SwarmBox:

A Plug-and-Play Drone Swarm Framework for Streamlined Development and Comprehensive Analysis

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CompSec Lab

Drone Swarm: breaks the limit.

Drone Swarm: A decentralized, collaborative multi-agent system tackling shared objectives.

Drone Swarm: breaks the limit?

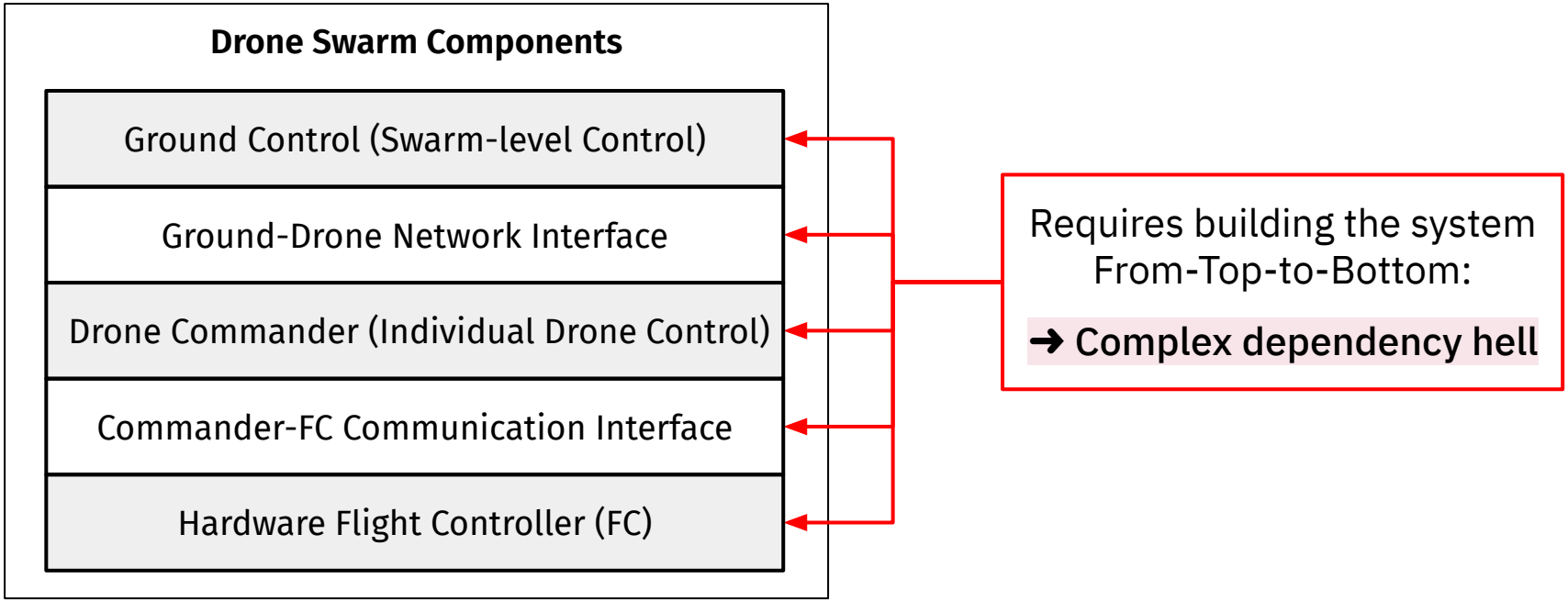
Drone swarms are expected to **break the boundaries of human activities** via **efficient, scalable, flexible, and resilient** operations.

Disaster Response

Infrastructure Surveillance

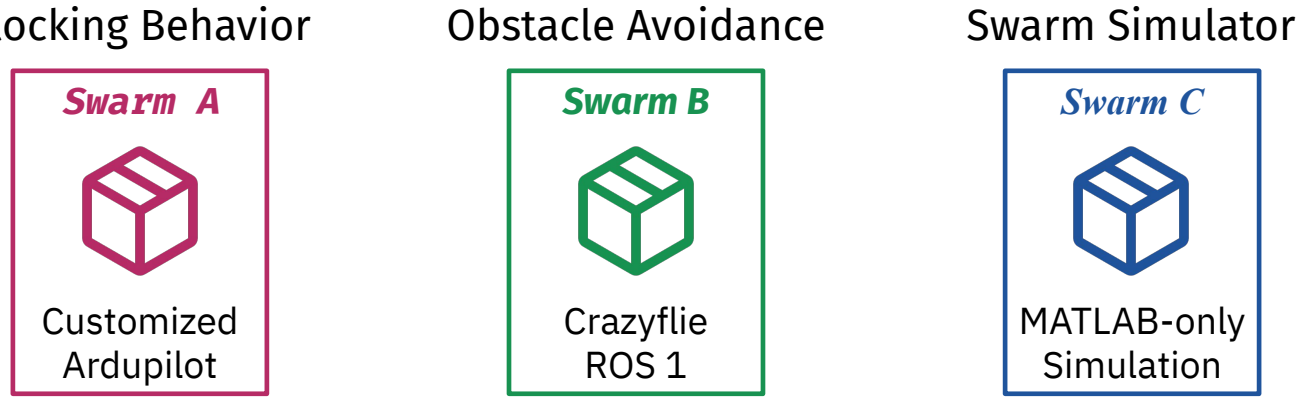
AI generated images used.

Complexity of Drone Swarm System



Fragmentation of Swarm Ecosystem

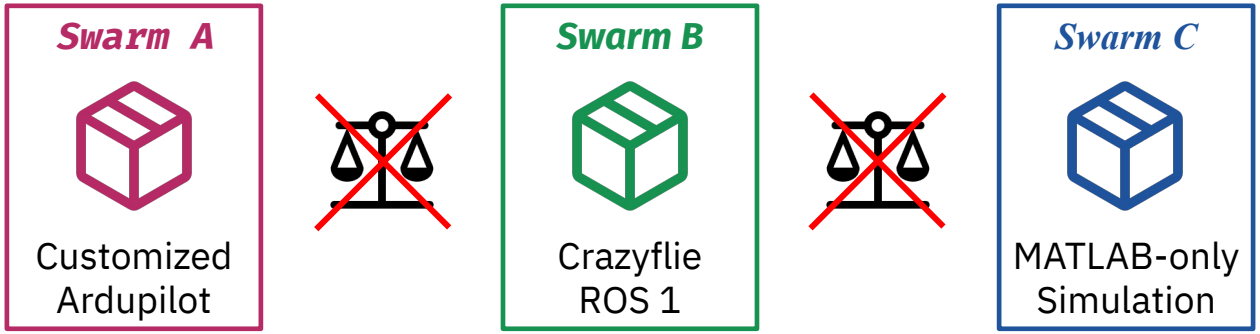
Researchers had to constantly “reinvent the wheel.”



