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ETI Annual Workshop – 2023

Collaborative SLAM for Facilitating Radiological Search and Mapping on a UWB Enabled Multi-Agent Platform

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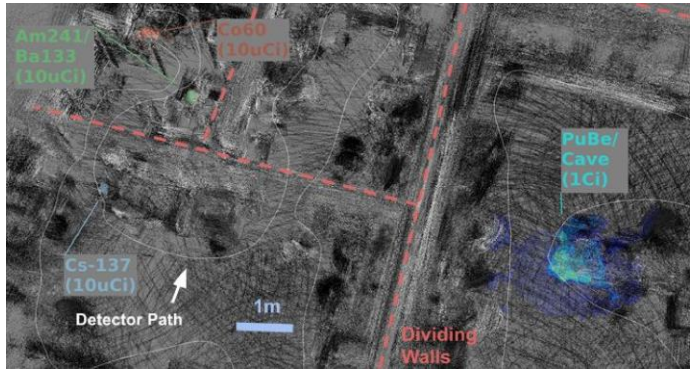
Consortium for Enabling Technologies & Innovation

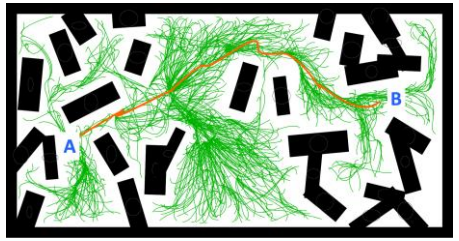
Introduction

Radiological Search, Agent Path Planning and Optimal Behavior

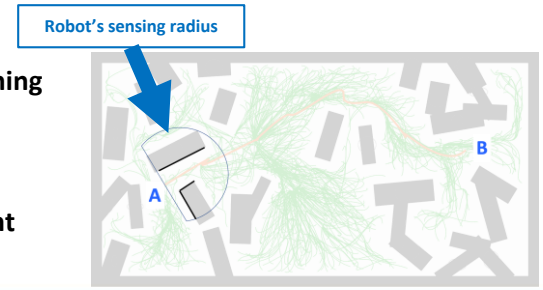
Localization and Mapping Platform (LAMP) from LBNL



3D map fused with radiological measurements for source localization



Route planning from points A ➔ B in known environment



Limited perspective of robot at point A. Shows importance of mapping for route planning.

Goal: enable fast/safe exploration & mapping in partially known/unknown environments:

(1) Rapid exploration
(2) Robust perception and planning
(3) Collaborative (global) mapping

Haiti Earthquake, 2010

New Orleans Hotel Collapse, 2019

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For radiological search, optimal agent behavior is directly tied to how well the swarm understands its environment. Since there are no maps, we need SLAM.

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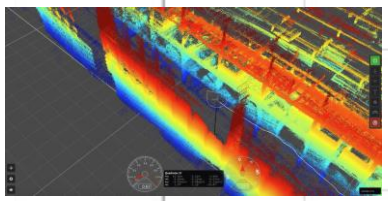
Under the Hood of SLAM

Factor Graphs, Odometry, and Features

Velodyne Puck
3D LiDAR



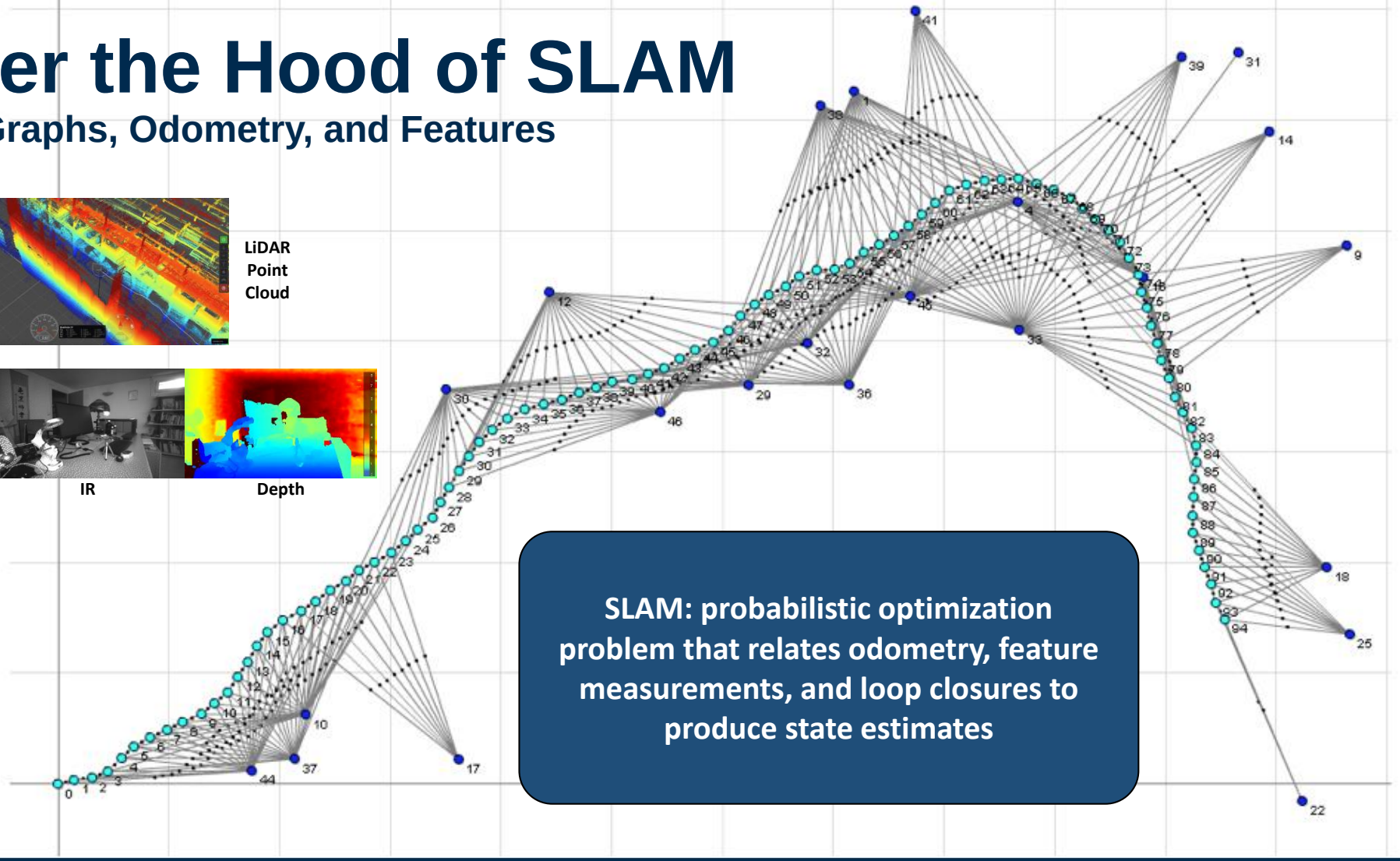
LiDAR
Point
Cloud

Intel Realsense
RGBD Camera

RGB

IR

Depth



SLAM: probabilistic optimization problem that relates odometry, feature measurements, and loop closures to produce state estimates

