Determinism and Reproducibility in Resource-Constrained Cyber-Physical System Simulation Using Operational Data

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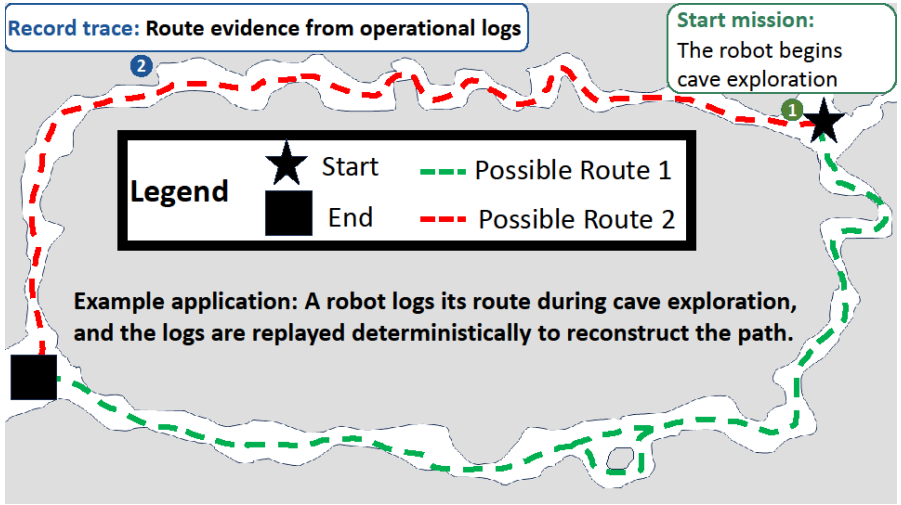
Websites:

- https://labs.engineering.asu.edu/kim/
- https://saipavan4.github.io/
- https://hokeun.github.io/

Motivation & Problem

Motivation

- **Operational data can drive CPS simulation** and connect physical executions with system-level analysis [1]
- Operational data capture robot execution.
- Enable mission reconstruction and analysis.
- Useful in hard-to-observe environments, such as cave exploration.



Cave-mapping example for operational-data-driven CPS simulation.

[1] A. Wasicek et al., “System simulation from operational data,” Proc. 52nd Annual Design Automation Conference (DAC), 2015, pp. 1–6.

Motivation & Problem

Problem

- Limited sensing & computation.
- Limited storage & communication.

- Deterministic replay requires
  1.Controller state
  2.Actuator commands
  3.Timing information

Goal

- **Develop a deterministic and reproducible operational-data-driven simulation workflow for low-cost robotic CPS.**

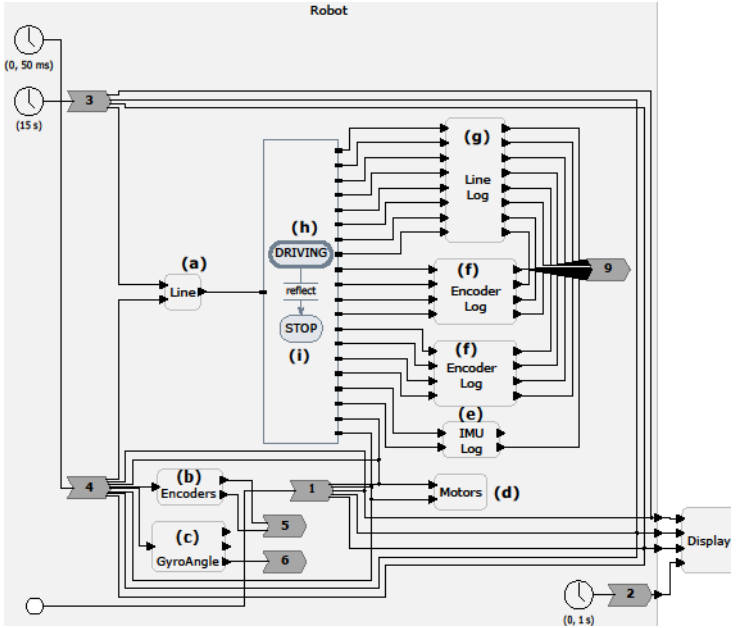
Background

Reactor Model [1]

- A reactor is a **modular, event-driven component** that encapsulates computation and state.