➜ Fragmented ecosystem; existing works are rarely maintained.

Incomparability of existing works

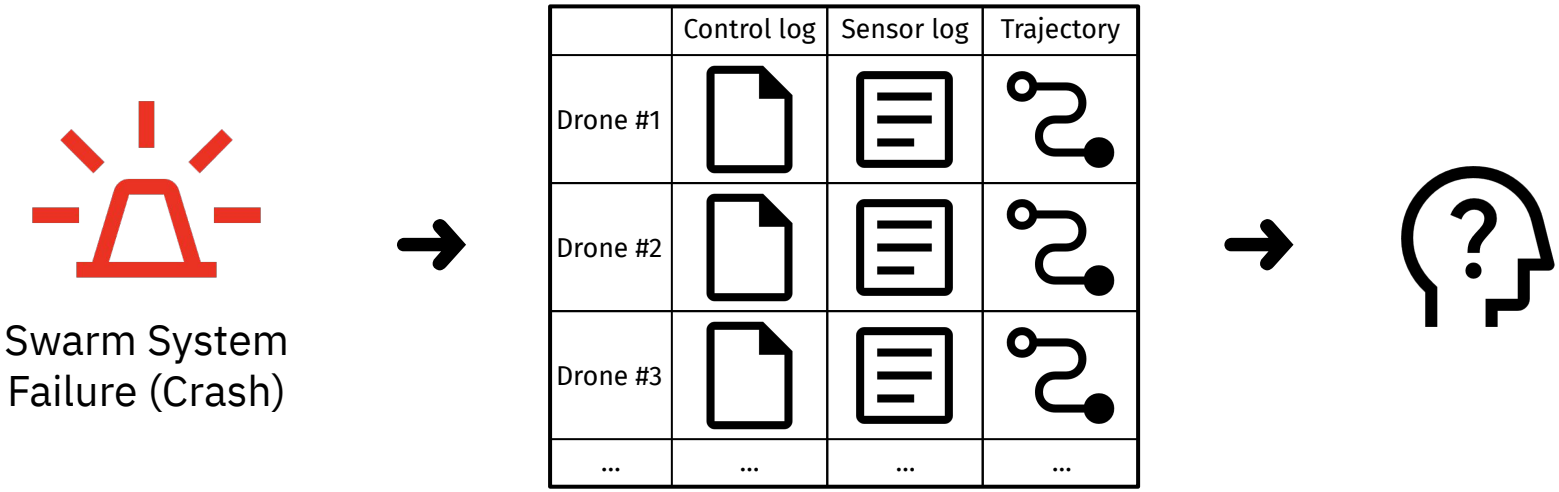
Bespoke testbeds of existing works have architectural differences.



➜ Hindering reproducibility, making fair comparison impossible.

Lack of Swarm-level Observability

Researchers have to manually debug each layer upon failure.



➜ Hard to observe and understand swarm-emergent behaviors.

Challenges in Drone Swarm Development

Fragmentation
Lack of standardized interfaces forces bespoke testbeds.

Complexity
Tight coupling of flight control, middleware, and swarm logic.

Observability
Absence of time-synchronized, swarm-level analysis tools.

Incomparability
Architectural differences make results difficult to reproduce.

SwarmBox:

A plug-and-play drone swarm foundation for reproducible research & development.

From Challenges to Design Goals

Fragmentation
Lack of standardized interfaces forces bespoke testbeds.

Reusable and Effortless Integration

Complexity
Tight coupling of flight control, middleware, and swarm logic.

Abstraction of Multi-layered System Complexity

Observability
Absence of time-synchronized, swarm-level analysis tools.