Estimated States
Observed Features
Measurements
Odometry Measurements
Feature Measurements

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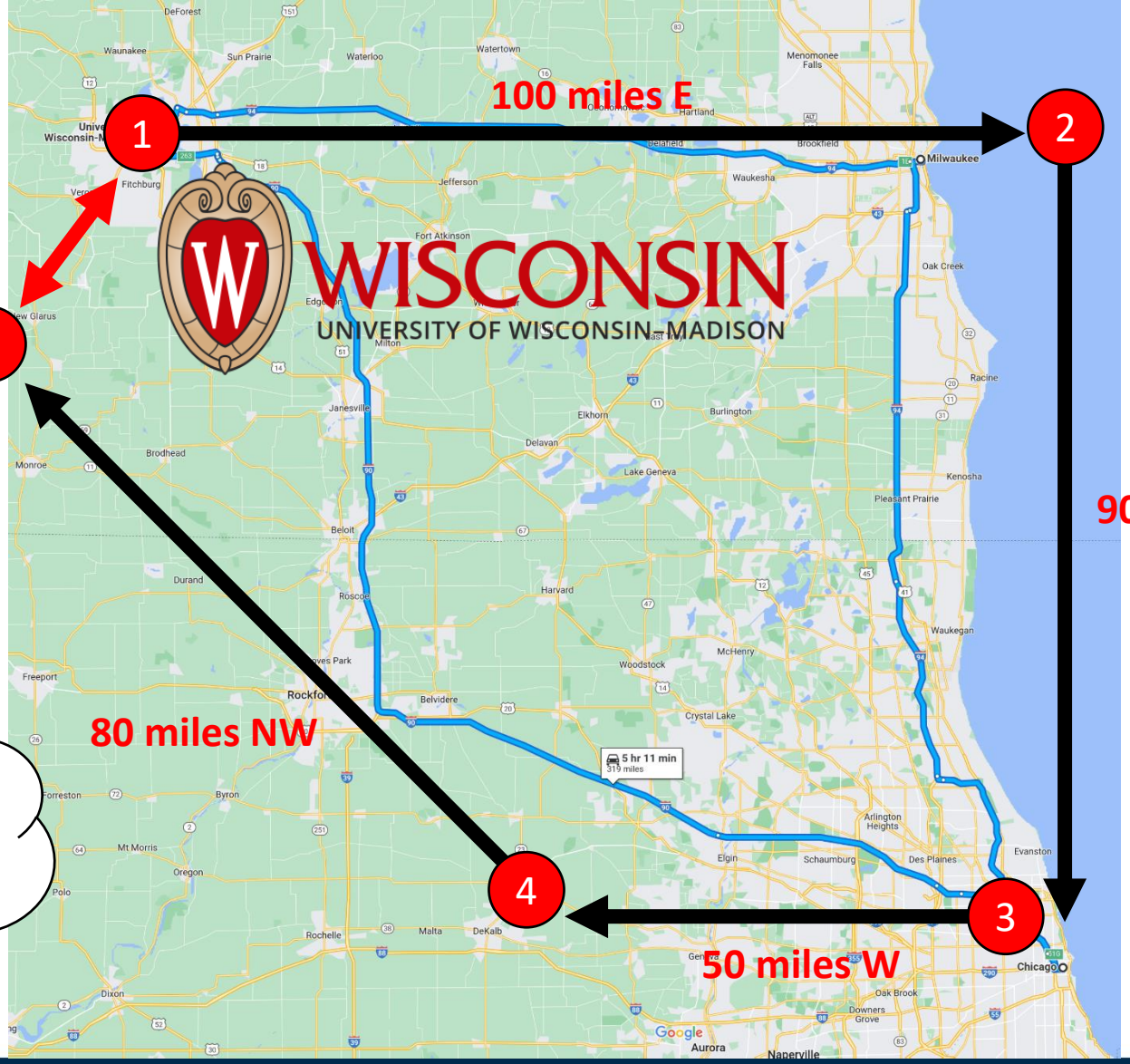
Under the Hood of SLAM

Accumulated Odometry Error & Loop Closures

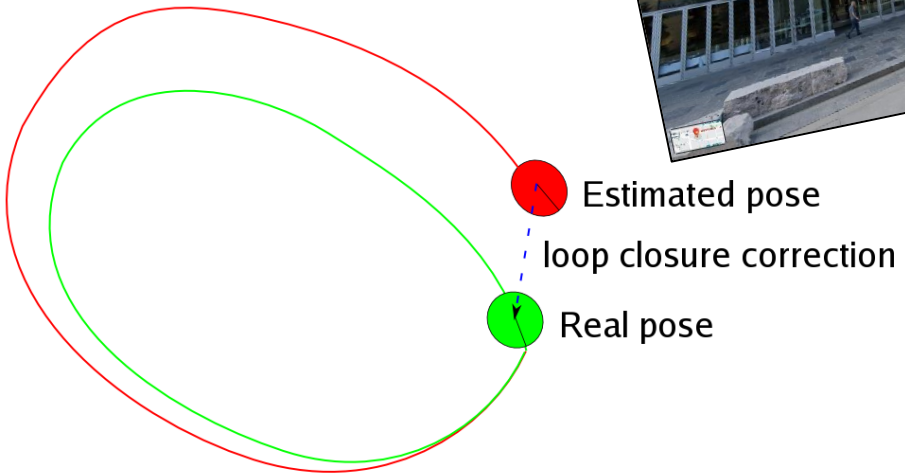
Wait, I know this place. I've been here before!

