Towards Persistent Space Observations through Autonomous Multi-Agent Formations

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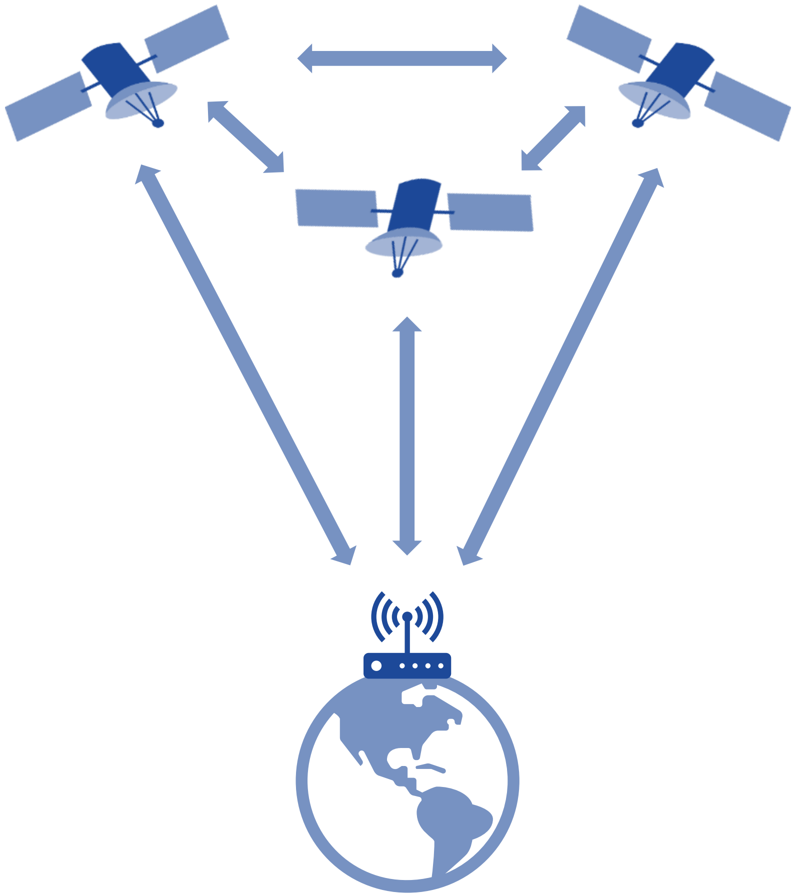
Motivation

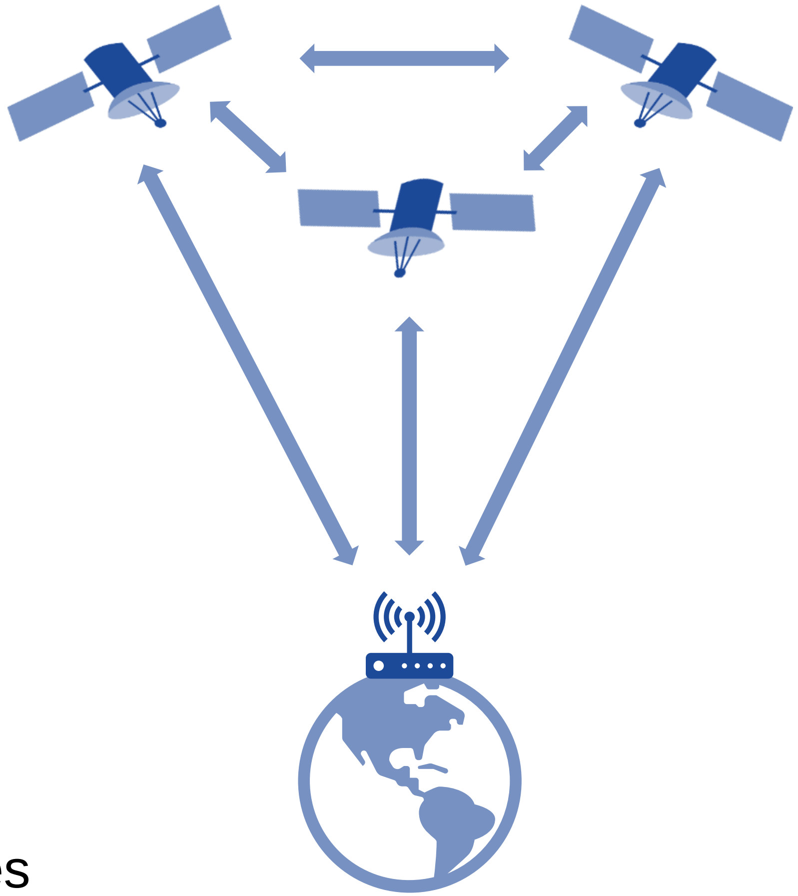
- Autonomous, persistent, distributed sensing
  - Trend and change identification
  - Situational awareness
- Many applications
  - Earth and space science observation
    - Correlative data collection
  - Intelligence, surveillance, and reconnaissance (ISR)
    - Area search, continuous monitoring
  - On-orbit and on-surface servicing, assembly, and manufacturing
    - Ad hoc communication, sensing, and manipulation



MACPOS

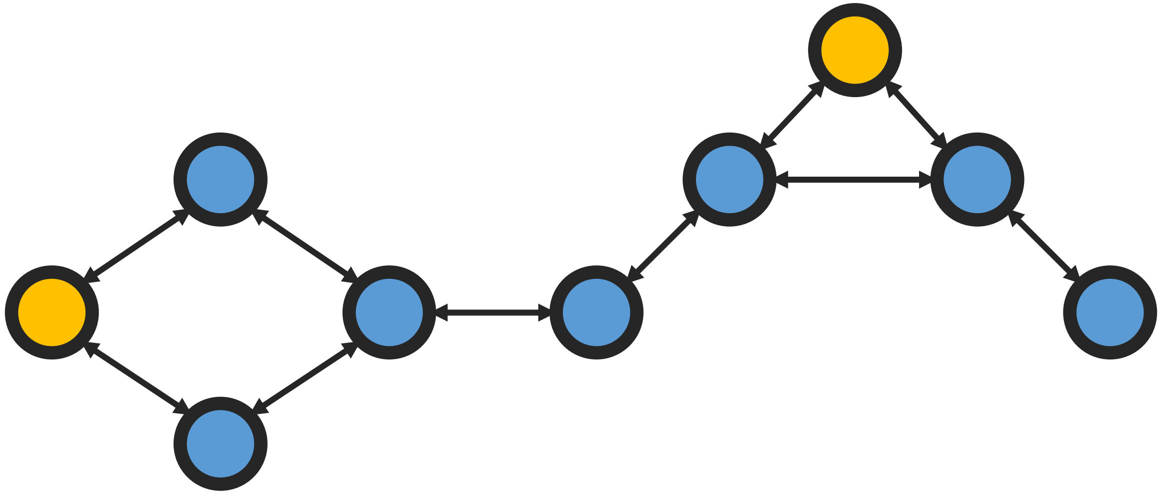
Multi-Agent Clusters for Persistent Observations from Space