Lingua Franca (LF) [2]

- **Lingua Franca** is a coordination language based on the reactor model.
- Uses **logical time** to coordinate concurrent reactors.
- This enables **deterministic sensing, control, actuation, and logging** in cyber-physical systems.



LF reactor model for deterministic sensing, control, actuation, and data logging.

- **Deterministic execution and simulation** uses logical time to establish a deterministic ordering of sensing, control, actuation, and logging, enabling repeatable execution.

[1] M. Lohstroh et al., “Reactors: A deterministic model for composable reactive systems,” in CyPhy 2019. Springer, 2019, pp. 59–85.
[2] M. Lohstroh et al., “Toward a Lingua Franca for deterministic concurrent systems,” ACM TECS, vol. 20, no. 4, pp. 1–27, 2021.

Proposed Workflow

Physical Execution

Ground Robot

- Line sensors



- Encoders sensor
- IMU sensor
- Bump sensors

Drone



- ToF sensors

Deterministic Operational Data Collection

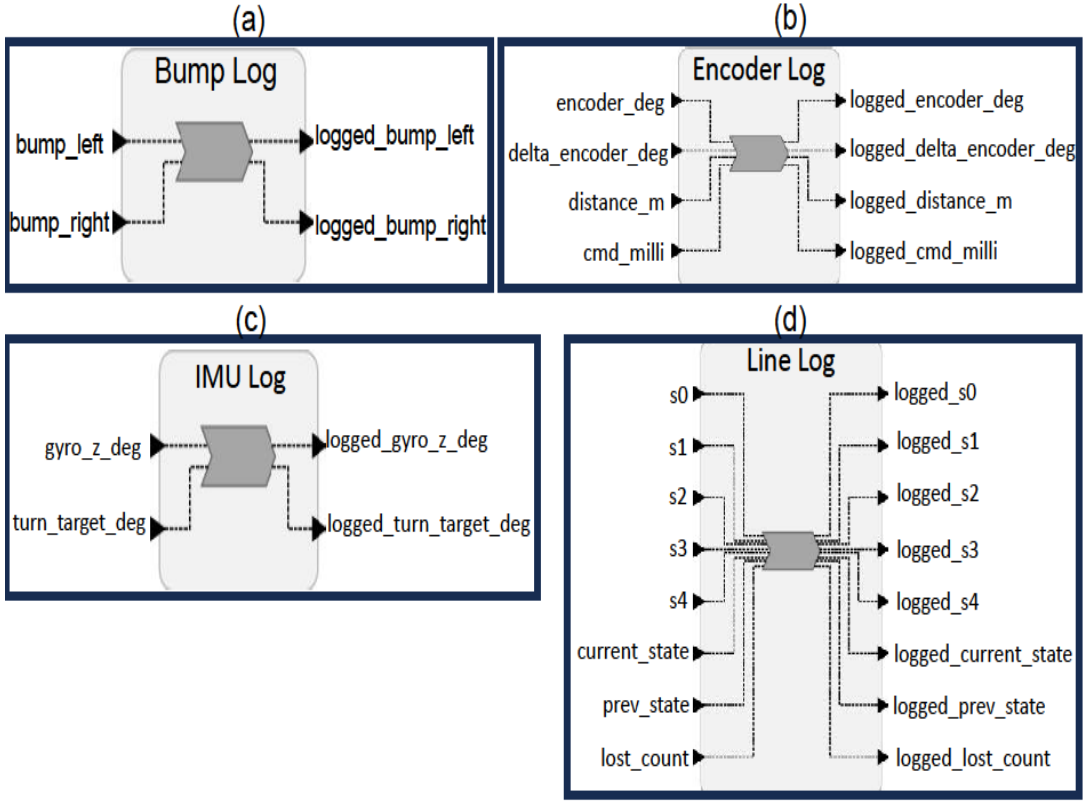
Sensor-specific Lingua Franca (LF) Reactors

Structured Operational Data

Deterministic Simulation

- Robot trajectory
- Controller behavior
- Route comparison
- Repeatable replay

Reusable Sensor-Specific Logging Reactors



Modular sensor-specific LF logging reactors for structured operational-data collection for Pololu robots, together with timing information