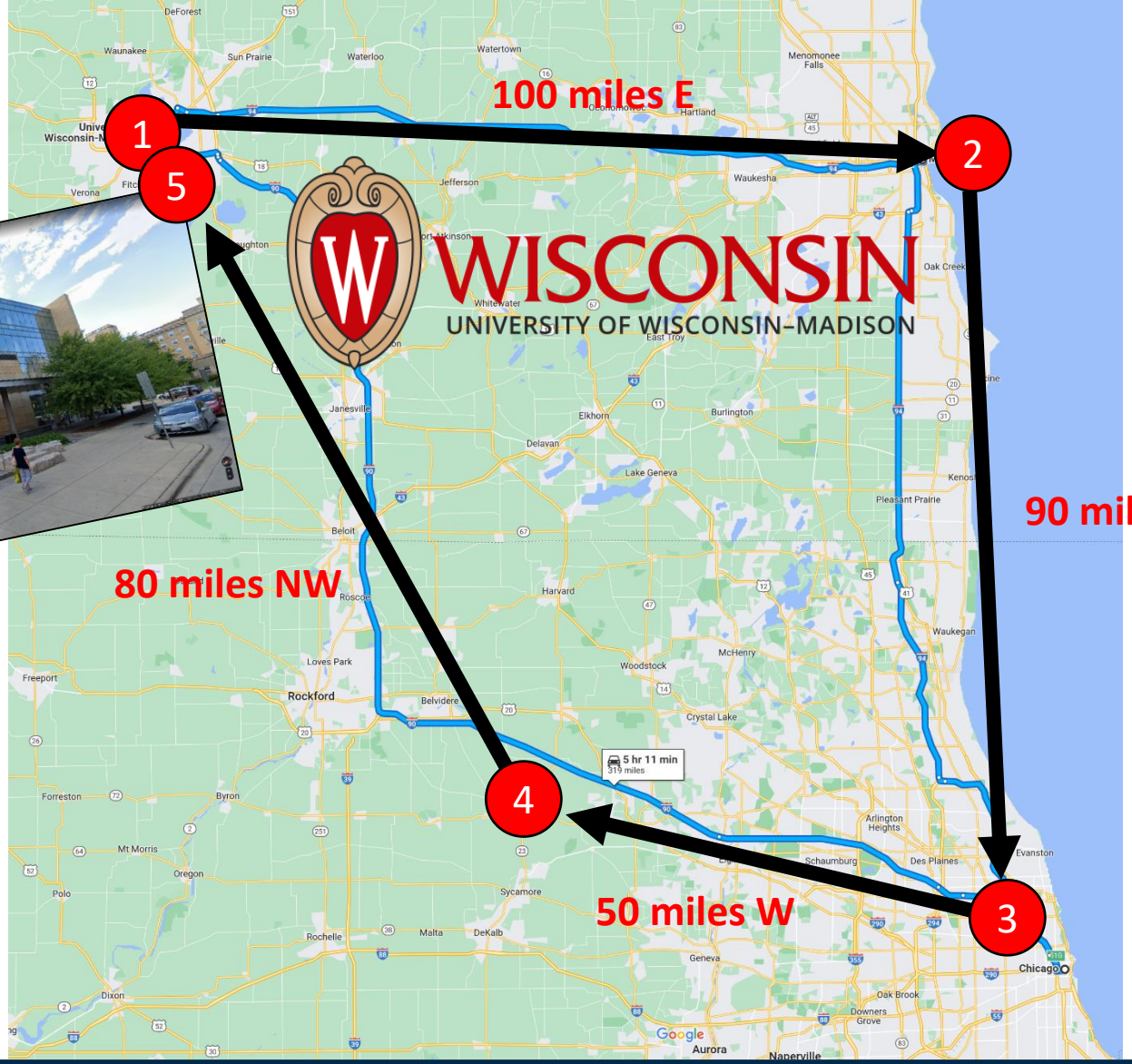
I must have accumulated odometry error!



Under the Hood of SLAM

Accumulated Odometry Error & Loop Closures





Loop closure correction probabilistically associates first and last state of loop, thus improving all estimated poses along the loop.

Loop closures are special measurement of relative pose between two states.
A single agent loop closes when it realizes: "I've been here before."

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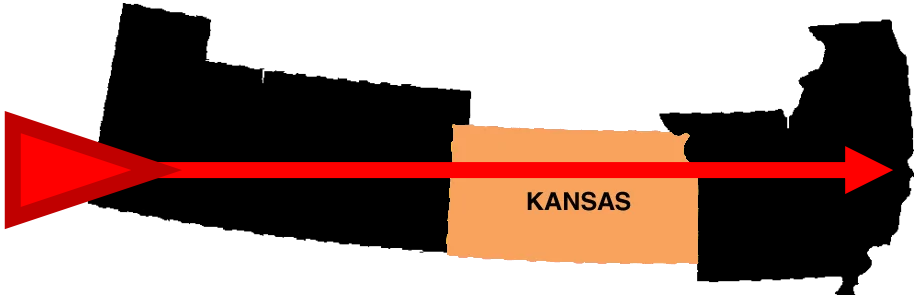
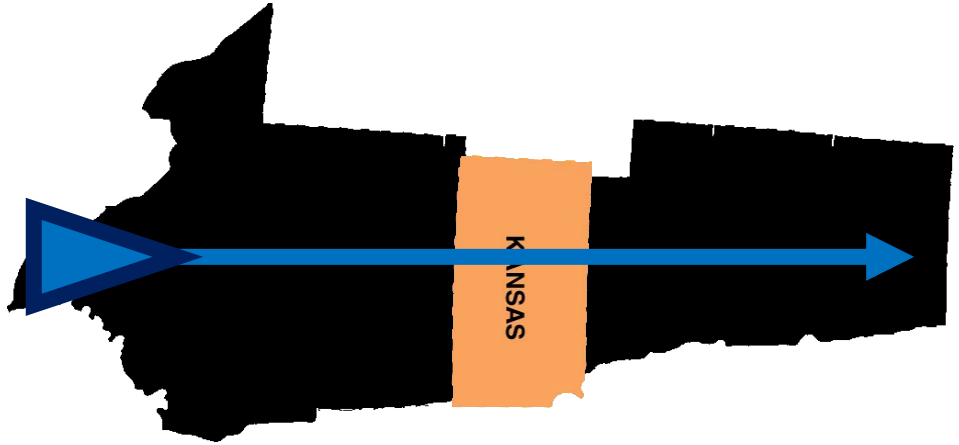
Under the Hood of SLAM