Comprehensive Swarm-Level Analysis Support

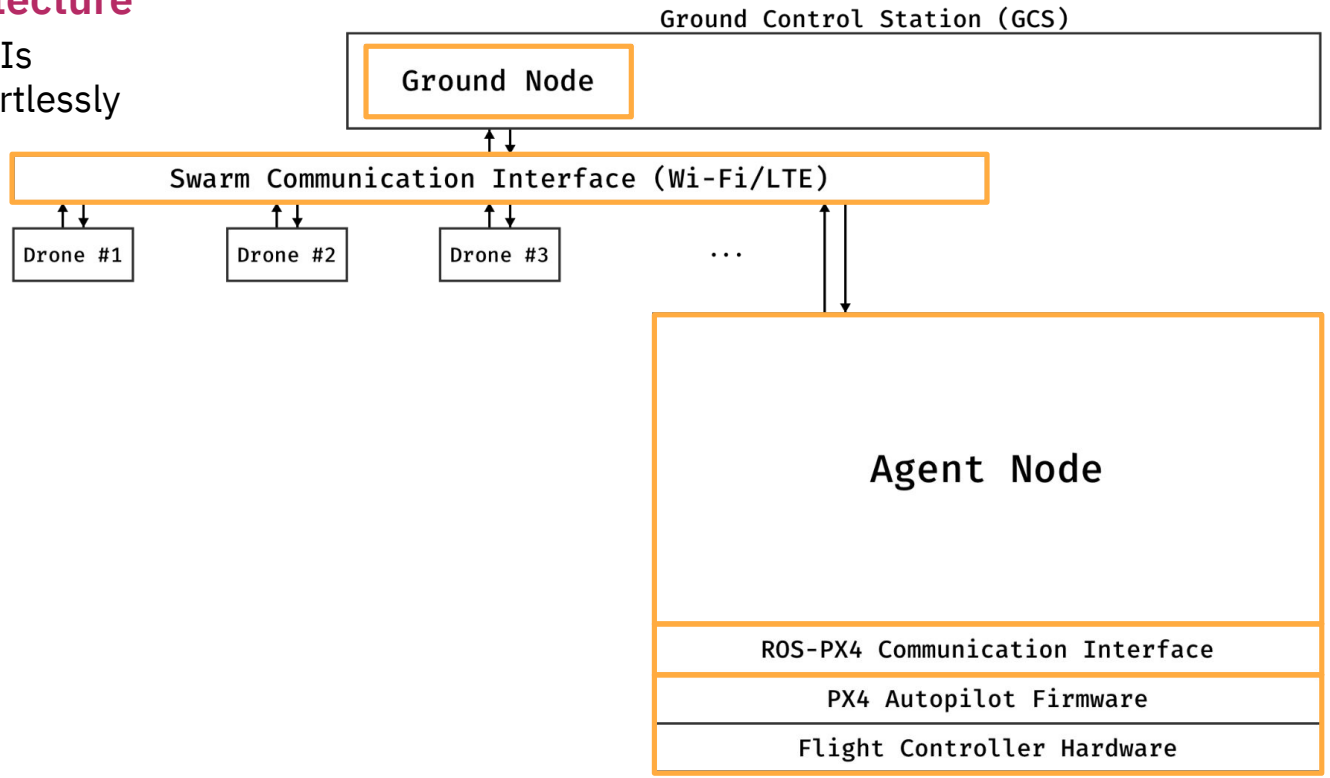
Incomparability
Architectural differences make results difficult to reproduce.

Reproducible and Standardized Execution

Reusable and Effortless Integration

Generalized Architecture

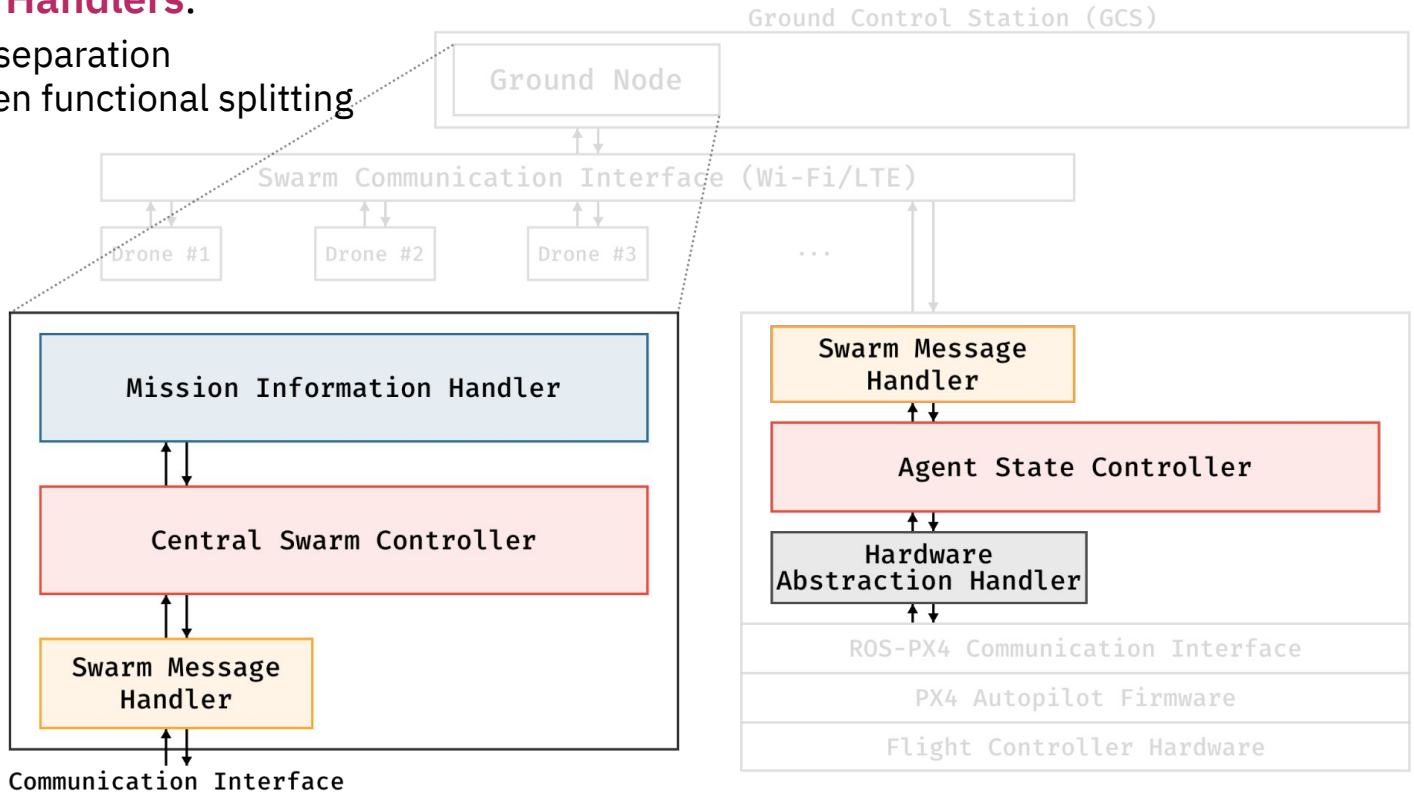
- lifecycle-based APIs
- plug-and-play effortlessly



Abstraction of Multi-layered System Complexity

4 specialized Handlers:

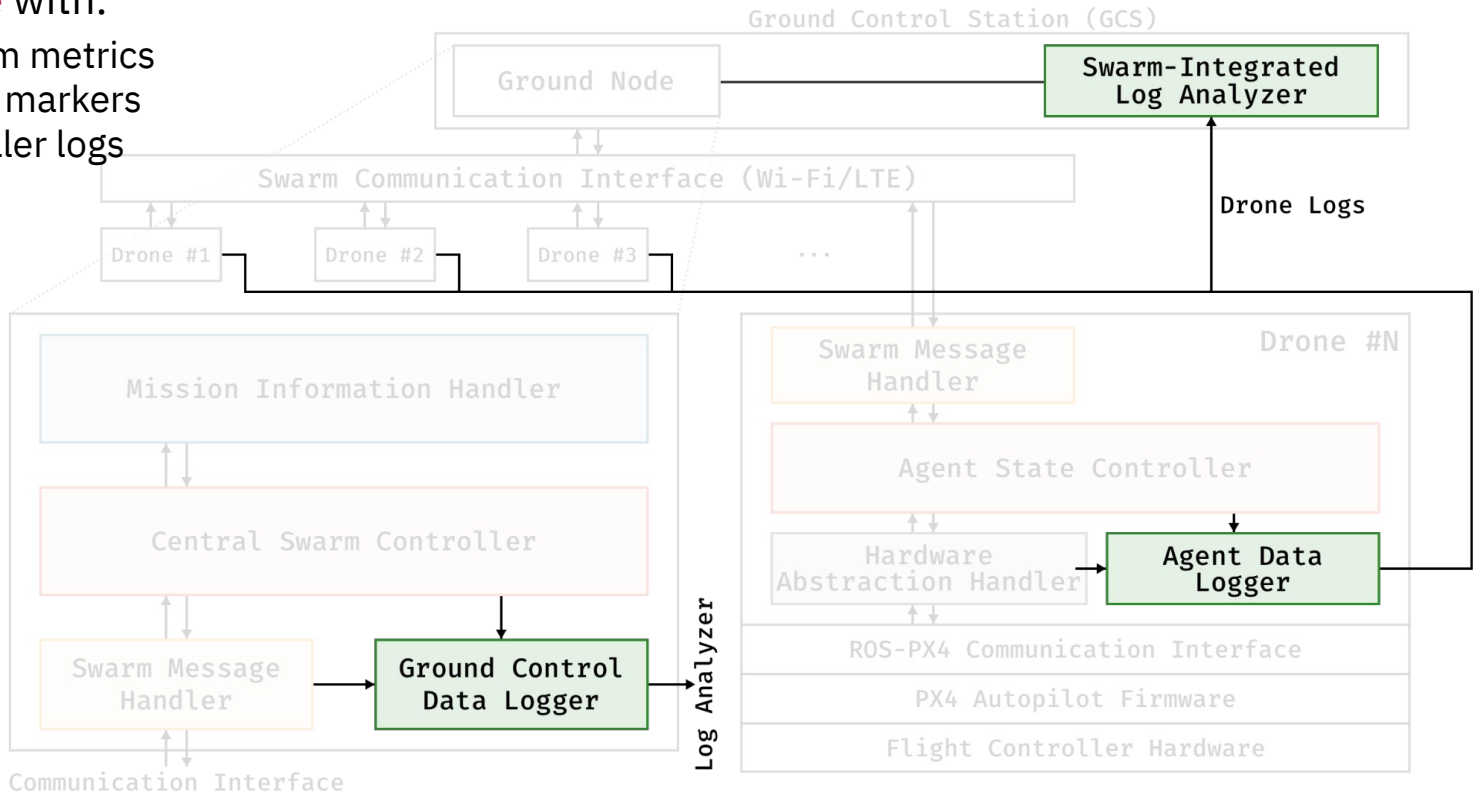
- Hierarchical separation
- Context-driven functional splitting



Comprehensive Swarm-Level Analysis Support

Log & Analyze with:

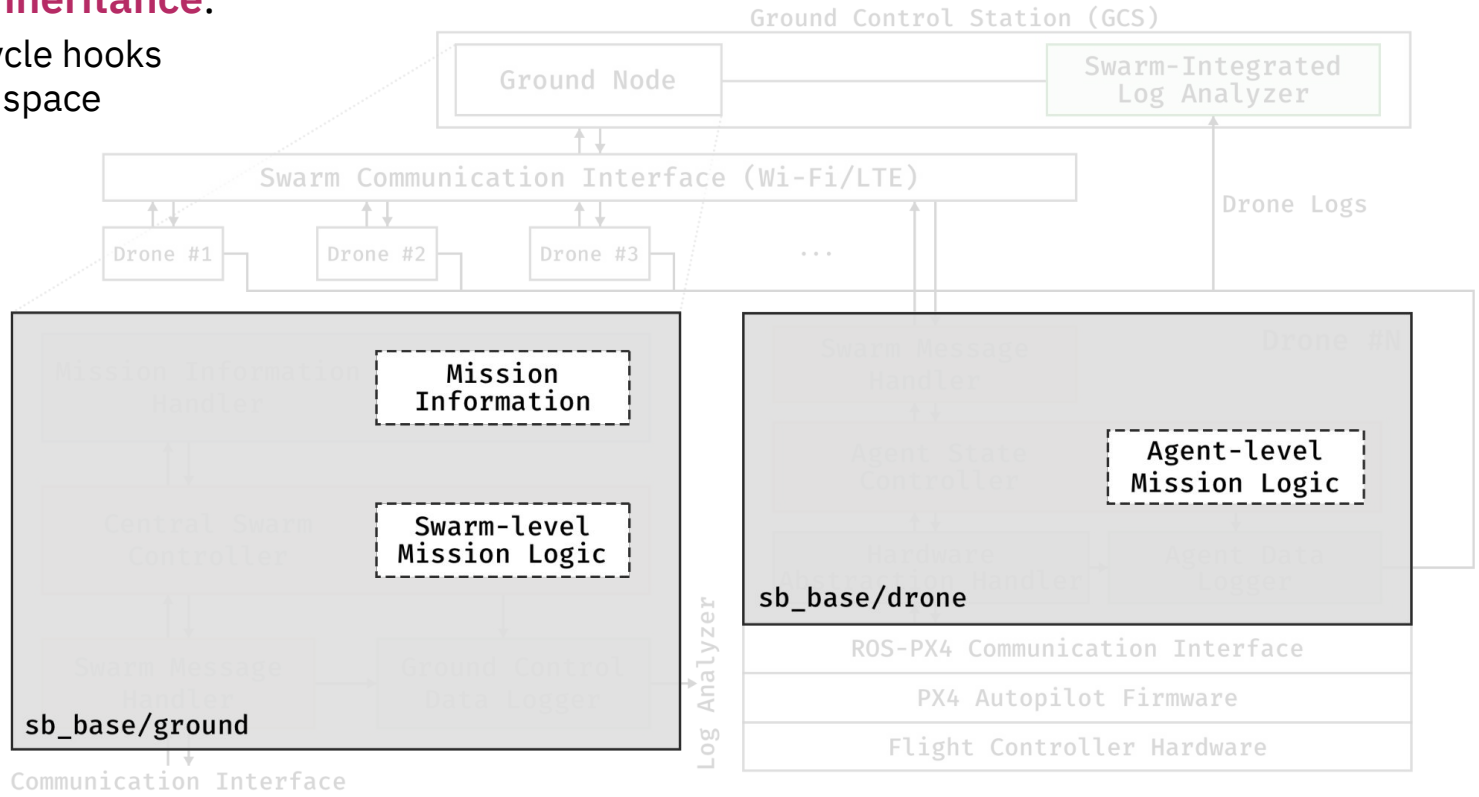
- Built-in swarm metrics
- User-defined markers
- Flight Controller logs