- Two-year research project to develop formation flying capabilities
  - Dynamic formations
  - Trajectory generation
  - Time-critical coordination
  - Software framework
- Platform-agnostic software and framework
  - Rovers, UAVs, SmallSats
  - Simulated, real, and mixed reality assets
- Demonstration-driven development
  - Design reference mission (DRM) showing above capabilities
  - Subsystem and integration demos building up to DRM



R&D Efforts

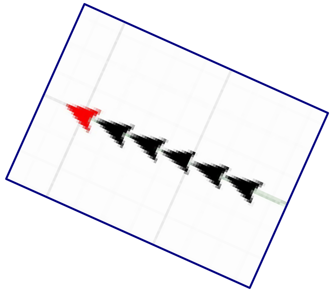
- Autonomous Multi-Agent Clusters:
  - Dynamic formations
  - Trajectory generation
  - Time-critical coordination
  - Software framework

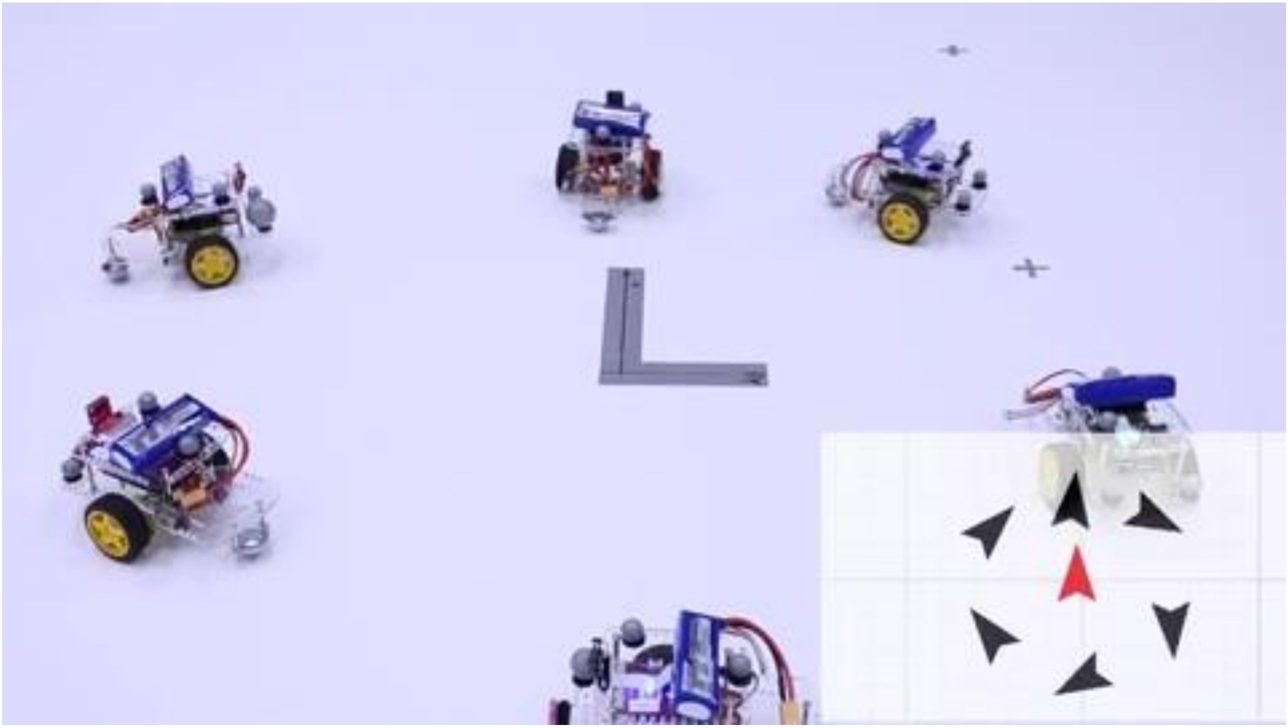


Dynamic Formations

- Dynamic formation transitions
  - Adaptive physical layout of agents
  - Adaptive hierarchy of control
    - Fully centralized
    - Leader/follower clusters
    - Fully decentralized

- Uncertain network connectivity
  - Maintain connectivity in an integral sense (everyone is connected “often enough”)
  - Formal proofs describe degradation of performance with network quality





