$$\mathcal{X}^*_{k-l:k} = \underset{\mathcal{X}_{k-l:k}}{\operatorname{argmin}} \Big(\|\boldsymbol{e}_{k-l-1}\|^2_{\boldsymbol{\Sigma}_0} + \Sigma_{(i,j)\in\mathcal{M}_{k-l:k}} \|\boldsymbol{e}_{\mathcal{I}_{ij}}\|^2_{\boldsymbol{\Sigma}_\mathcal{I}} + \Sigma_{i\in\mathcal{M}_{k-l:k}} \|\boldsymbol{e}_{\mathcal{R}_i}\|^2_{\boldsymbol{\Sigma}_\mathcal{R}} + \Sigma_{i\in\mathcal{M}_{k-l:k}} \|\boldsymbol{e}_{\mathcal{L}_i}\|^2_{\boldsymbol{\Sigma}_\mathcal{L}} \Big)$$

Measurement Handling: IMU

1- Add IMU data to buffer

- Ready to add node to the graph at the radar measurement
- Addition of pre-integrated IMU factor to connect the new state
- Implementation from GTSAM following [1]



Create state at new radar measurement and add IMU factor

- Prior Factor (Initialization)
- IMU Factor
- Radar Factor
- LiDAR Plane Factors
- LiDAR Line Factors

Errors: $e_{\mathcal{I}} = \left[e^{\top}_{\Delta_W R_I} \quad e^{\top}_{\Delta_W v_I} \quad e^{\top}_{\Delta_W p_I} \right]^{\top}$ [1]

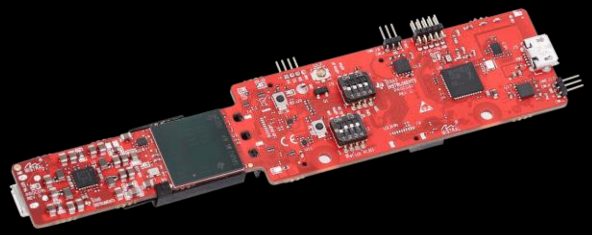
Jacobians: refer to [1]

[1] Forster, Christian, et al. "On-manifold preintegration for real-time visual--inertial odometry." IEEE Transactions on Robotics 33.1 (2016): 1-21

Measurement Handling: Radar

1 - Radar point cloud includes

- Geometry (range, azimuth, elevation)
- Doppler (radial speed)
- Radar cross section



Texas Instruments IWR6843AOPEVM

(Ideal for SWaP constraints)

Chirp Parameters	Value
Start frequency	60 GHz
Bandwidth	1911.273 MHz
Maximum Range	15.999 m
Maximum Doppler	3.995 m/s
Range Resolution	0.0785 m
Doppler Velocity Resolution	0.133 m/s
Azimuth/Elevation Resolution	23 deg