Multi-agent SLAM & Multi-agent Loop Closures

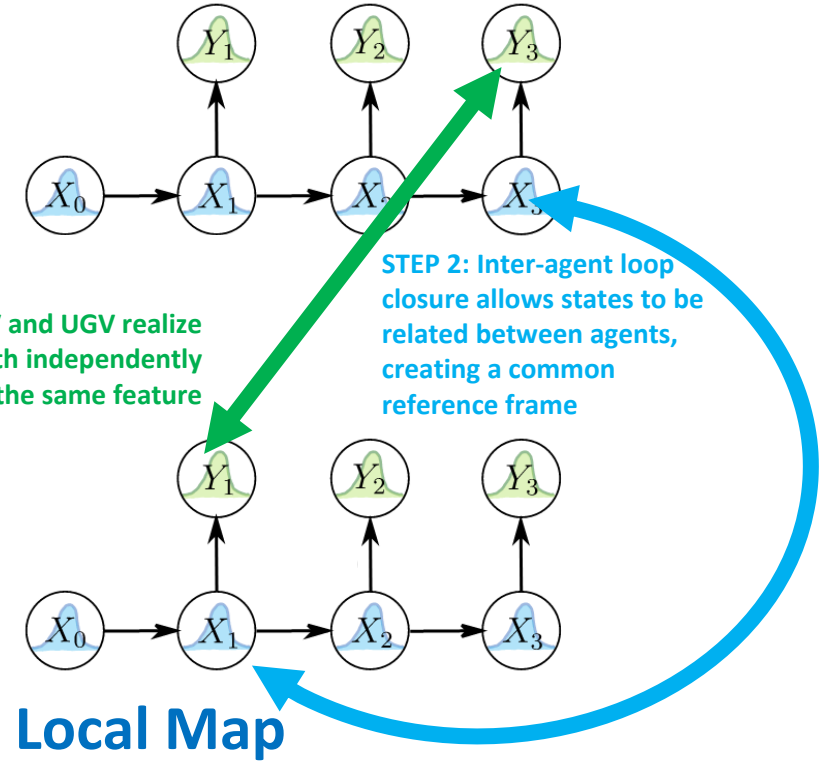
UAV



UGV



UAV's Local Map

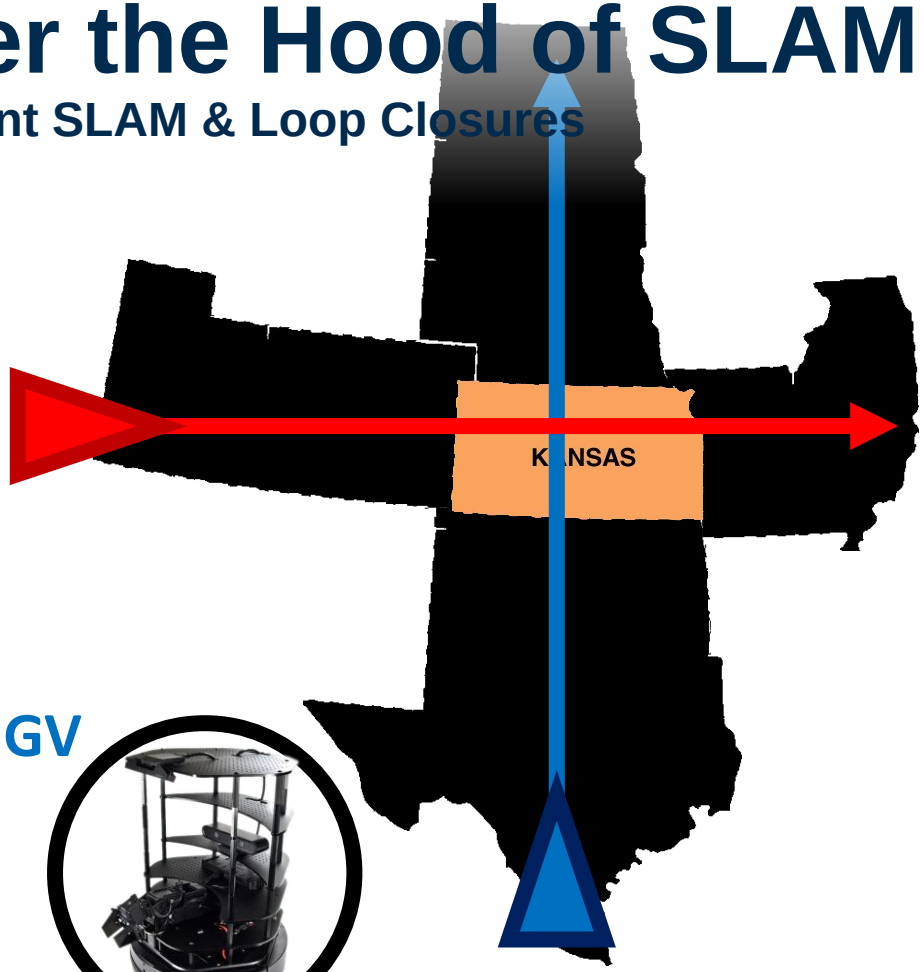


UGV's Local Map

Under the Hood of SLAM

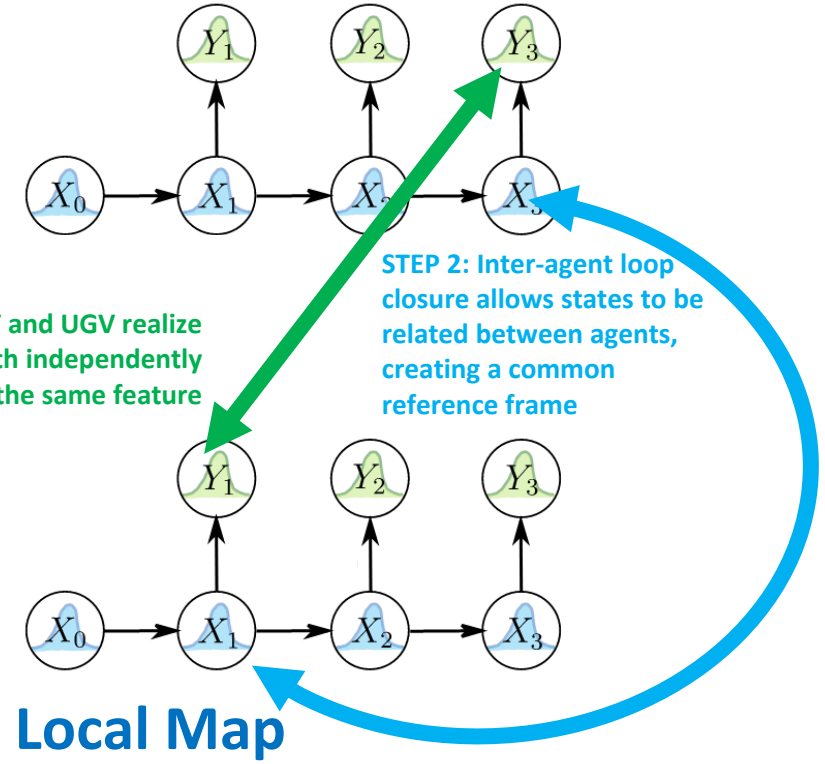
Multi-agent SLAM & Loop Closures

UAV



UGV

UAV's Local Map



UGV's Local Map

Agents are placed in common reference frame by detecting inter-agent loop closures. Common sensors only allow for inter-agent loop closures when agents "cross paths."

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Adding Additional Sensors

Inter-agent Ranging & Relative Pose Estimates with Ultrawide-Band (UWB)

Nooploop LinkTrack P

(Current UWB sensor of choice)

- UWB around since 1990's, but only recently become cheap, accessible, and reliable enough to consider
- Range measurements do not require external infrastructure

Advertised UWB properties:

- Precision of ~10cm ranging at 50Hz up to 100m
- Relative range computed via Time of Arrival (TOA) or Time Difference of Arrival (TDOA)
- Operates without line of sight (LOS) and resilient to multipath

By adding UWB ranging sensors, we can get inter-agent relative poses (i.e. inter-agent loop closures) without needing to cross paths.