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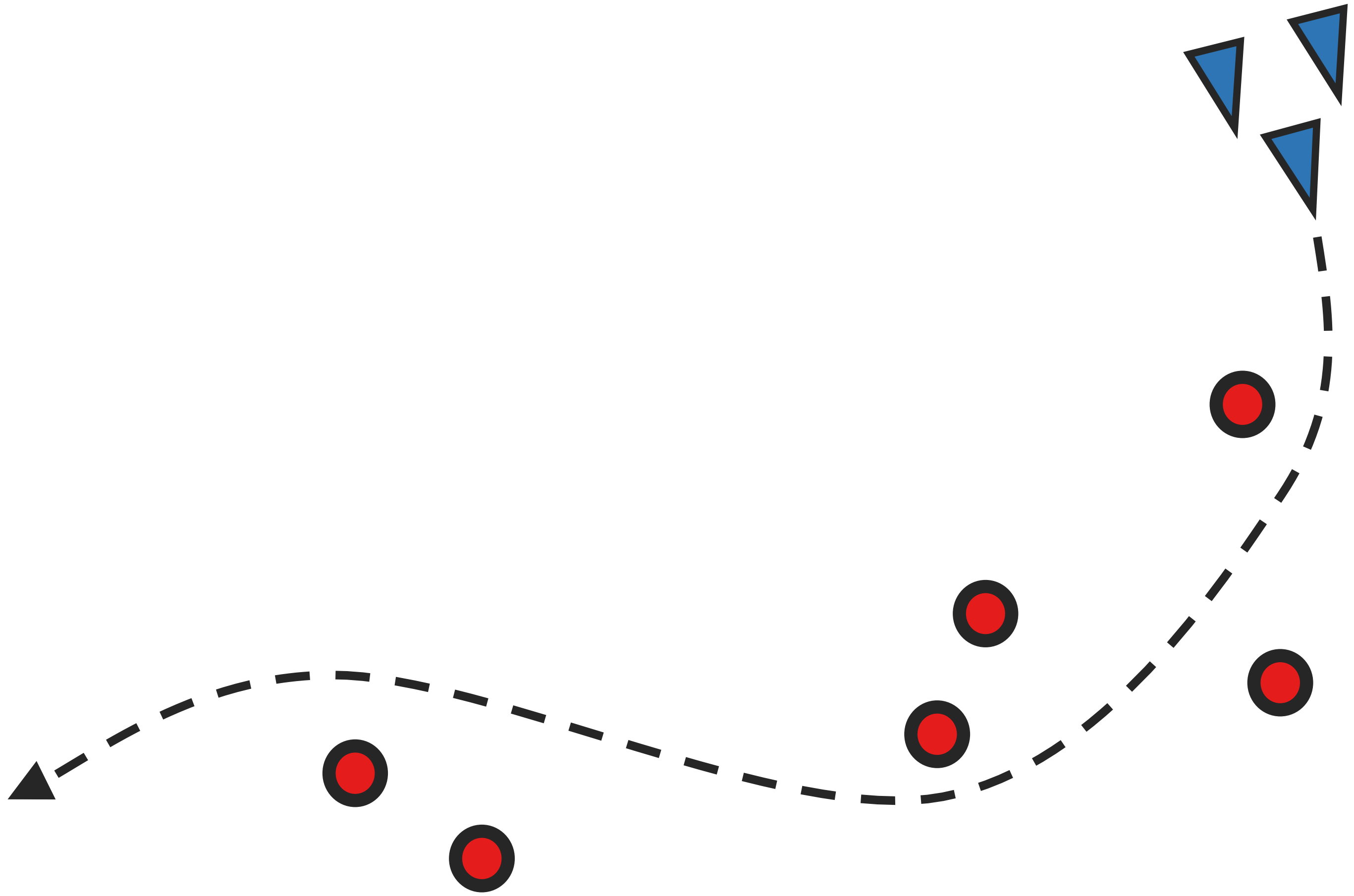
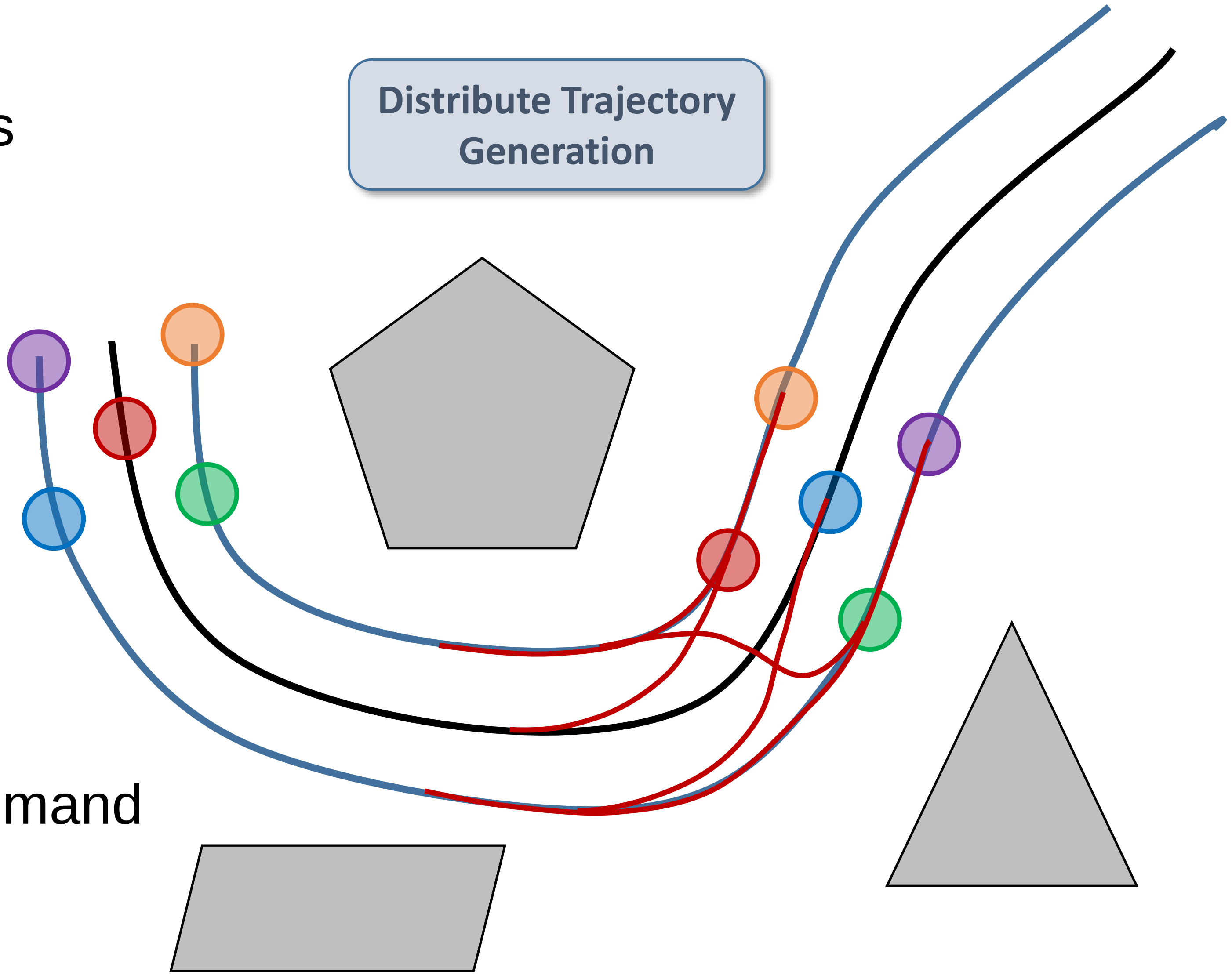


Trajectory Generation

- Fleet of **cooperating** agents
- **Time parameterized** trajectories
- Smooth
- Safe separation
  - Obstacles
  - Cooperating agents
- Meet vehicle constraints
- Visit points of interest
- **Transition under operator** command