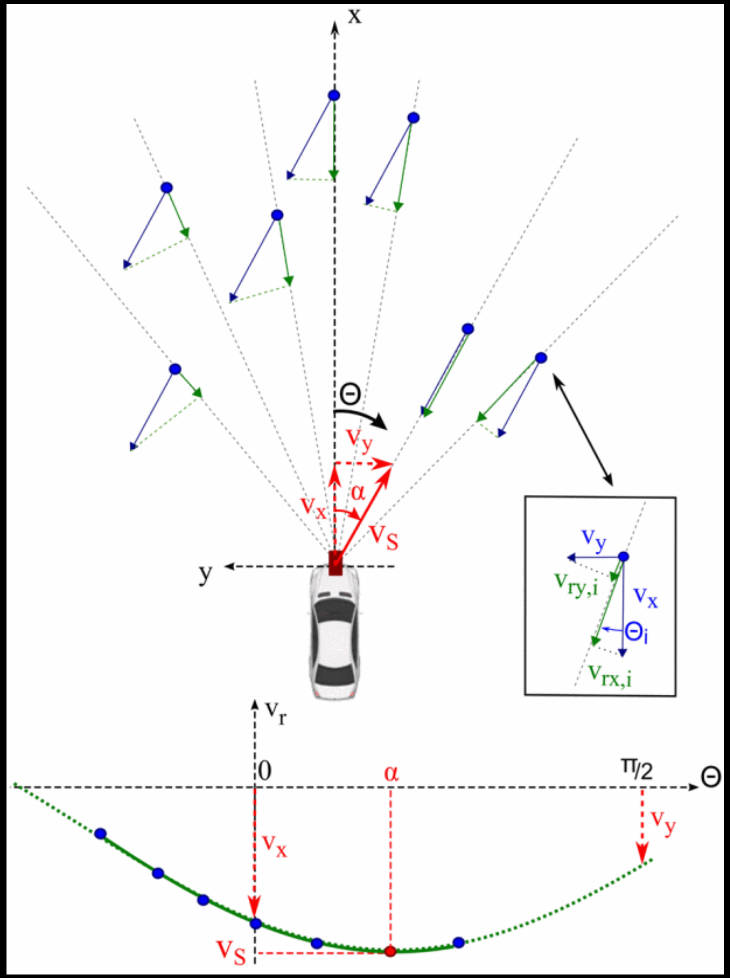


Image courtesy of D. Kellner, et. al., "Instantaneous ego-motion estimation using Doppler radar," 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)

Measurement Handling: Radar

1 - Radar point cloud includes

- Geometry (range, azimuth, elevation)
- Doppler (radial speed)
- Radar cross section

2 - RANSAC Least Squares

- Angular rate from IMU buffer
- Get linear velocity 3-vector
- Estimate solution covariance

$$v_r = -{}_{\mathrm{R}}\bar{\boldsymbol{r}}^{\top}{}_{\mathrm{R}}\boldsymbol{v}$$

$${}_{\mathrm{R}}\boldsymbol{v} = {}_{\mathrm{R}}\mathbf{R}_{\mathrm{I}}\left({}_{\mathrm{I}}\mathbf{R}_{\mathrm{W}}{}_{\mathrm{W}}\boldsymbol{v} + \left({}_{\mathrm{I}}\boldsymbol{\omega} - \boldsymbol{b}_g\right) \times {}_{\mathrm{I}}\boldsymbol{p}_{\mathrm{R}}\right)$$

$$\begin{bmatrix} v_r^1 \\ v_r^2 \\ \vdots \\ v_r^N \end{bmatrix} = \begin{bmatrix} \left({}_{\mathrm{R}}\bar{\boldsymbol{r}}^1\right)^{\top} \\ \left({}_{\mathrm{R}}\bar{\boldsymbol{r}}^2\right)^{\top} \\ \vdots \\ \left({}_{\mathrm{R}}\bar{\boldsymbol{r}}^N\right)^{\top} \end{bmatrix} \begin{bmatrix} {}_{\mathrm{R}}v_x \\ {}_{\mathrm{R}}v_y \\ {}_{\mathrm{R}}v_z \end{bmatrix}$$

$$\boldsymbol{v}_r = \mathbf{X}_{\mathrm{R}}\boldsymbol{v}$$

$$e_{\mathcal{R}} = {}_{\mathrm{R}}\mathbf{R}_{\mathrm{I}}\left({}_{\mathrm{I}}\mathbf{R}_{\mathrm{W}}{}_{\mathrm{W}}\boldsymbol{v} + \left({}_{\mathrm{I}}\boldsymbol{\omega} - \boldsymbol{b}_g\right) \times {}_{\mathrm{I}}\boldsymbol{p}_{\mathrm{R}}\right) - {}_{\mathrm{R}}\tilde{\boldsymbol{v}}$$