Modular Reactor Library

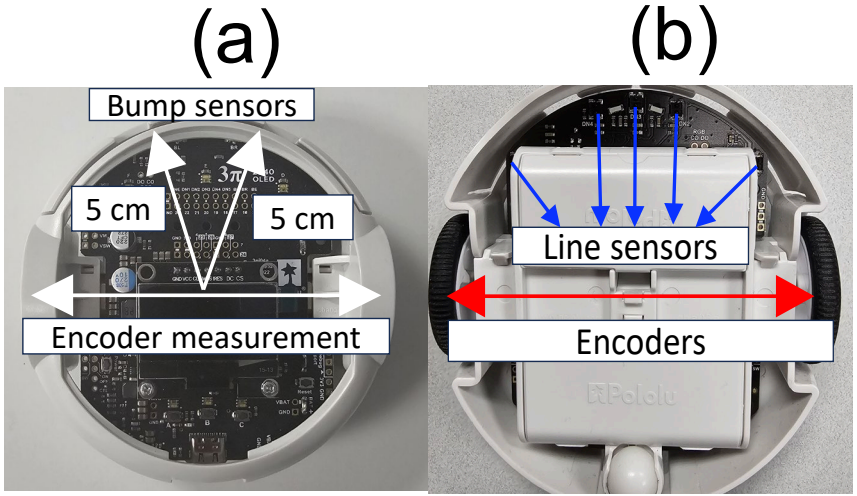
Each sensor is implemented as an independent LF logging reactor.

- Line sensor reactor
- Encoder reactor
- IMU reactor
- Bump sensor reactor

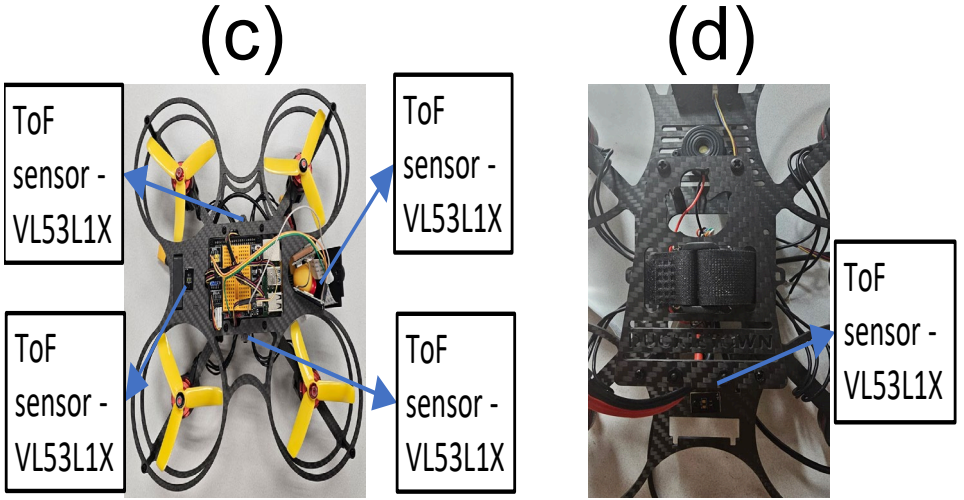
Each logged record contains

- Logical timestamp
- Sensor readings
- Platform/controller state
- Actuator commands

Physical Hardware



Pololu 3pi+ 2040 robot: (a) top view showing the bump sensors, located approximately 5 cm ahead of the encoder-based pose reference for bump-based localization
(b) Bottom view showing the 5-line sensors used for track-following case studies.



Duckiedrone time-of-flight (ToF) sensing setup for directional obstacle-distance measurements: (c) top view and (d) bottom view.

Evaluation & Case studies

Deterministic replay

- Preserve the ordering of sensor, controller, actuator, and timing information.
- Replay operational data using LF logical-time scheduling.

Reconstruction accuracy

- Square and stadium tracks: path-length error.
- Maze: distance between detected contacts and ground-truth walls.

Behavioral response

- Modify logged ToF data through obstacle injection.
- Verify that changes propagate through planning and actuation.