Leader Trajectories

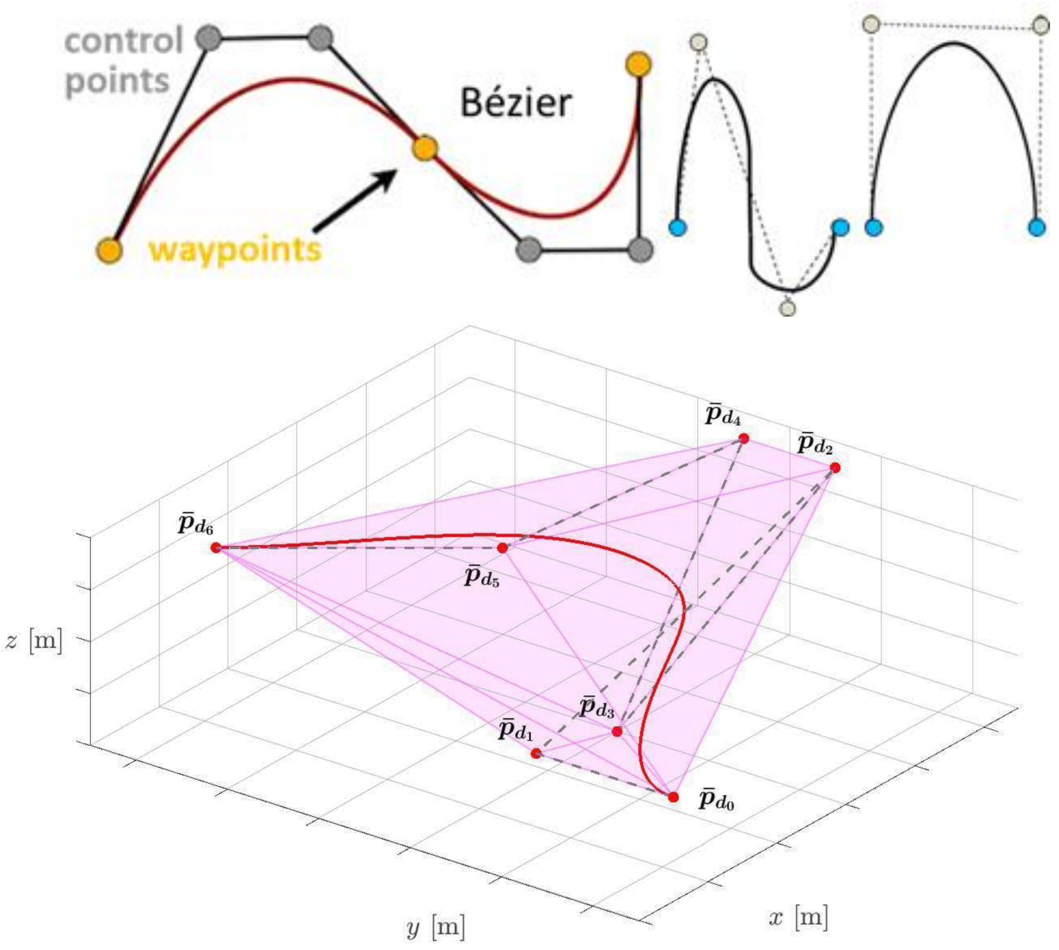
- **Piecewise Pythagorean Hodograph (PH) Bézier** curves

Bézier

- Numerical stability
- Availability of algorithms for analysis
- Easy bounding volume
- In-house proximity queries
- Shape handles → easy to modify shape

PH

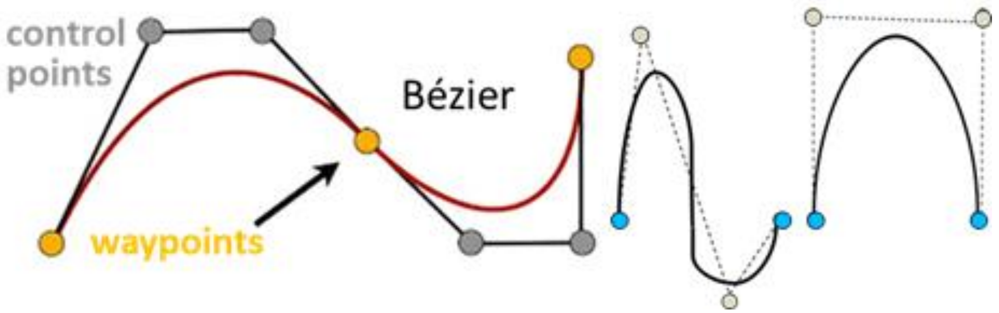
- Closed form solution for
  - Arc length
  - Parametric speed
  - Curve frames → long & cross track errors