Measurement Handling: Radar

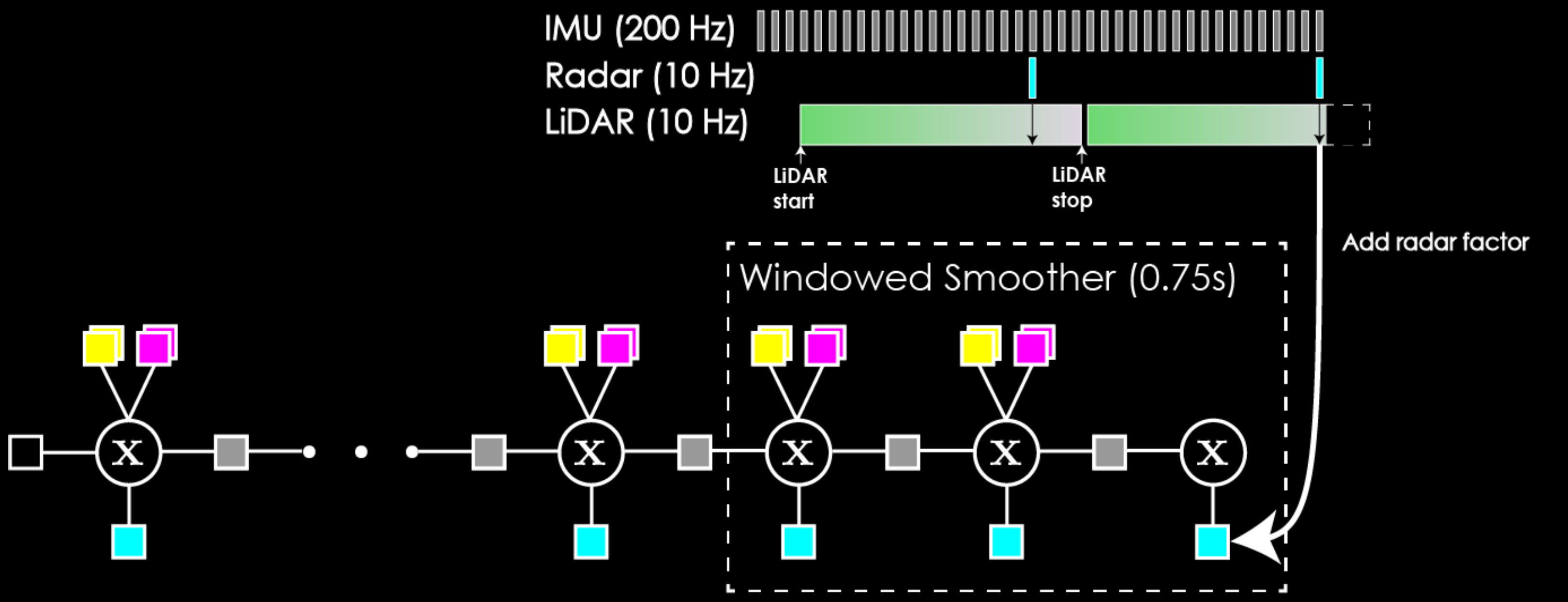
1 - Radar point cloud includes

- Geometry (range, azimuth, elevation)
- Doppler (radial speed)
- Radar cross section

2 - RANSAC Least Squares

- Angular rate from IMU buffer
- Get linear velocity 3-vector
- Estimate solution covariance

3 - Add to factor graph



- Prior Factor (Initialization)
- IMU Factor
- Radar Factor
- LiDAR Plane Factors
- LiDAR Line Factors

Error $\left\{ \boldsymbol{e}_{\mathcal{R}} = {}_{\mathrm{R}}\mathbf{R}_{\mathrm{I}} \left({}_{\mathrm{I}}\mathbf{R}_{\mathrm{W}} {}_{\mathrm{W}}\boldsymbol{v}_{\mathrm{I}} + \left({}_{\mathrm{I}}\boldsymbol{\omega} - \boldsymbol{b}_g \right) \times {}_{\mathrm{I}}\boldsymbol{p}_{\mathrm{R}} \right) - {}_{\mathrm{R}}\tilde{\boldsymbol{v}} \right.$

Jacobians
$$\left\{ \begin{aligned} \frac{\partial \boldsymbol{e}_{\mathcal{R}}}{\partial_{\mathrm{W}}\mathbf{R}_{\mathrm{I}}} &= {}_{\mathrm{R}}\mathbf{R}_{\mathrm{I}} \left({}_{\mathrm{I}}\mathbf{R}_{\mathrm{W}} {}_{\mathrm{W}}\boldsymbol{v}_{\mathrm{I}} \right)^{\wedge} \\ \frac{\partial \boldsymbol{e}_{\mathcal{R}}}{\partial_{\mathrm{W}}\boldsymbol{v}_{\mathrm{I}}} &= {}_{\mathrm{R}}\mathbf{R}_{\mathrm{I}} {}_{\mathrm{I}}\mathbf{R}_{\mathrm{W}} \\ \frac{\partial \boldsymbol{e}_{\mathcal{R}}}{\partial \boldsymbol{b}_g} &= {}_{\mathrm{R}}\mathbf{R}_{\mathrm{I}} \left({}_{\mathrm{I}}\boldsymbol{p}_{\mathrm{R}} \right)^{\wedge} \end{aligned} \right.$$