Evaluation & Case studies

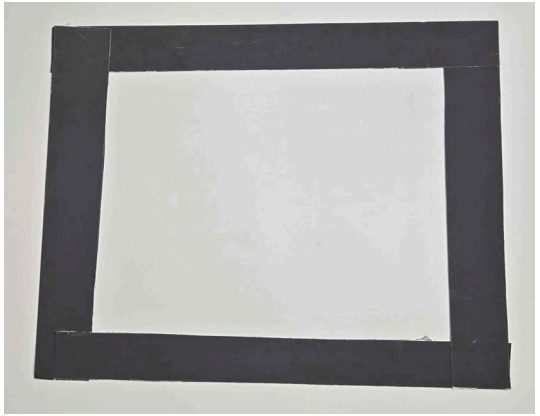
Four case studies:

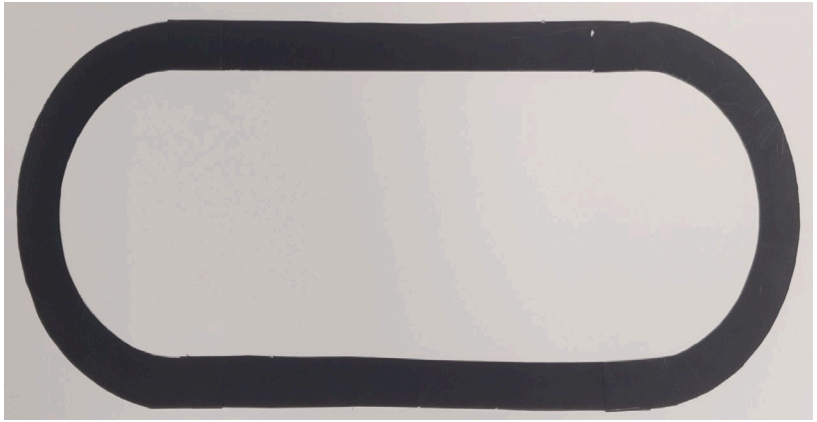
Case study 1: Square-track following

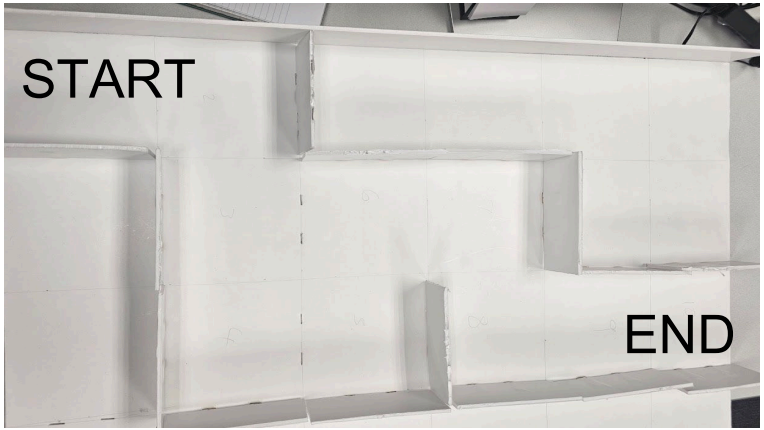
Case study 2: Stadium-track following

Case study 3: Bump-based maze exploration

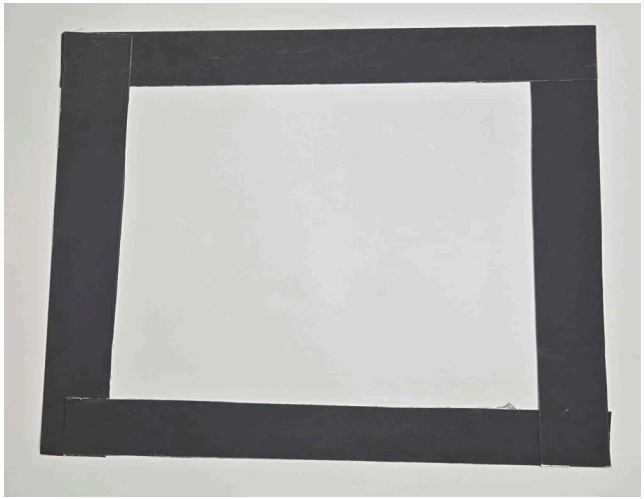
Case study 4: Drone obstacle avoidance.