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Our Previous Work

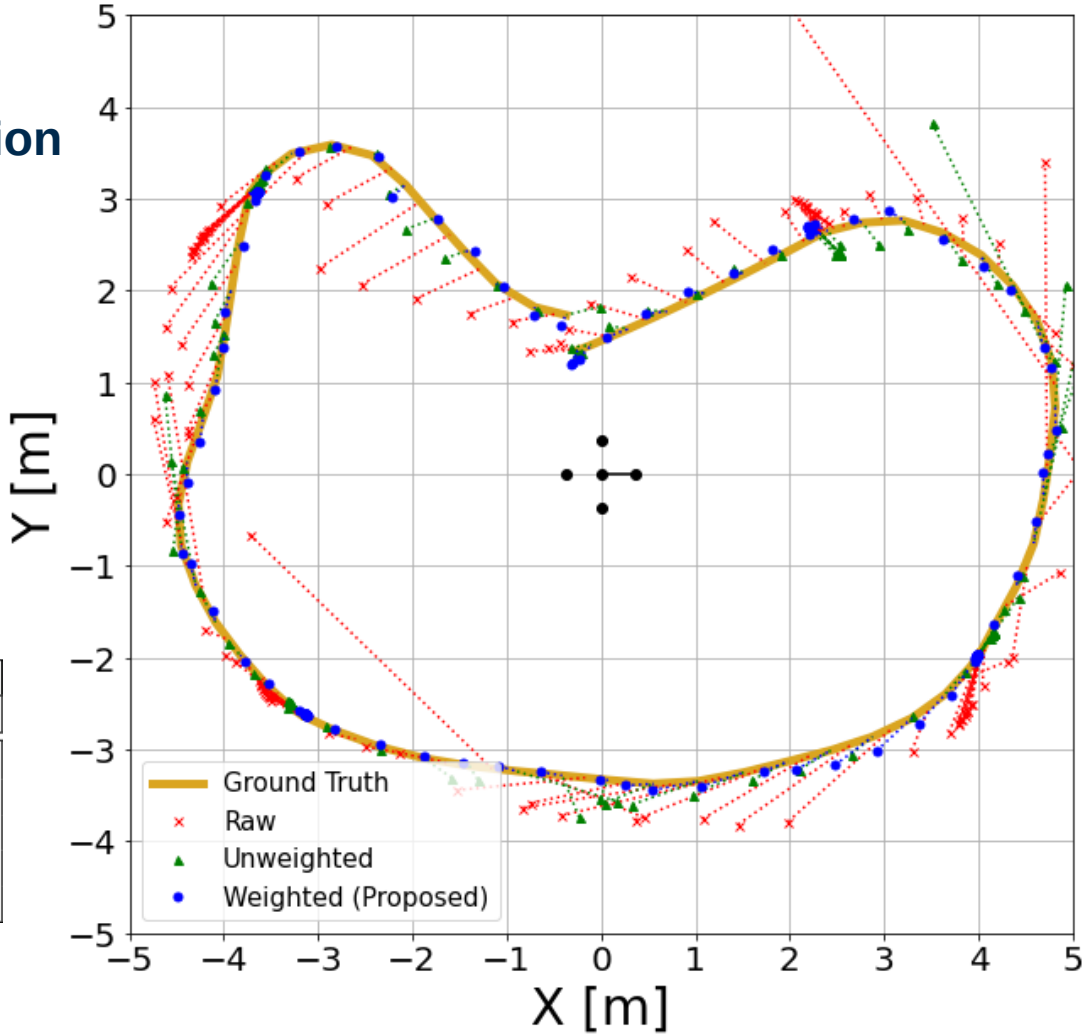
2D Inter-agent Loop Closures / Rel. Pose Estimation

Scan QR Code for Full Paper

See our full paper, presented last Oct at IEEE's IROS'22 Conference in Kyoto Japan.

Position Error [m]	kidney-bean		
Method	**Mean**	**Max**	**Std**
Raw	0.76	5.20	0.68
Shift only	0.47	4.77	0.73
MovingAvg only	0.68	3.40	0.47
Unweighted (Eq. 3)	0.36	2.91	0.44
Weighted (Eq. 8) **[Proposed]**	**0.13**	**0.52**	**0.11**

Abs Heading Error [deg]	kidney-bean		
Method	**Mean**	**Max**	**Std**
Raw	12.06	70.33	12.17
Shift only	8.10	80.20	12.72
MovingAvg only	10.32	57.96	8.73
Unweighted (Eq. 3)	6.15	58.70	8.38
Weighted (Eq. 8) **[Proposed]**	**3.95**	**11.97**	**2.98**



Simple calibration routine and correcting for antenna obstructions ➔ Our results are competitive with prior state-of-the-art UWB approaches even without needing to transmit measurements (odometry) between agents.

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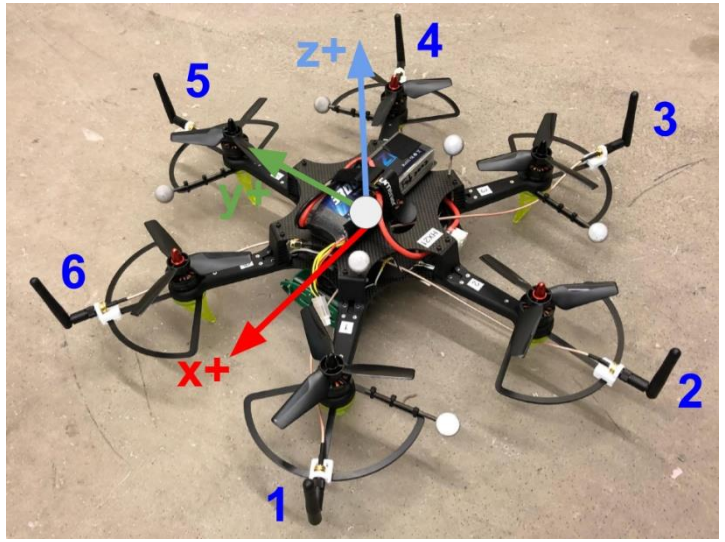
Our Recent Work

3D Inter-agent Loop Closures / Relative Pose Estimation



$$\underset{\mathbf{x}}{\operatorname{argmin}} \overbrace{\sum_{i\in\{1,\ldots,N\}} \sum_{j\in\{1,\ldots,N\}}}^{\text{Sum over all pairs of inter-agent antennas}} w_{ij}(\mathbf{x}) \underbrace{\left(d_{ij}(\mathbf{x}) - \hat{z}_{ij}^{(t)}\right)^2}_{\text{UWB Range Terms}}$$