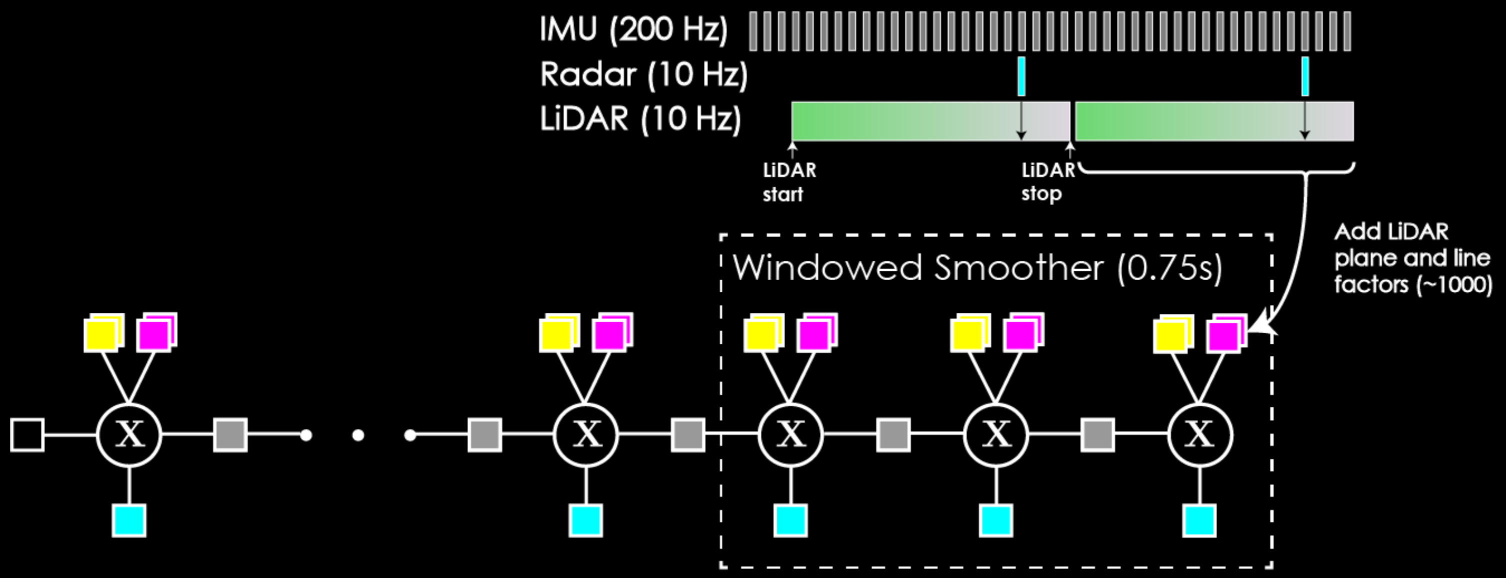
Measurement Handling: LiDAR

1 - De-skew point cloud to radar measurement timestamp

2 - Extract point/line features by curvature

3 - Find correspondences in feature submap (global map)

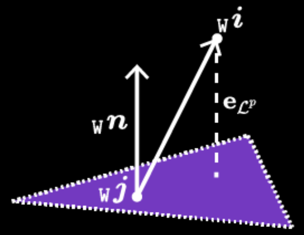
4 - Add feature factors to graph



- Prior Factor (Initialization)
- IMU Factor
- Radar Factor
- LiDAR Plane Factors
- LiDAR Line Factors

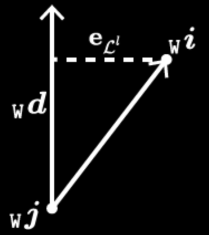
Error: $\boldsymbol{e}_{\mathcal{L}^p} = (({}_{\mathrm{W}}\boldsymbol{i} - {}_{\mathrm{W}}\boldsymbol{j}) \cdot {}_{\mathrm{W}}\boldsymbol{n})\,{}_{\mathrm{W}}\boldsymbol{n}$