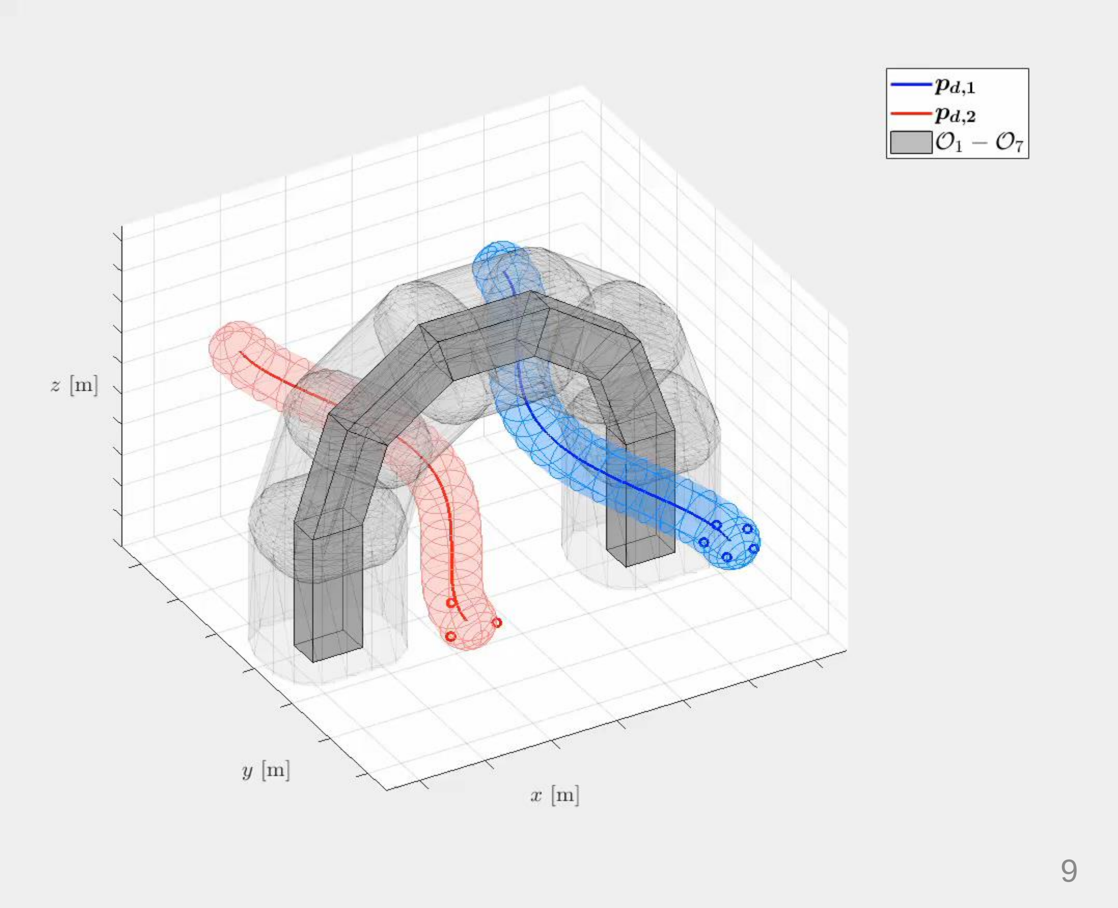


Bézier curve and bounding volume

Follower Trajectories

- **Rational Bézier** curves + **trigonometric** terms
  - Design ensures curves are contained within a tubular corridor
    - Reduces number of collision checks with obstacles and vehicles in other teams
    - Bounds the problem complexity
  - Curve offsets produce flight formations
    - Line, grid, sphere, arrow, circle, polygons…
  - **Challenges**
    - Fast proximity queries
    - Online transitions





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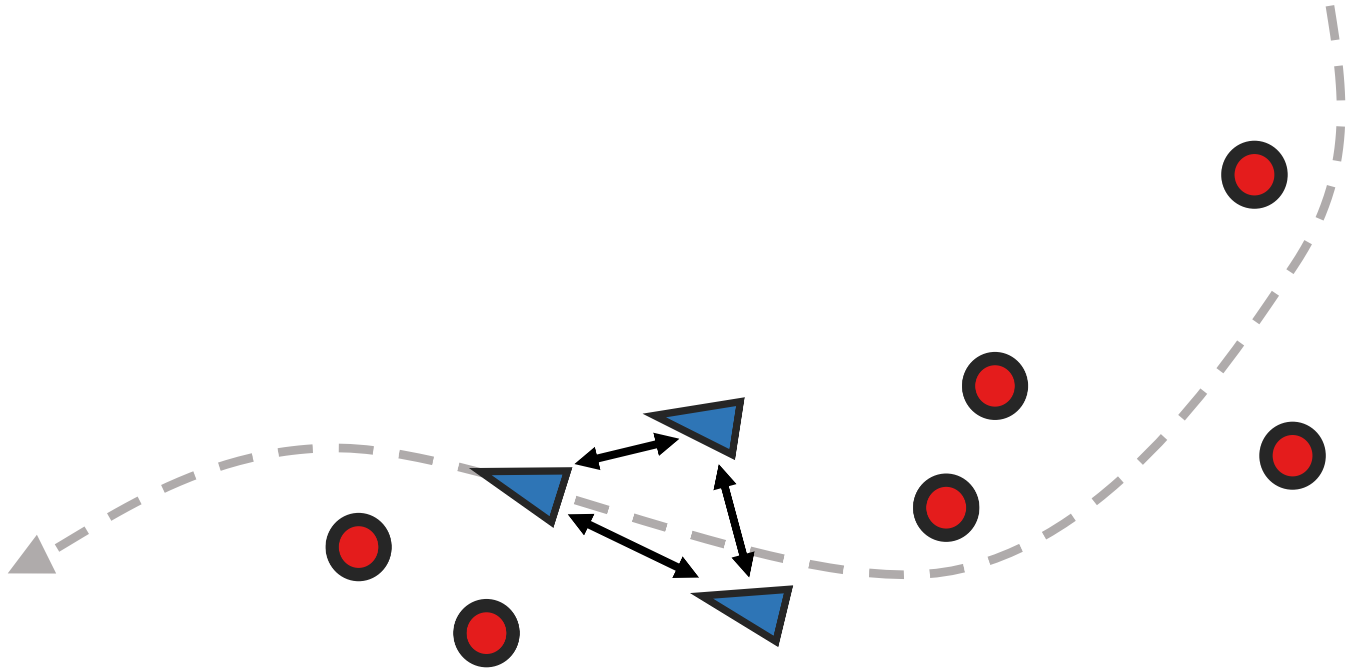
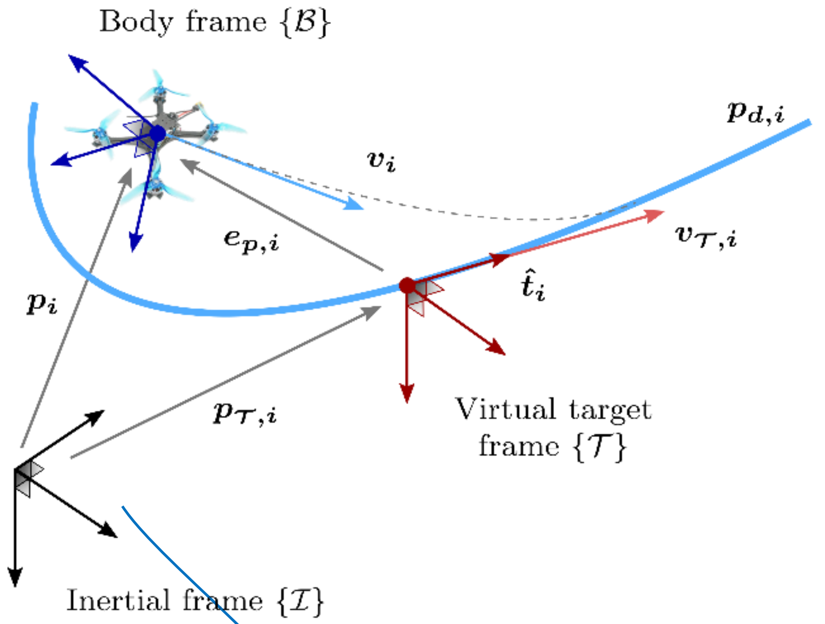
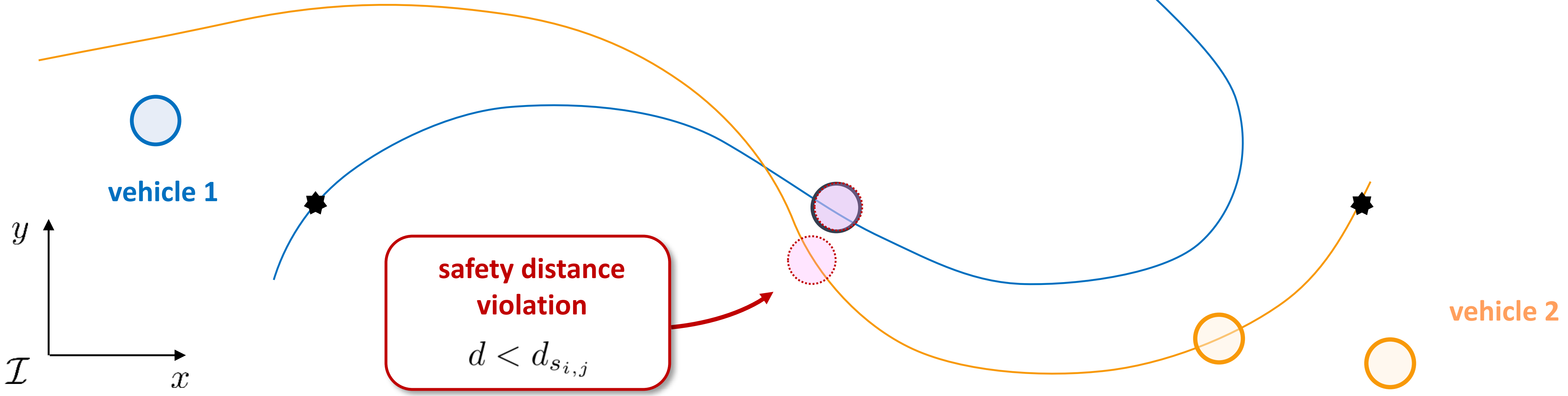