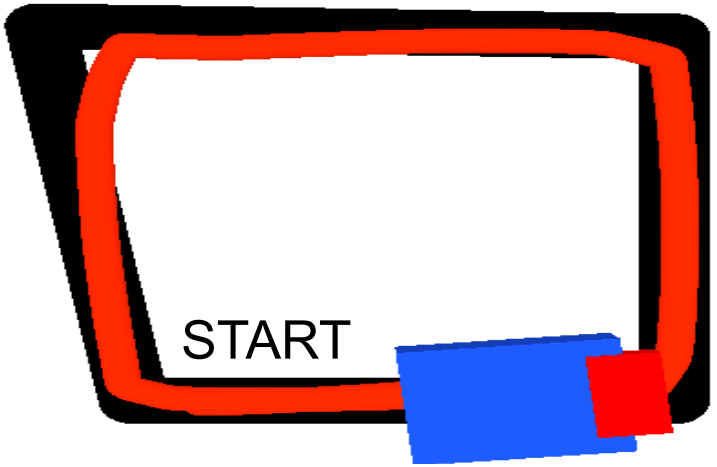




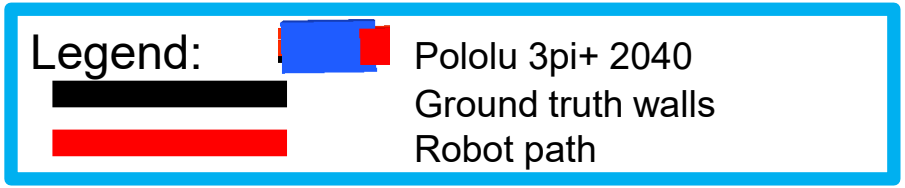
Case study 1: Line following (Square track)



Physical experimental setup for the Pololu 3pi+ robot for operational data collection for Line following (Square track)



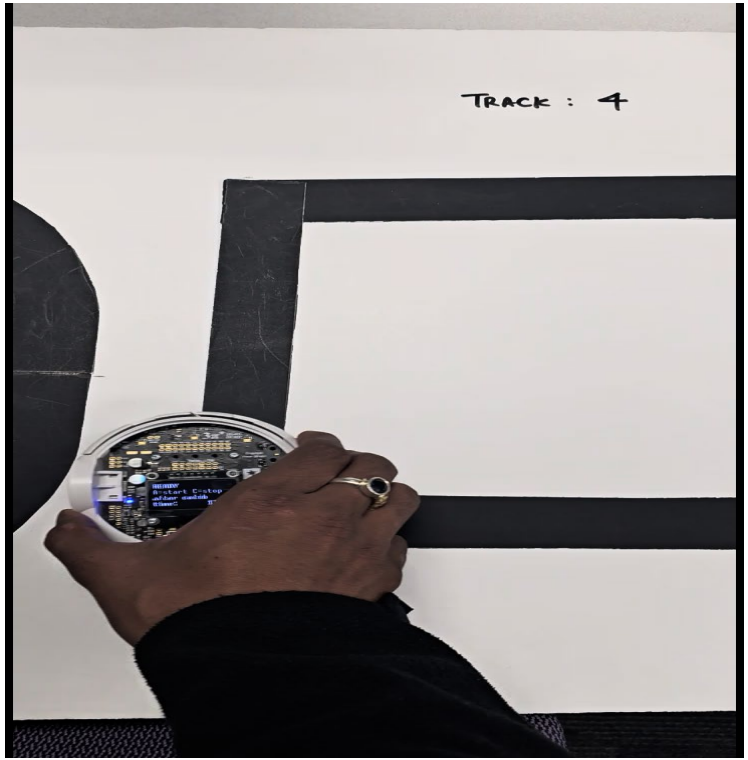
Simulated trajectory for the Pololu 3pi+ robot for operational data collection for Line following (Square track)



Track Following

- Square track reconstruction error: **3.20%**

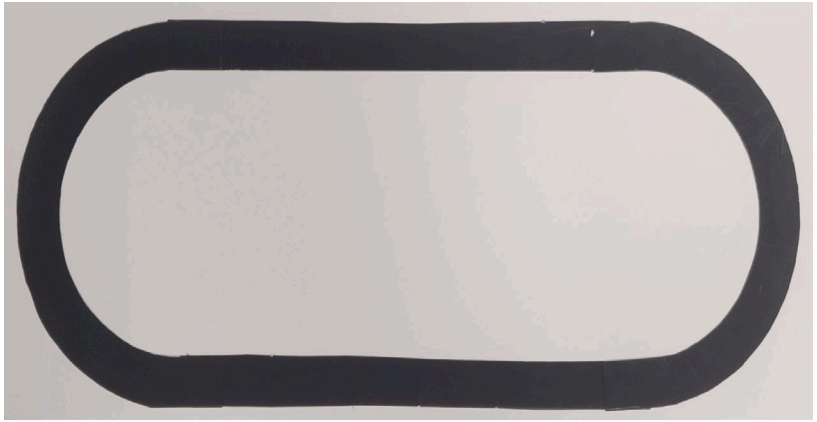
Case Study 1 Demo: Physical Execution vs. Simulation Replay