Reproducible and Standardized Execution

Hierarchical inheritance:

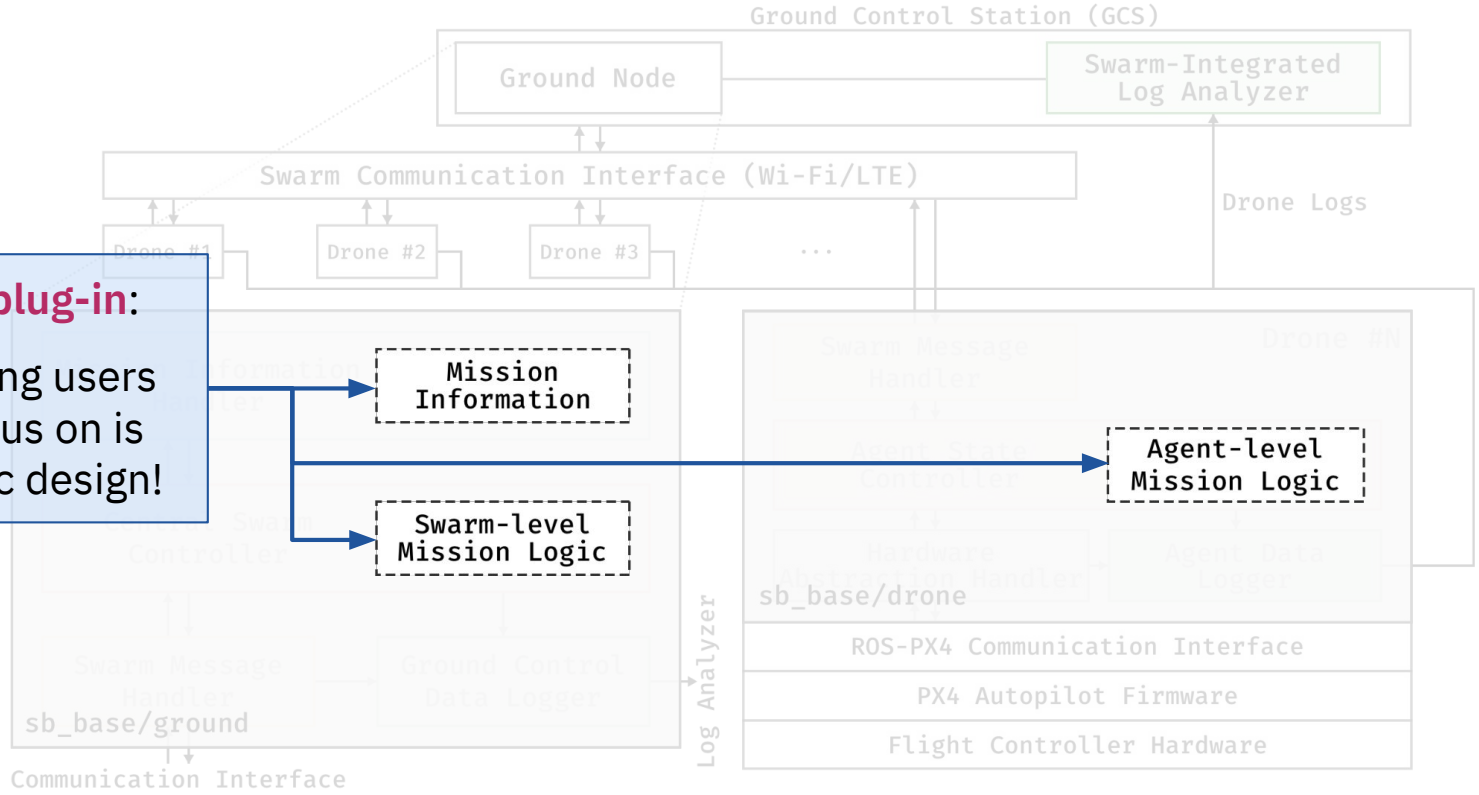
- Drop-in lifecycle hooks
- Minimal user space



Reproducible and Standardized Execution

Ready-to-plug-in:

The only thing users need to focus on is mission logic design!



Evaluation Setup

Software Stack

PX4 Autopilot
v1.15

ROS 2
Humble

Ubuntu
22.04.5

Execution Environments

SITL (Simulation-In-The-Loop):
Fully simulated on Workstation

SIH (Simulation-In-Hardware):
Simulated physics, Computation on FC

Physical:
Real-World Flight, Computation on FC

Hardware Setup

in-silico (SITL/SIH):
- CPU: AMD 9800X3D
- RAM: 64GB DDR5
- Gazebo Simulator

in-situ (SIH/Physical):
- Holybro X500 V2
- Pixhawk 6C
- Raspberry Pi 3 Model B

Evaluation Criteria

Evaluated 5 core capabilities required for drone swarms

Engineering Effort Reduction

How effectively does SwarmBox reduce the engineering effort?