Jacobian: $\dfrac{\partial \boldsymbol{e}_{\mathcal{L}^p}}{\partial_{\mathrm{W}} \mathbf{T}_{\mathrm{I}}} = {}_{\mathrm{W}}\boldsymbol{n}\,{}_{\mathrm{W}}\boldsymbol{n}^{\top} \left[-{}_{\mathrm{W}}\mathbf{R}_{\mathrm{I}}\,{}_{\mathrm{I}}\boldsymbol{i}^{\wedge} \quad {}_{\mathrm{W}}\mathbf{R}_{\mathrm{I}}\right]$



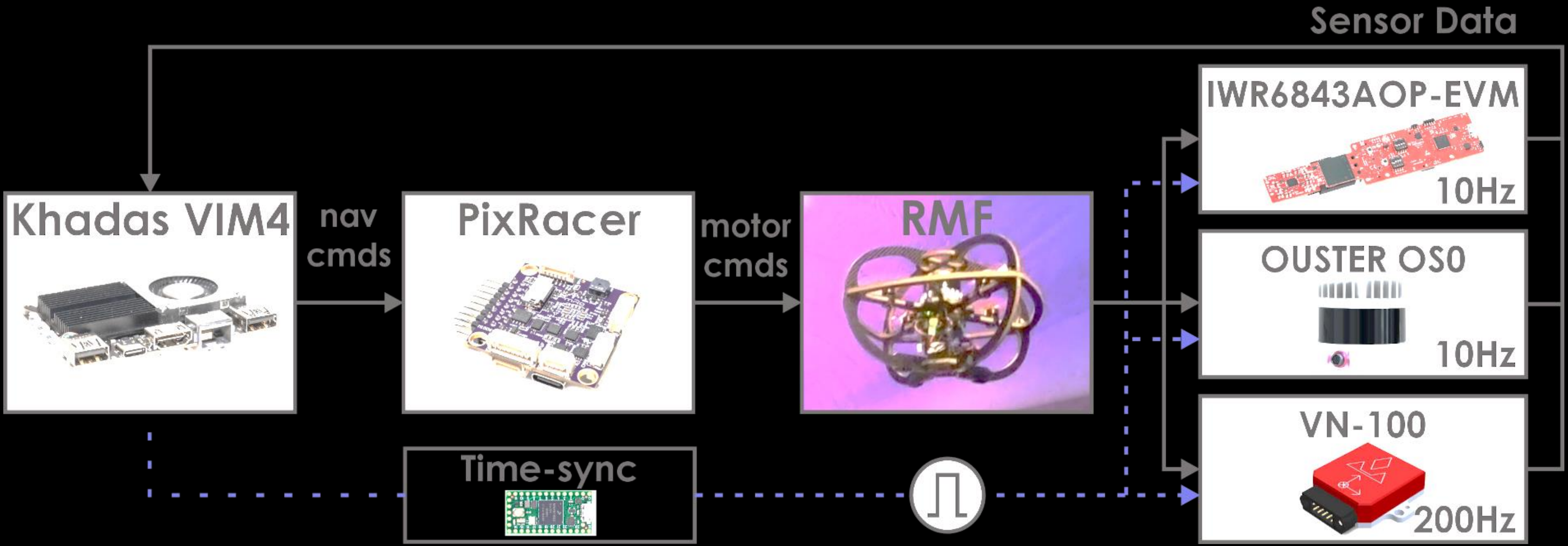
Error: $\boldsymbol{e}_{\mathcal{L}^l} = ({}_{\mathrm{W}}\mathbf{T}_{\mathrm{I}}\,{}_{\mathrm{I}}\boldsymbol{i} - {}_{\mathrm{W}}\boldsymbol{j}) - (({}_{\mathrm{W}}\mathbf{T}_{\mathrm{I}}\,{}_{\mathrm{I}}\boldsymbol{i} - {}_{\mathrm{W}}\boldsymbol{j}) \cdot {}_{\mathrm{W}}\boldsymbol{d})\,{}_{\mathrm{W}}\boldsymbol{d}$

Jacobian: $\dfrac{\partial \boldsymbol{e}_{\mathcal{L}^l}}{\partial_{\mathrm{W}} \mathbf{T}_{\mathrm{I}}} = \left(\mathbf{I}_3 - {}_{\mathrm{W}}\boldsymbol{d}\,{}_{\mathrm{W}}\boldsymbol{d}^{\top}\right) \left[-{}_{\mathrm{W}}\mathbf{R}_{\mathrm{I}}\,{}_{\mathrm{I}}\boldsymbol{i}^{\wedge} \quad {}_{\mathrm{W}}\mathbf{R}_{\mathrm{I}}\right]$