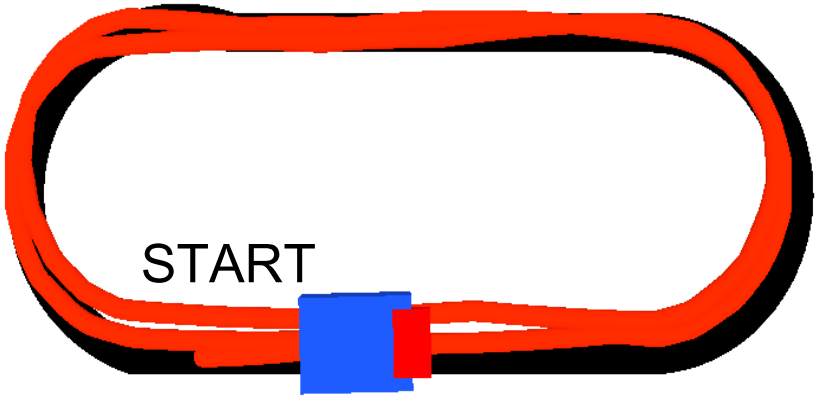
Physical experimental setup for the Pololu 3pi+ robot for operational data collection for Line following (Square track)

Simulated trajectory for the Pololu 3pi+ robot for operational data collection for Line following (Square track)

Case study 2: Line following (Stadium track)



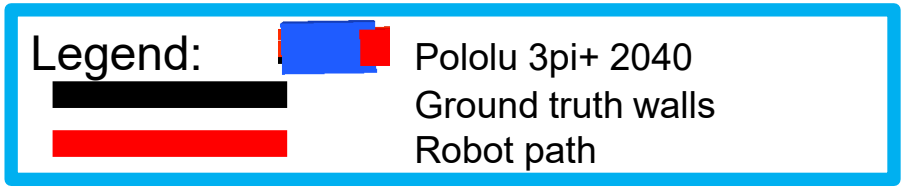
Physical experimental setup for the Pololu 3pi+ robot for operational data collection for Line following (Stadium track)



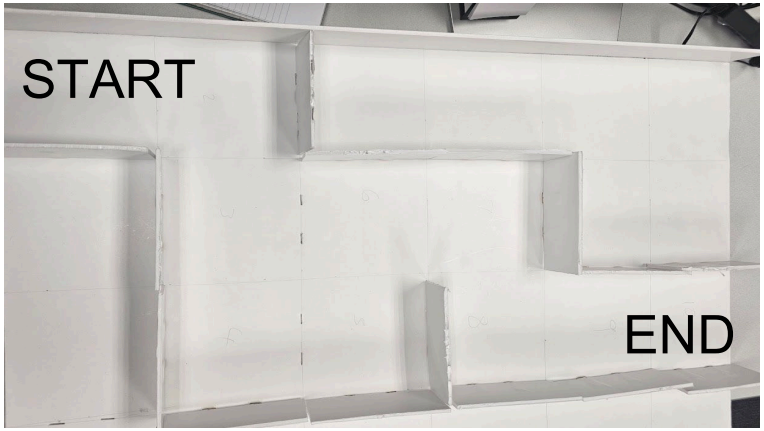
Simulated trajectory for the Pololu 3pi+ robot for operational data collection for Line following (Stadium track)