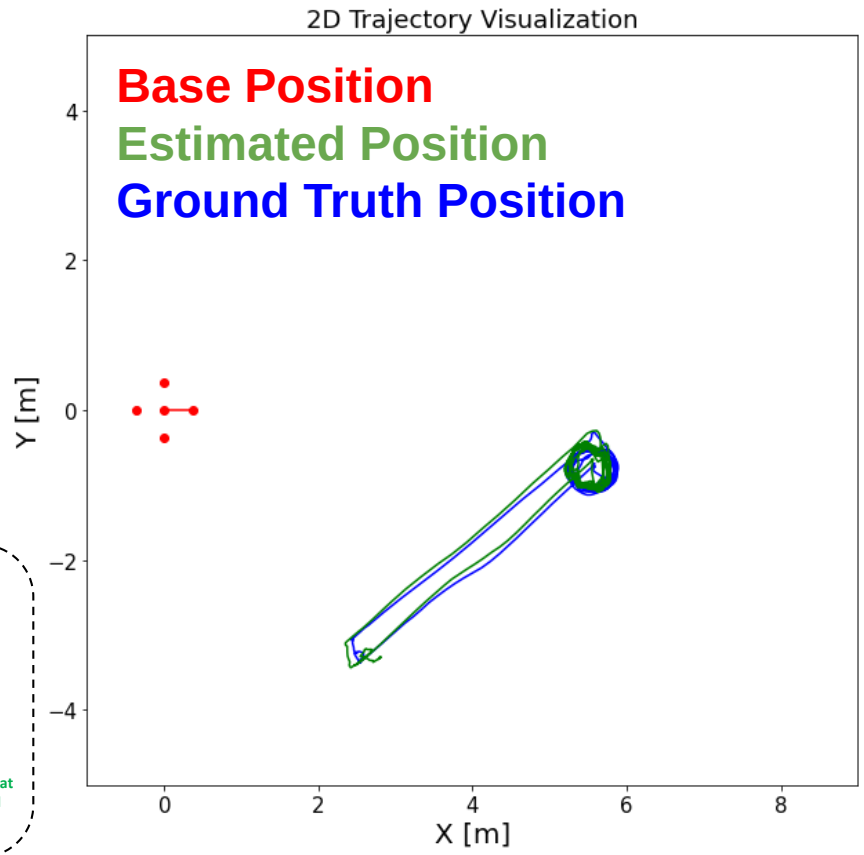
Calibrated UWB relative range measurement

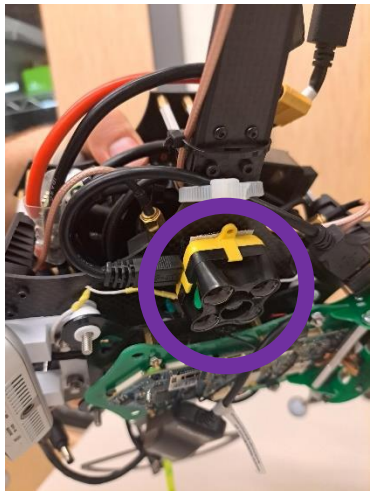
Weighting Function

Function of θ and ϕ that devalues terms using an antenna obstructed by the robot body

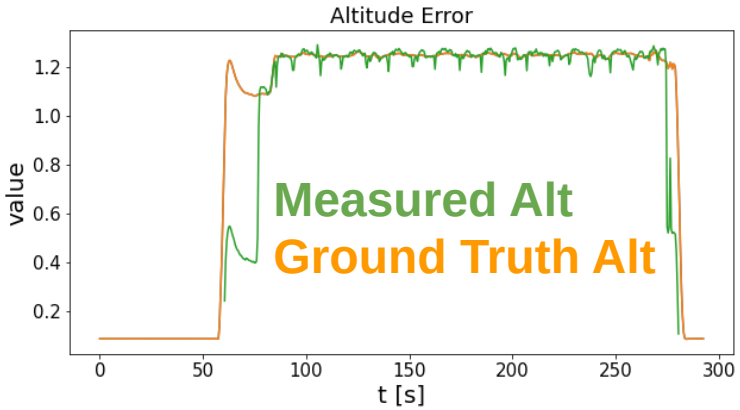
UWB Range Terms

Minimize error between each pair of inter-agent antennas at known relative locations on each agent's body frame and the received range measurement





Downward facing LiDAR ensures altitude envelope



APE: ~20±10 cm
AHE: ~6±10 degrees

Extensions to 3D are working with only slight (expected) performance degradation verses 2D.
Downward facing LiDAR helps address z-axis sensitivity from having all antennas in a single plane.
Follow up journal paper is in the works!

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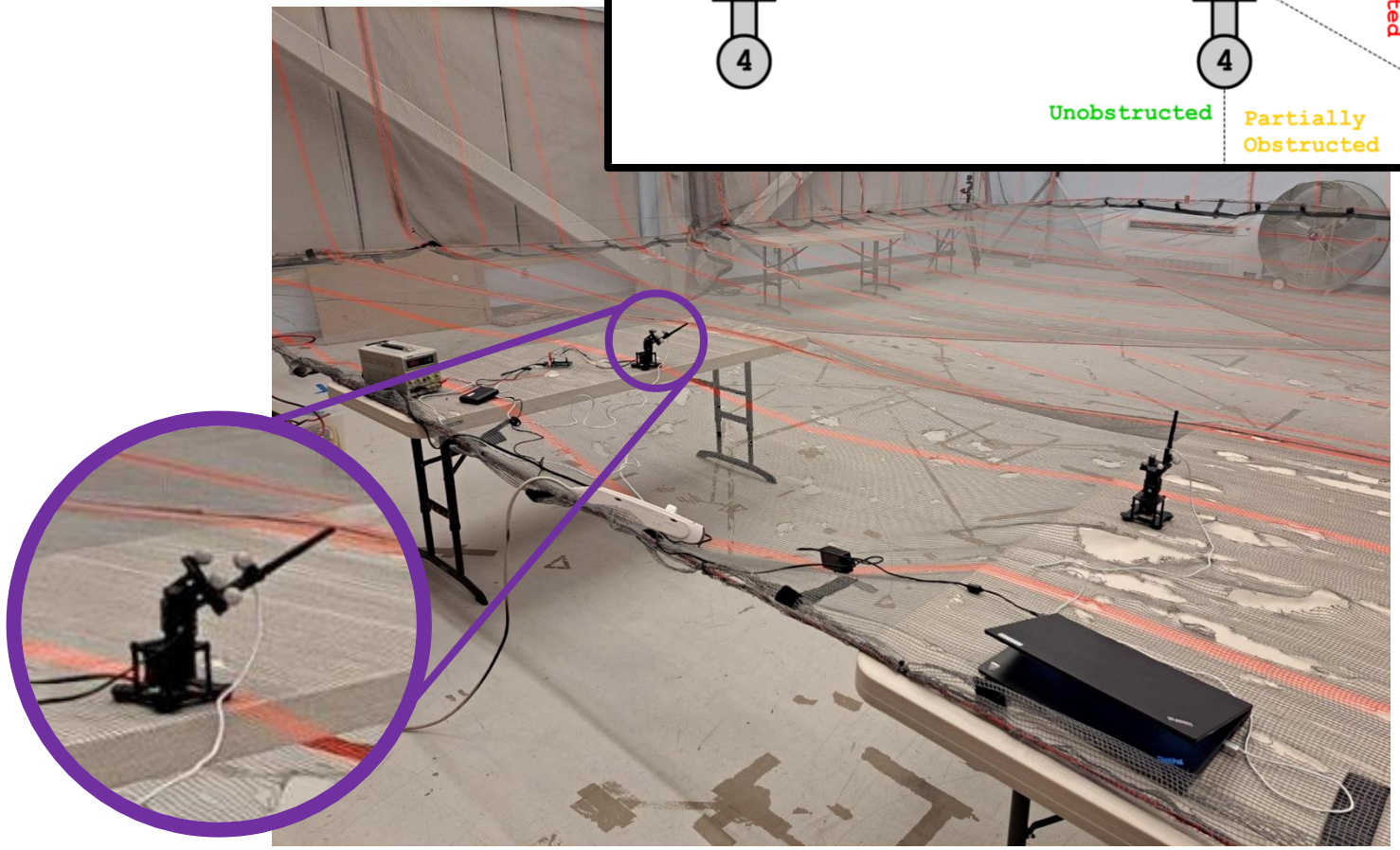
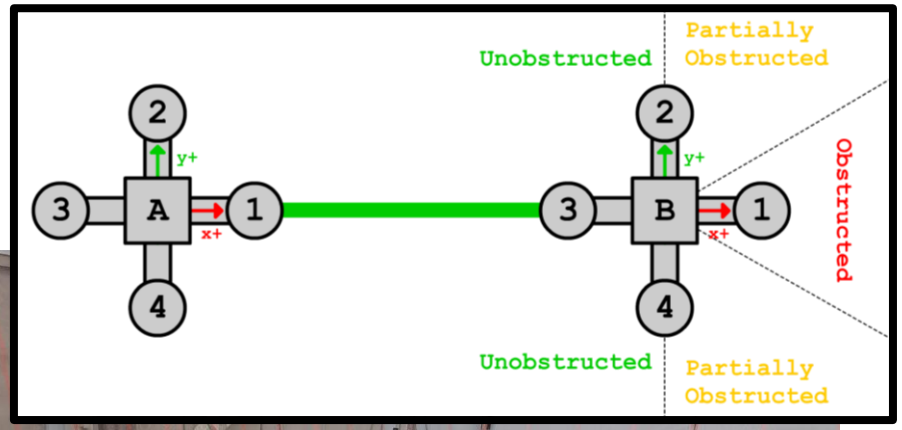
Our Recent Work