Hardware Setup

- Microcontroller triggers sensors and timestamps their measurements



Degradation Resilient LiDAR-Radar-Inertial Odometry

Morten Nissov*, Nikhil Khedekar*, and Kostas Alexis

* Equal contribution

The Research Council of Norway

This material was supported by the Research Council of Norway under project Sentient (NO-321435)

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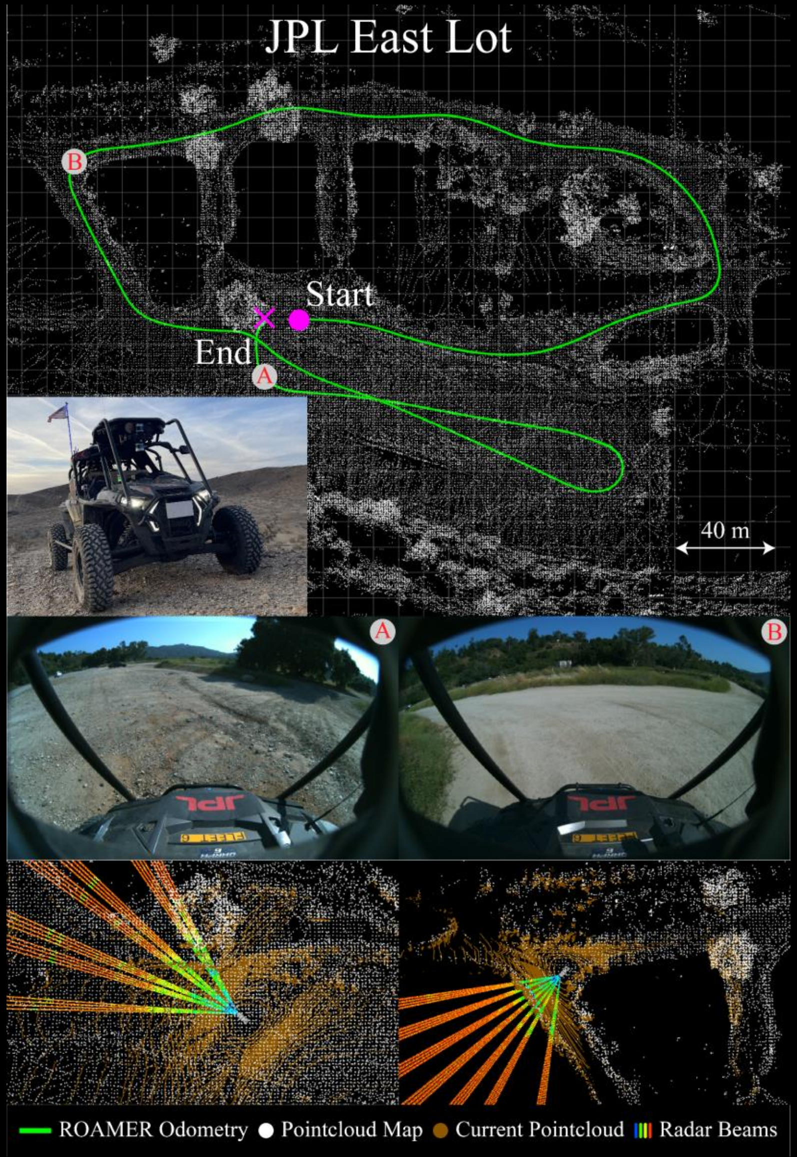
ROAMER – Robust Odometry on JPL RACER

Motivation: More robust estimation for off-road vehicle.

Method: Include radar velocity

- Uses unique 4D radar sensor
  - Returning 3x4 grid of RD-Maps (4x7.5 degrees of azimuth/elevation)
- Driving up to 12 m/s

Investigating usage of radar for stabilizing noisy LiDAR-IMU fusion in barren, off-road terrain



[1] Nissov, Morten, et al. "ROAMER: Robust Offroad Autonomy using Multimodal State Estimation with Radar Velocity Integration." *arXiv preprint arXiv:2401.17404* (2024).

Thank you