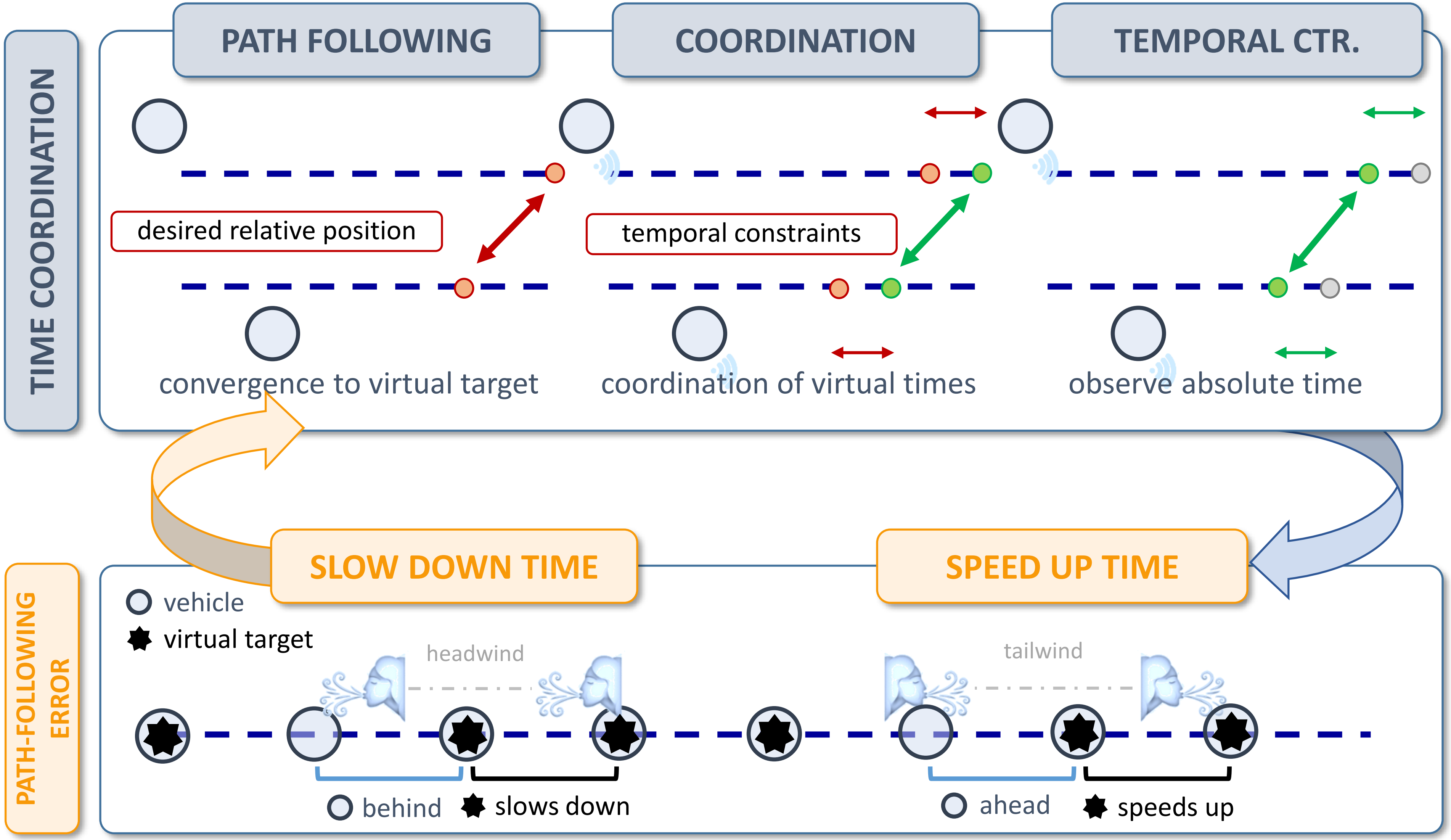
Time-Critical Coordination

- Closed-loop trajectory execution
  - Compute path-following commands
  - Insufficient to guarantee safety in multi-agent system
- Augment with coordination dynamics
  - 1D virtual times keep track of agents' progress
  - Speed up or slow down execution