Improved 2D Platform & 3D Sensor Modeling

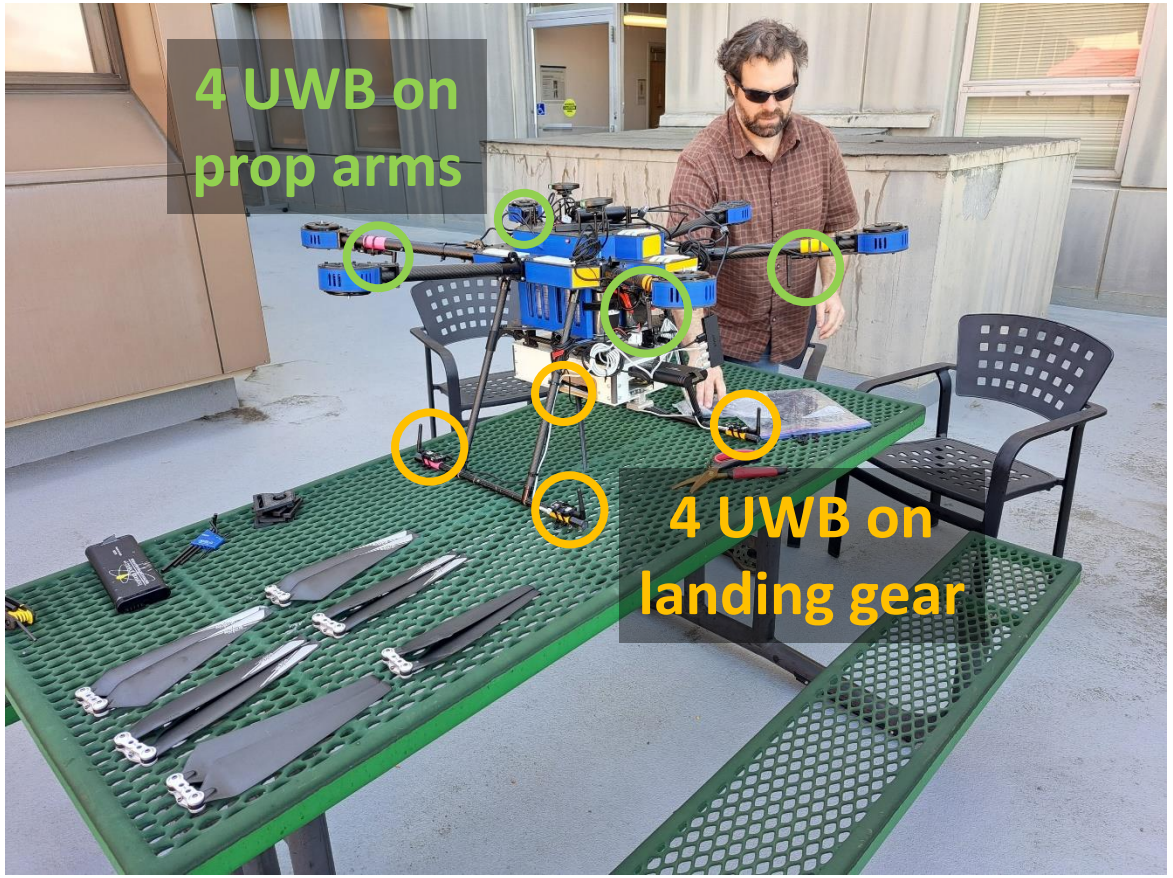


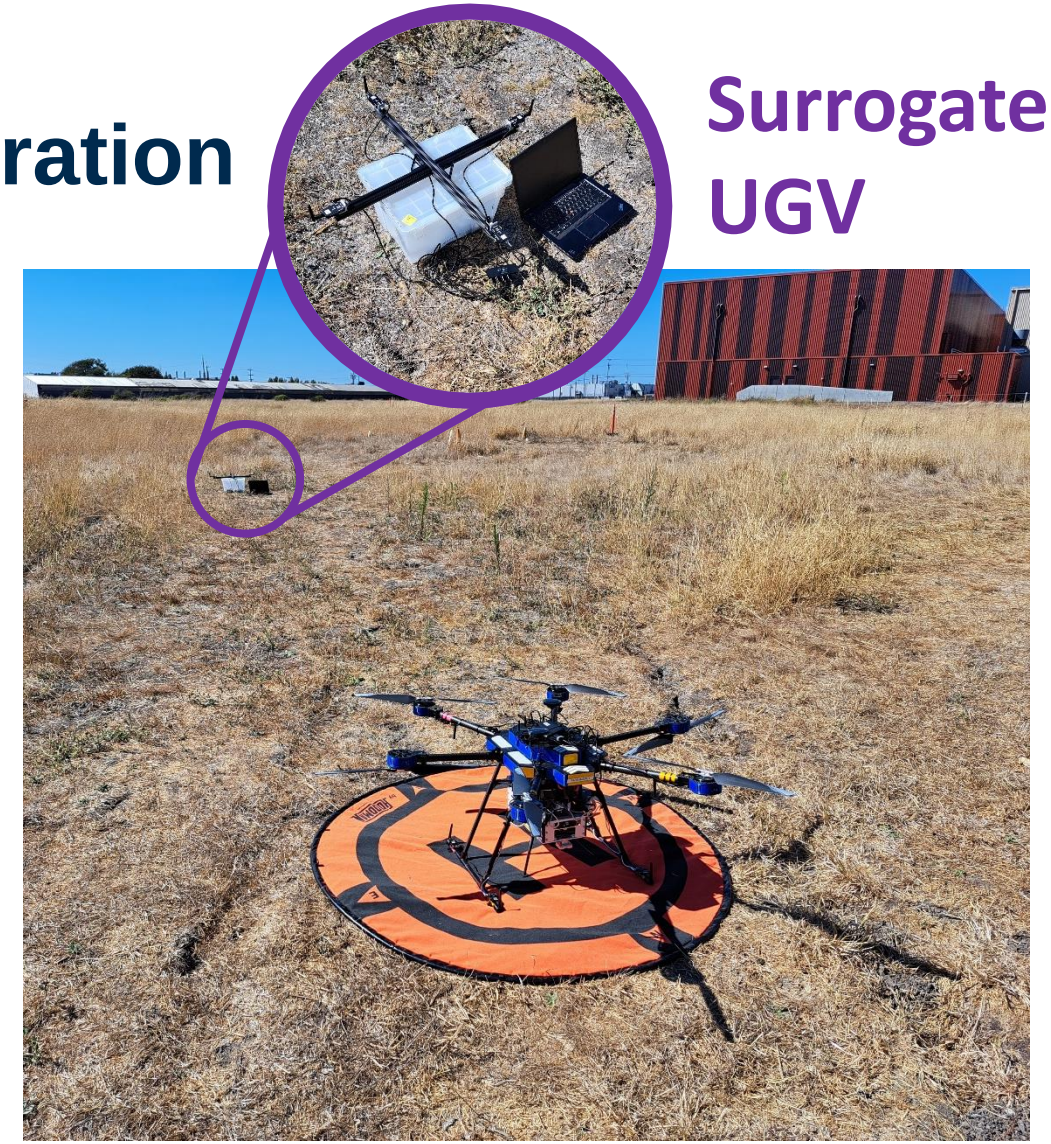


Improved 2D platform will allow for outdoor testing and full integration with Kimera-Multi. Testing how the “black box” UWB measurements are affected by relative orientation helps us build a better sensor model for our 3D work.

Our Recent LBNL Collaboration

Testing Hardware on LAMP Platform





Initial field test at LBNL showed 3D UWB relative pose system working on LAMP platform.
Larger aerial platform allows for UWB sensors to be in multiple z-planes without destabilizing flight.
Additional tests with LAMP coming soon!

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Our Recent MIT Collaboration

Kimera & Certifiably Optimal Range-Aided SLAM

Integration with Intel RealSense 435i lets us utilize Kimera-VIO (and eventually Kimera-Multi). Working with grad student collaborator, used platform to demonstrate results for certifiably optimal range-aided SLAM. Work was recently submitted and under review, stay tuned!

Collaborators: Current and Future!

Next Steps & Future Work

Next Steps:

- Complete 3D relative pose extension paper