Track Following

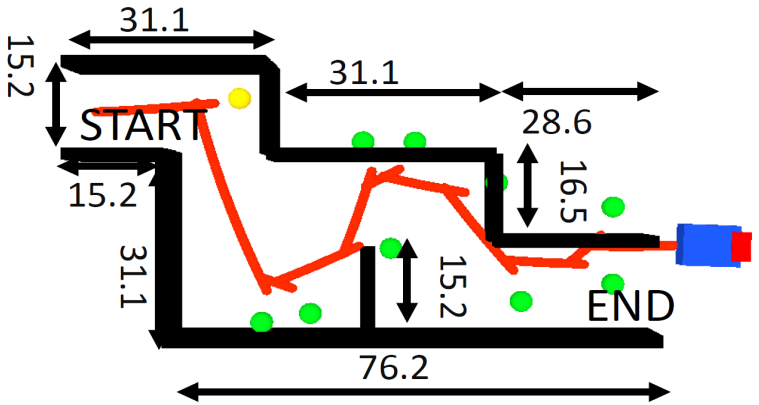
- Stadium track reconstruction error: **0.70%**



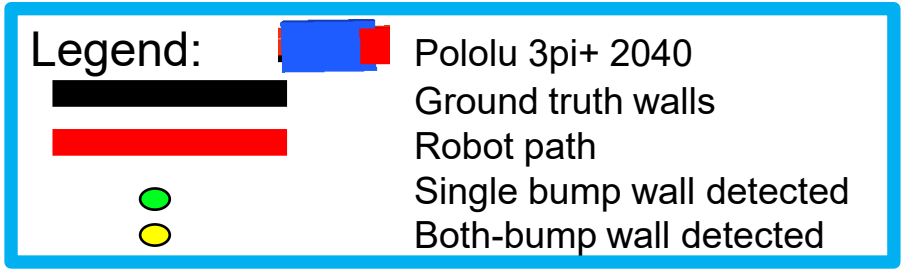
Case study 3: Bump-based maze exploration



Physical experimental setup for the Pololu 3pi+ robot for operational data collection for Bump-based maze exploration



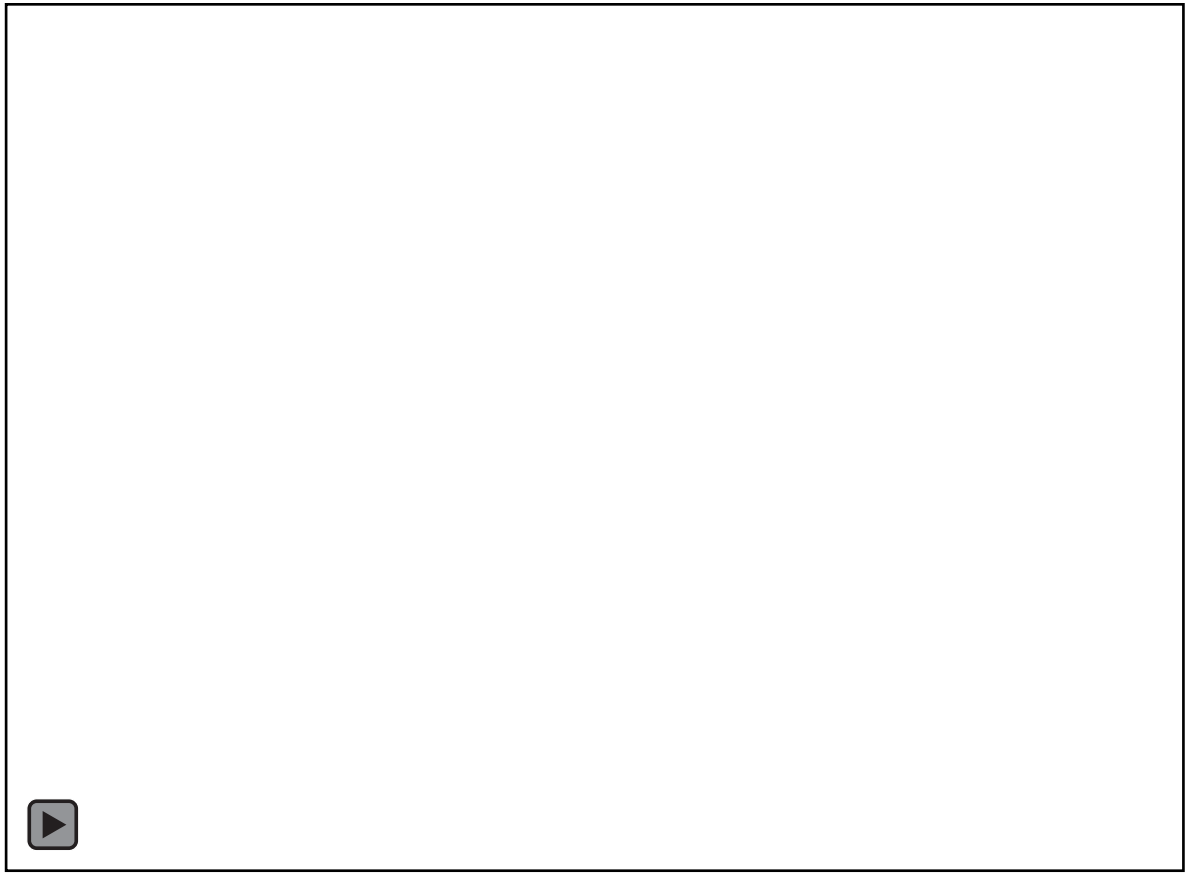
Simulated trajectory for the Pololu 3pi+ robot for operational data collection for Bump-based maze exploration