Cooperative Path-Following



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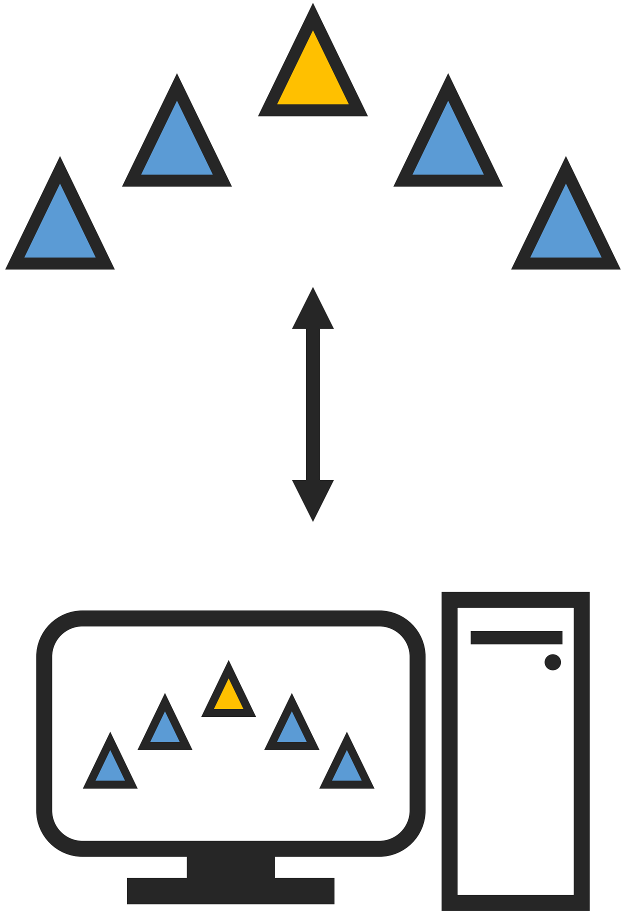
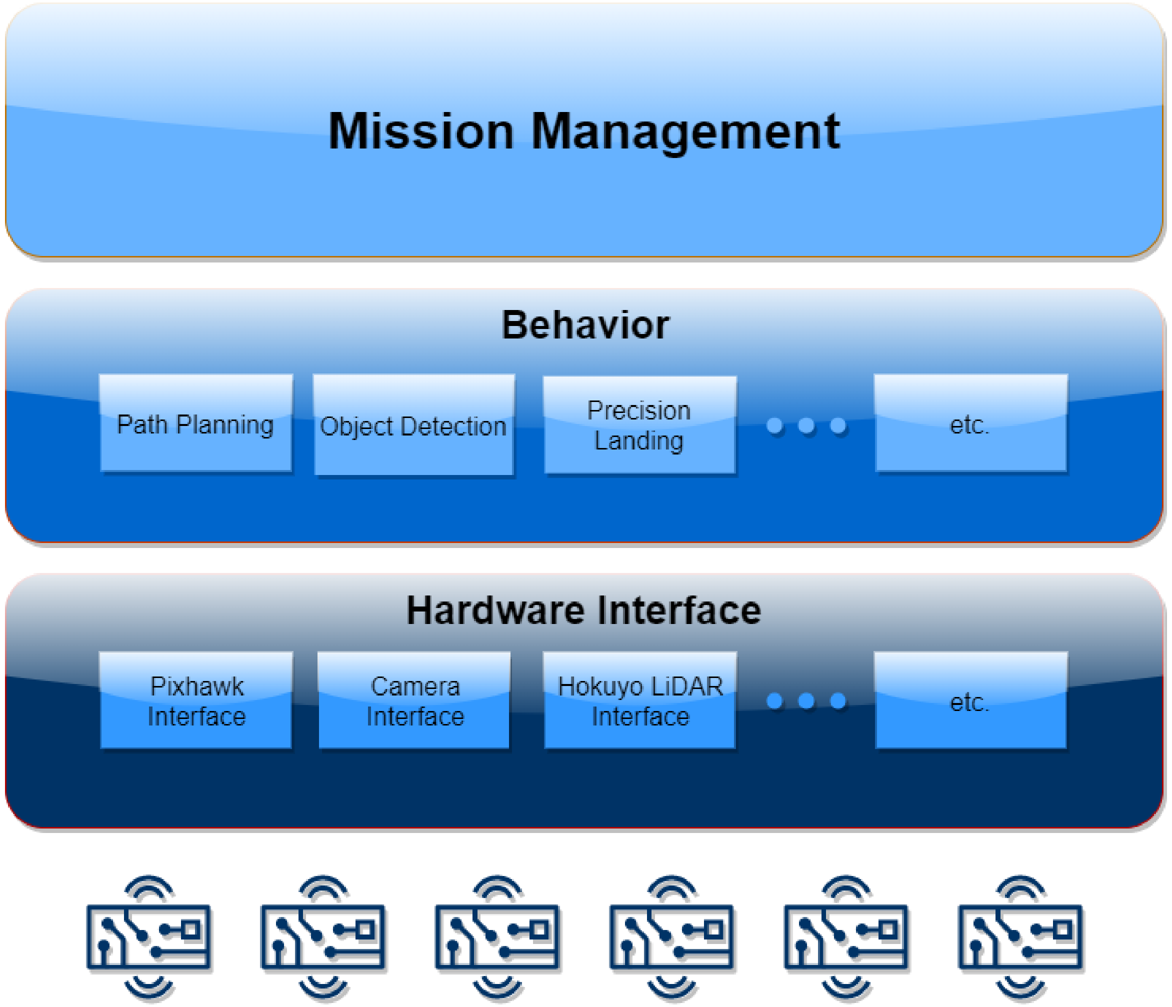


AEON

Autonomous Entity Operations Network

- Suite of libraries and standalone applications (or nodes) supporting autonomous systems
- Modular and extensible through development of new nodes to add capabilities to the system
- Enabled by Data Distribution Service (DDS) peer-to-peer communication standard