Sim-to-Real Fidelity

Does SwarmBox maintain high fidelity across sim-to-real environments?

Swarm-Level Observability

Can SwarmBox help diagnosing emergent, swarm-level faults?

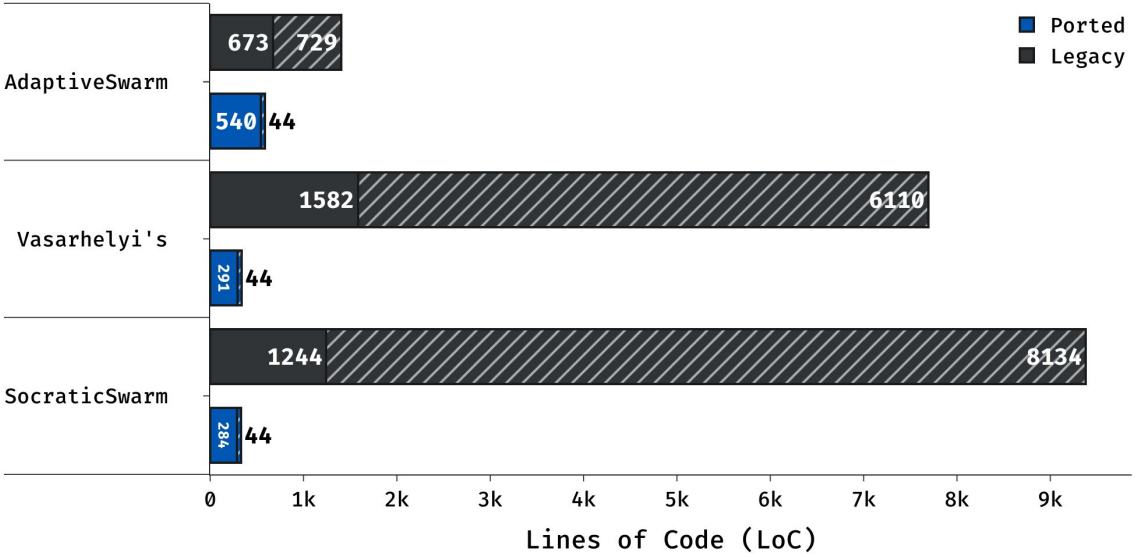
Benchmarking Capability

Can we utilize SwarmBox for a fair-comparison benchmarking?

Generality & Scalability: *Is SwarmBox suitable for various missions and large-scale usages?*

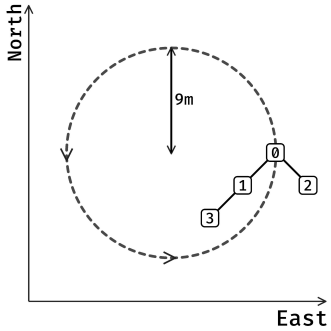
RQ1. Engineering Effort Reduction

Up to **99.5%** reduction of boilerplate implementation

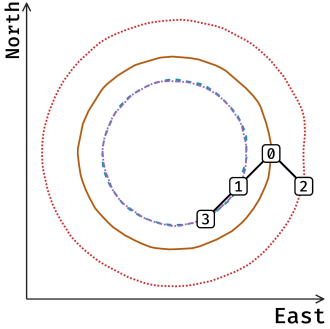


SwarmBox removes boilerplate burdens via Logic-Environment Isolation, empowering users to focus exclusively on scientific validation.

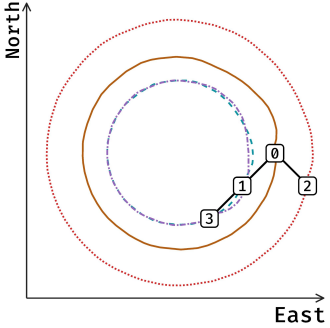
RQ2. Sim-to-Real Fidelity



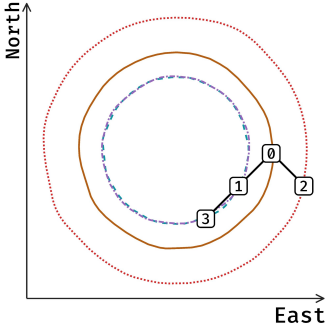
(a) Trajectory Plan



(b) SITL



(c) SIH



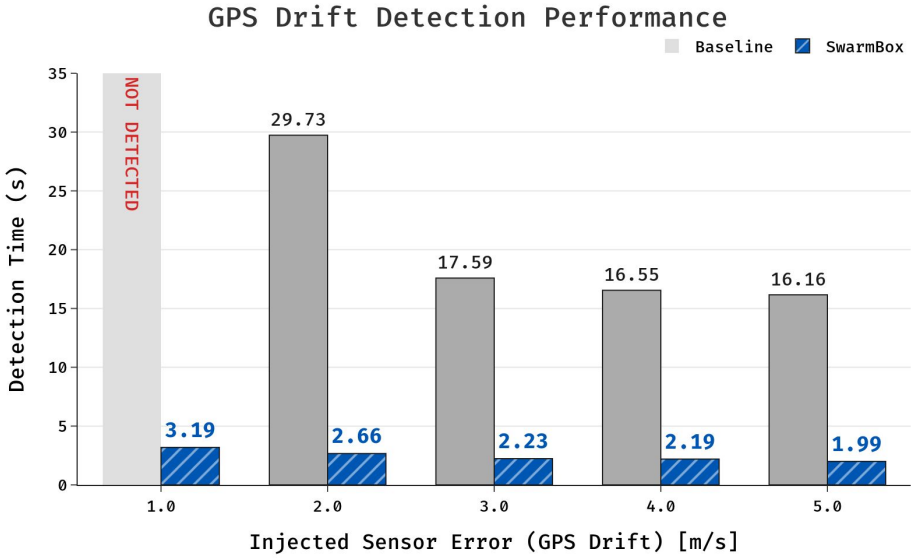
(d) Physical

SwarmBox bridges the sim-to-real gap
via Hardware-Fidelity Abstraction,
empowering users to achieve rapid deployment.