- Complete integration into Kimera-Multi SLAM pipeline
- Additional LAMP/radiological search demonstrations/tests at LBNL

Future Demos/Collaborators?

- Our relative pose estimation system is becoming increasingly mature.
- If you have other radiological search demos you think might be useful, please reach out!
- Other ideas we have discussed with folks at ETI/UPR include:
  - Football Stadium radiation monitoring
  - Compton camera multi-agent coordination

Collaborators

Jonathan Rogers
Georgia Tech

Brian Quiter
Lawrence Berkeley National Laboratory

John Fisher
MIT

Alfred Hero
University of Michigan

Graduate Students Supported

Jonathan P. How
PI/Adivsor

Andrew Torgesen
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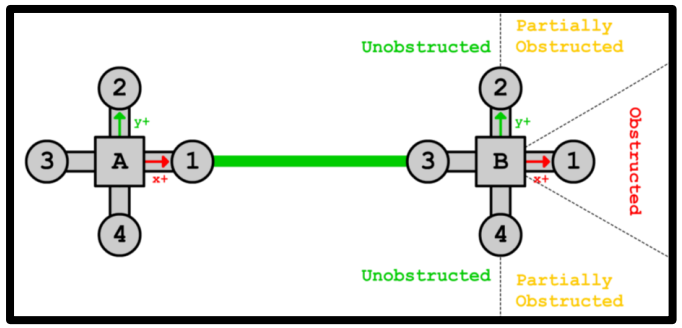
Questions?



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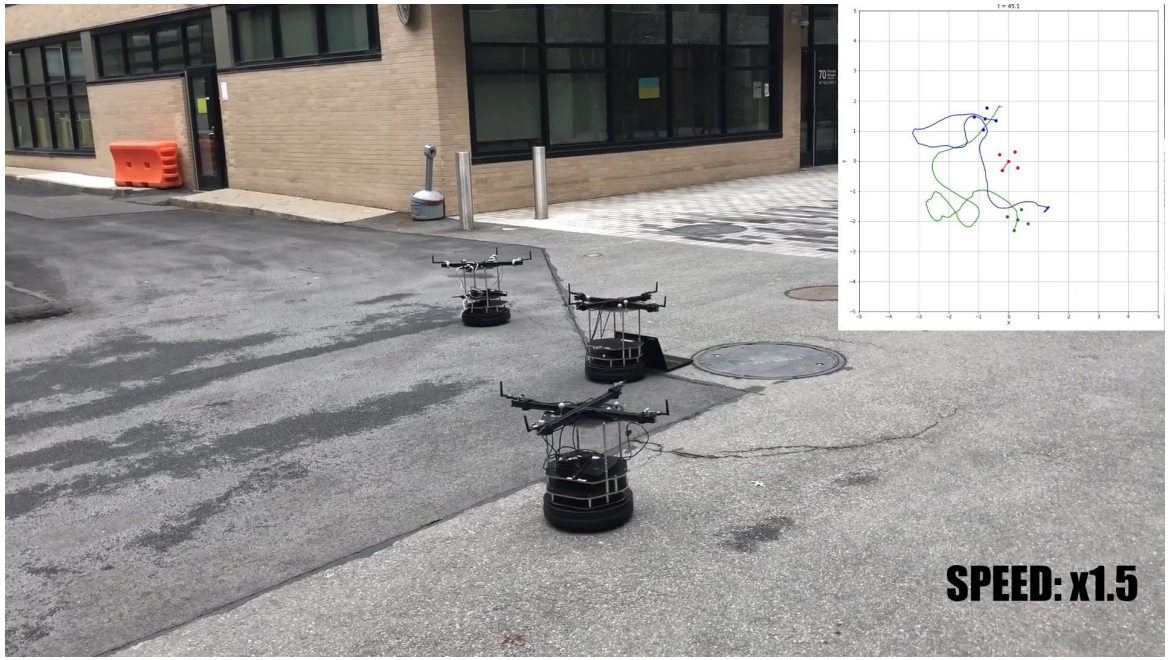

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- Torgesen, Andrew J. Autonomous Sensing and Navigation in Challenging Environments Using Unmanned Air Vehicles in Single and Multi-Agent Settings. Diss. Massachusetts Institute of Technology, 2021.
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