Maze Exploration

Mean wall localization error: **3.94 cm**

Case Study 3 Demo: Maze Reconstruction from Operational Data



Simulated trajectory for the Pololu 3pi+ robot for operational data collection for Bump-based maze exploration

Case study 4: Drone Obstacle Injection and Replay

Metric	Original data	Obstacle-injected Data
Path length (m)	0.954	1.117
Obstacle detections	160	171

- Structured logs from low-cost sensors support deterministic replay in our case studies.
- Injected ToF changes propagate through planning and actuation.
- Supports repeatable evaluation without expensive camera- or LiDAR-based perception.

Limitations

- Simulation accuracy depends on log quality.
- Sensor noise, timestamp errors, and actuator uncertainty can lead to simulation divergence.

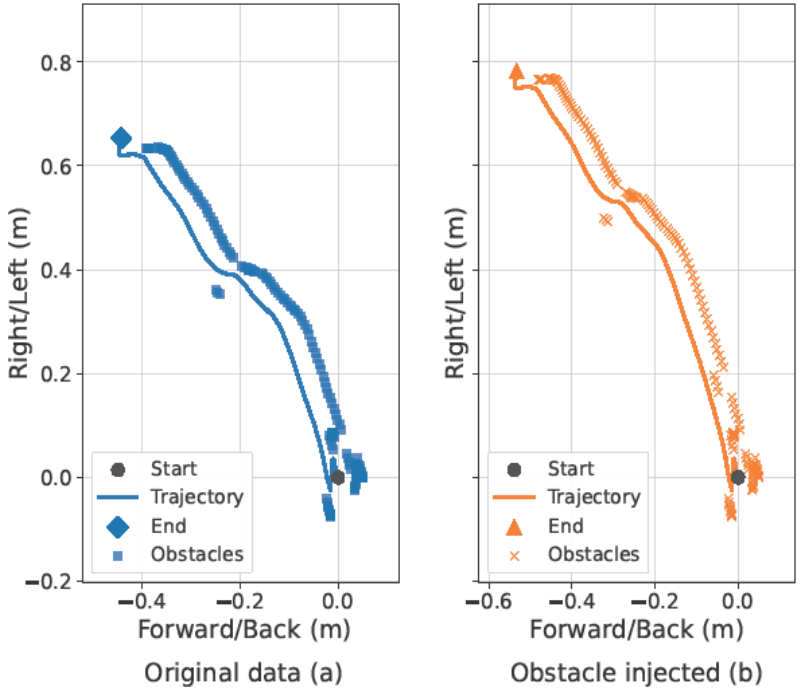


Figure: Drone trajectory reconstruction under original and obstacle-injected ToF data.

Conclusions and Future Work

ASU KIM
KNOWLEDGEABLE & INTERACTIVE MACHINES

- Developed a deterministic operational-data-driven simulation workflow using Lingua Franca.
- Designed reusable sensor-specific logging reactors for low-cost robotic platforms.
- Reconstructed robot executions using logical-time replay.
- Demonstrated effectiveness across four robotic case studies using only low-cost sensors.

Future Work

- Improve sensor calibration
- Investigate timestamp synchronization
- Add consistency checking during replay
- Evaluate larger and more complex environments

https://github.com/asu-kim/cps-operational-sim

EMBEDDED SYSTEMS WEEK

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