RQ3. Swarm-Level Observability

(1) Internal state uncertainty of each agent
  - sensor fault (GPS Drift)
(2) Inter-agent interaction faults
  - network latency / packet loss

- **Faster sensor fault detection**
- **Enables diagnosis of inter-agent interaction faults**



SwarmBox exposes complex inter-agent faults via Unified Behavior Analysis, empowering users with holistic diagnostic viewpoints.

RQ4. Benchmarking Capability

Evaluating SwarmBox's capability for thorough algorithmic comparison.

Scenario: Turnaround trip to 100 random targets with 5 drones (delivery)
Combinations of package assignment methods (3 sorting rules, 3 assignment methods)

Category	Metric	Unit
Cost Efficiency (General-Purpose)	Total flight distance	*m*
	Total mission duration	*s*
Resource Utilization (General-Purpose)	Idle time	*s*
	Utilization	%
	Workload deviation: distance	*m*
	Workload deviation: time	*s*
Delivery Quality (Mission-Specific)	Average delivery wait	*s*
	Maximum delivery wait	*s*

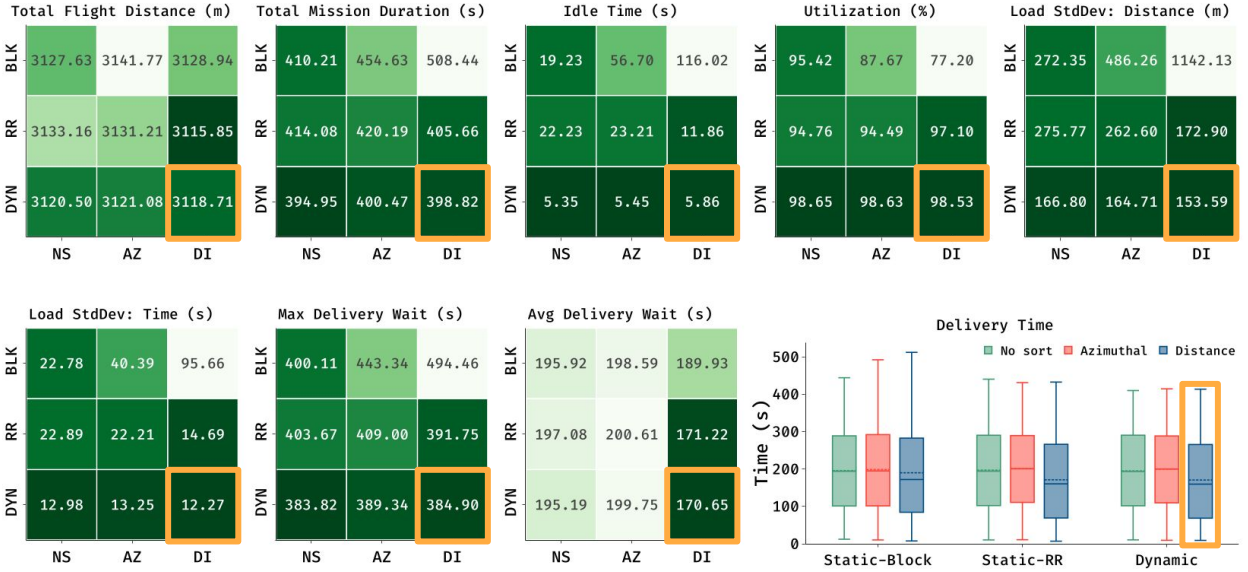
6 General-Purpose metrics

2 Mission-Specific metrics

RQ4. Benchmarking Capability

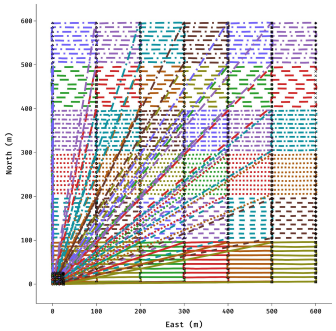
Benchmark-optimal:
Dynamic assignment &
Distance-ordered sort

darker cells, better performance.

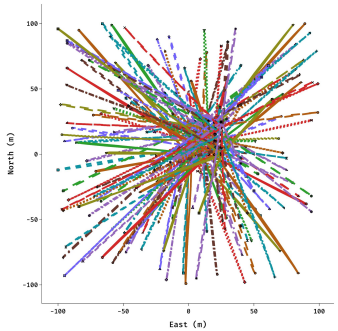


SwarmBox provides fair algorithmic comparison via Multi-Faceted Benchmarking, empowering users with a standardized evaluation platform.

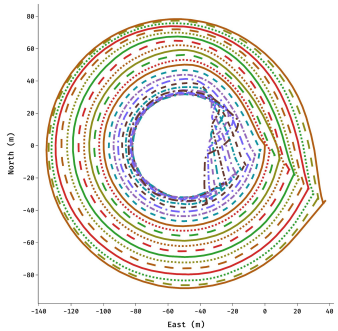
RQ5. Generality & Scalability



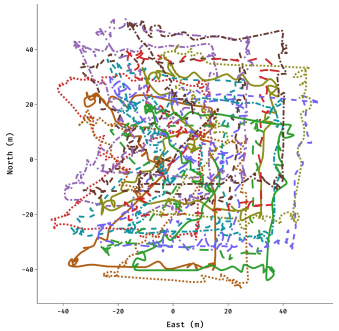
(a) airview



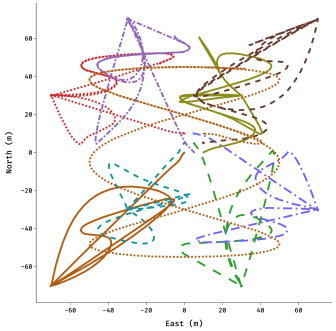
(b) delivery



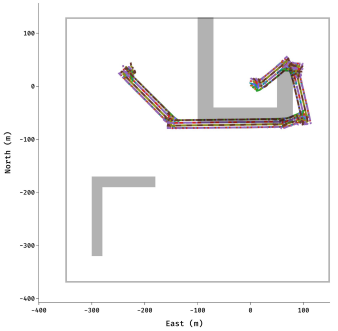
(c) formation



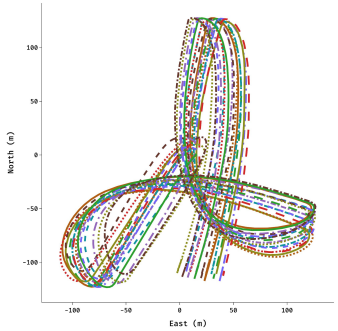
(d) network



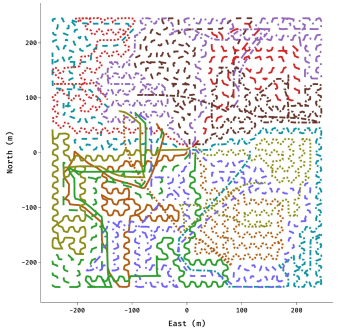
(e) tracking



(f) adaptive_swarm

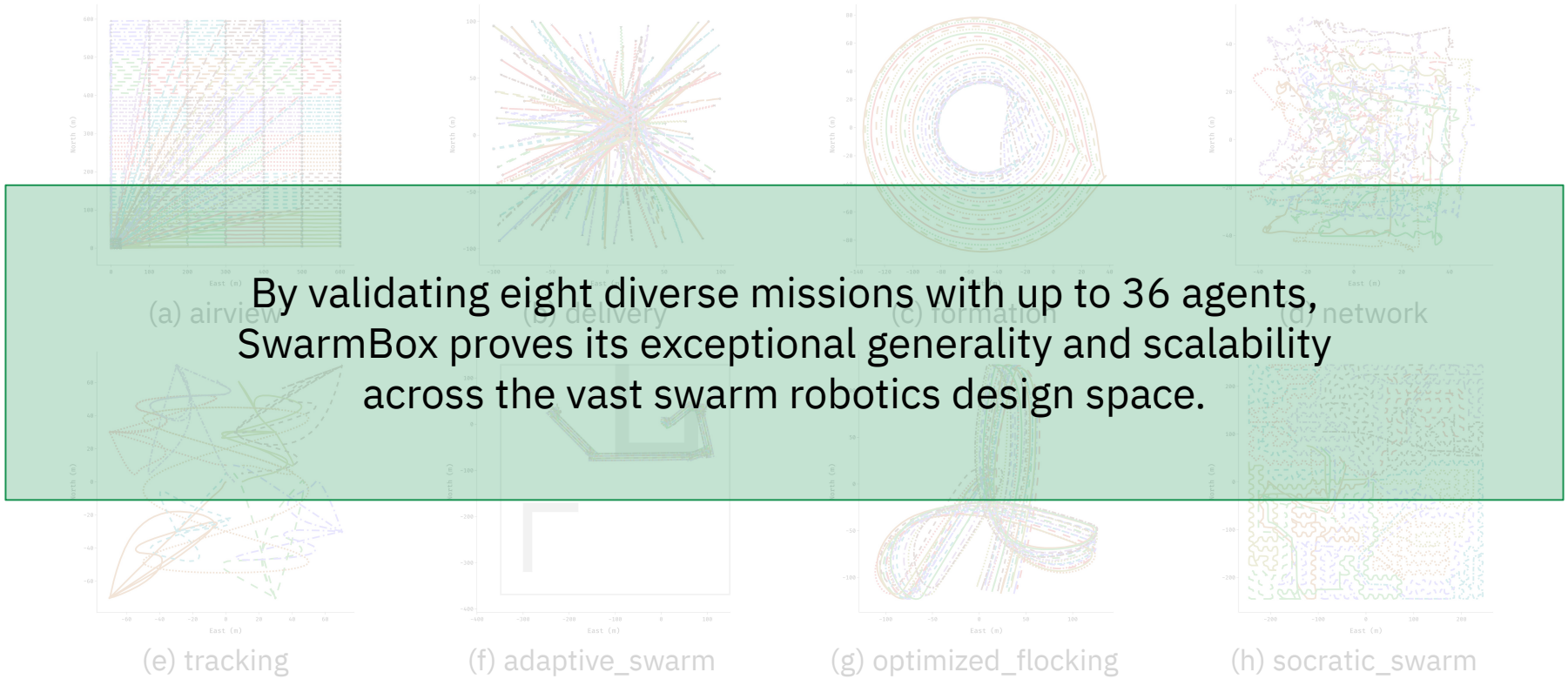


(g) optimized_flocking



(h) socratic_swarm

RQ5. Generality & Scalability



By validating eight diverse missions with up to 36 agents, SwarmBox proves its exceptional generality and scalability across the vast swarm robotics design space.

Open-Source, Active and Alive

To facilitate open innovation on the drone swarm ecosystem,
we released and are maintaining SwarmBox as an **open-source software**.

- **Artifacts Evaluated**:
  Available, Functional and Reusable.
- **Supporting modern stack**:
  Ubuntu 22.04 ➜ 24.04,
  ROS 2 Humble ➜ Jazzy,
  PX4 v1.15.4 ➜ v1.16.1
- **Upcoming features**:
  - Support for Multilayered DDS, No-DDS, and Ardupilot

Summary

SwarmBox provides a unified foundation
that breaks down engineering barriers to accelerate swarm research.

Effortless Integration

Removes boilerplate implementation effort up to 99.5%

Abstraction of Architecture

High sim-to-real fidelity: positioning errors are within GPS error range

Swarm-Level Analysis

Can detect swarm-level emergent faulty behaviors

Benchmarking Capability

Provides a standardized comparison platform

General & Scalable: Tested for 8 different missions, up to 36 drones

Open-Science: Open-sourced, actively maintained at https://compsec.postech.ac.kr/swarmbox

Q & A

SwarmBox provides a unified foundation
that breaks down engineering barriers to accelerate swarm research.

Contact: Minki LEE, leeminki@postech.ac.kr
https://compsec.postech.ac.kr/swarmbox

Appendix