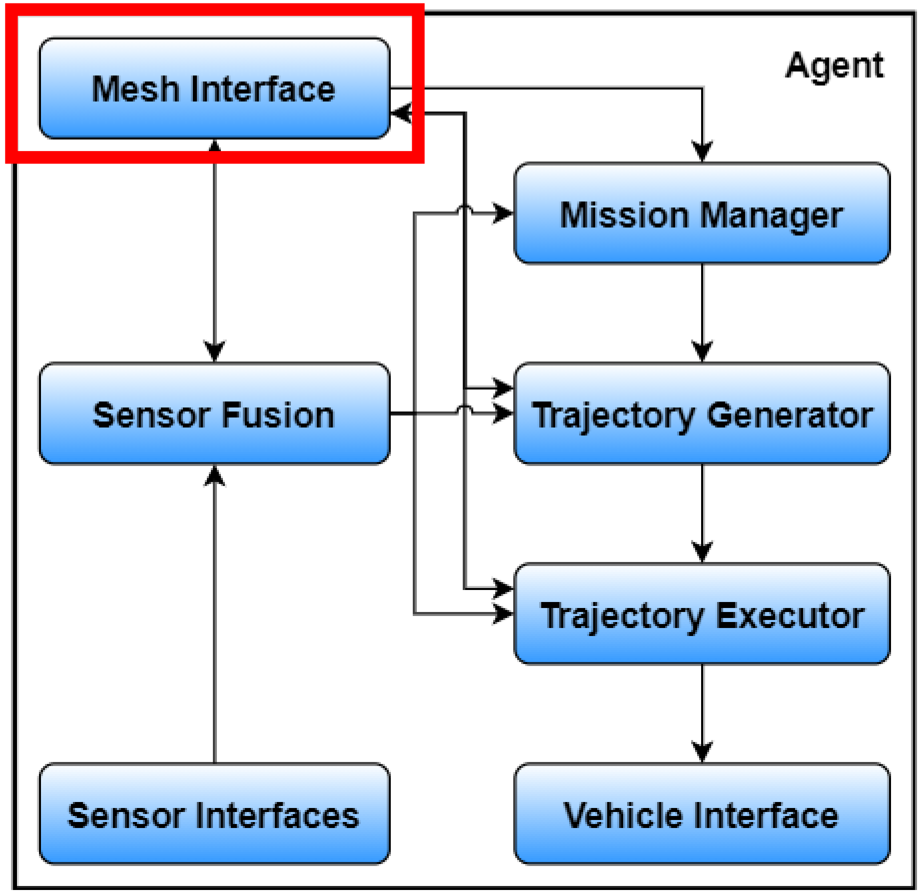


Single Agent Autonomy

MACPOS

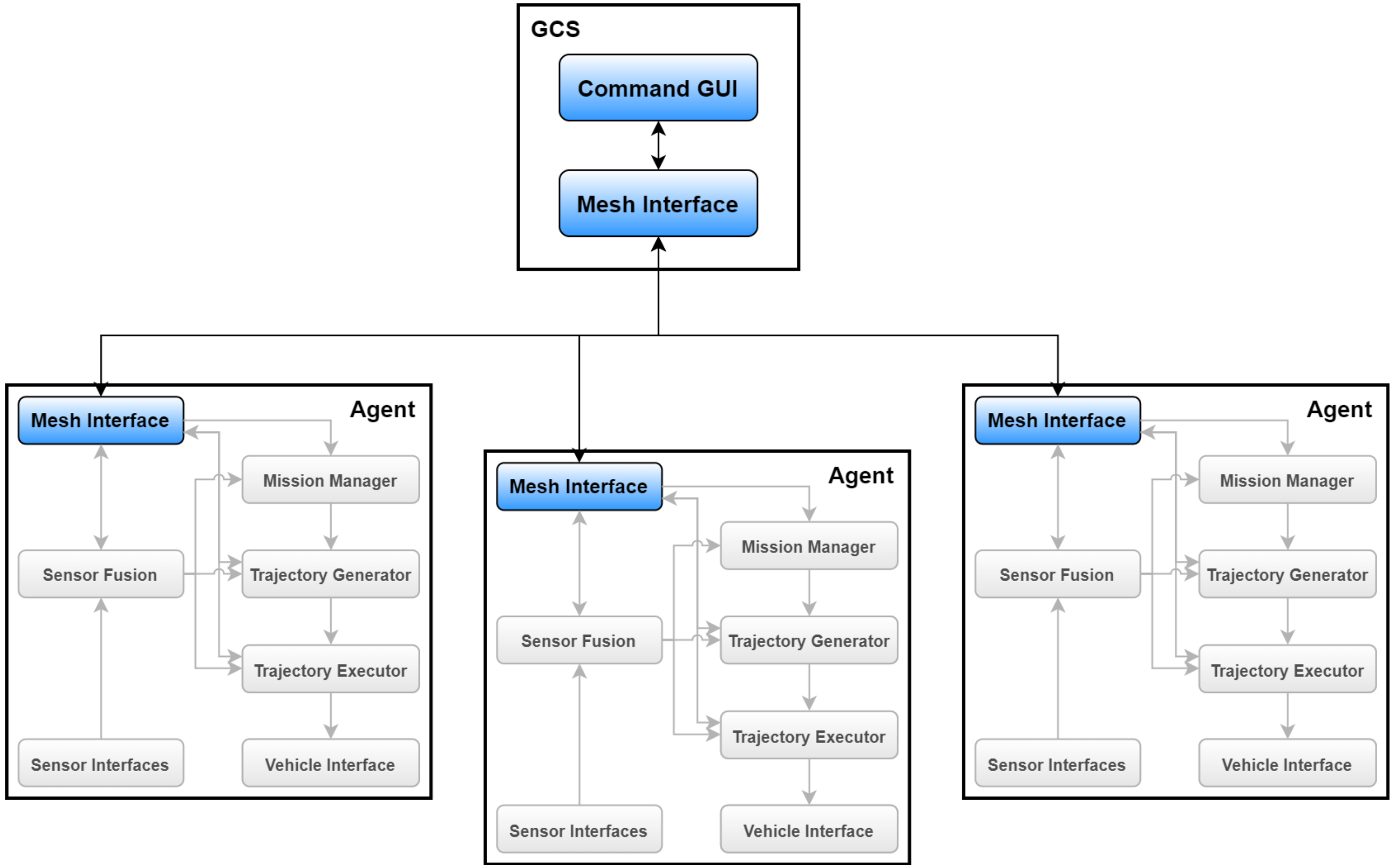
- Layers of increasing autonomy
  - Hardware interfaces
  - Controllers, planners, sensor fusion
  - Mission management

- Mesh interface throttles inter-agent comms
  - Controlled connectivity for design of experiments
  - Transparent substitution of emulated vs. real mesh communication hardware
  - Filters/relays messages according to configurable pipeline defining network characteristics



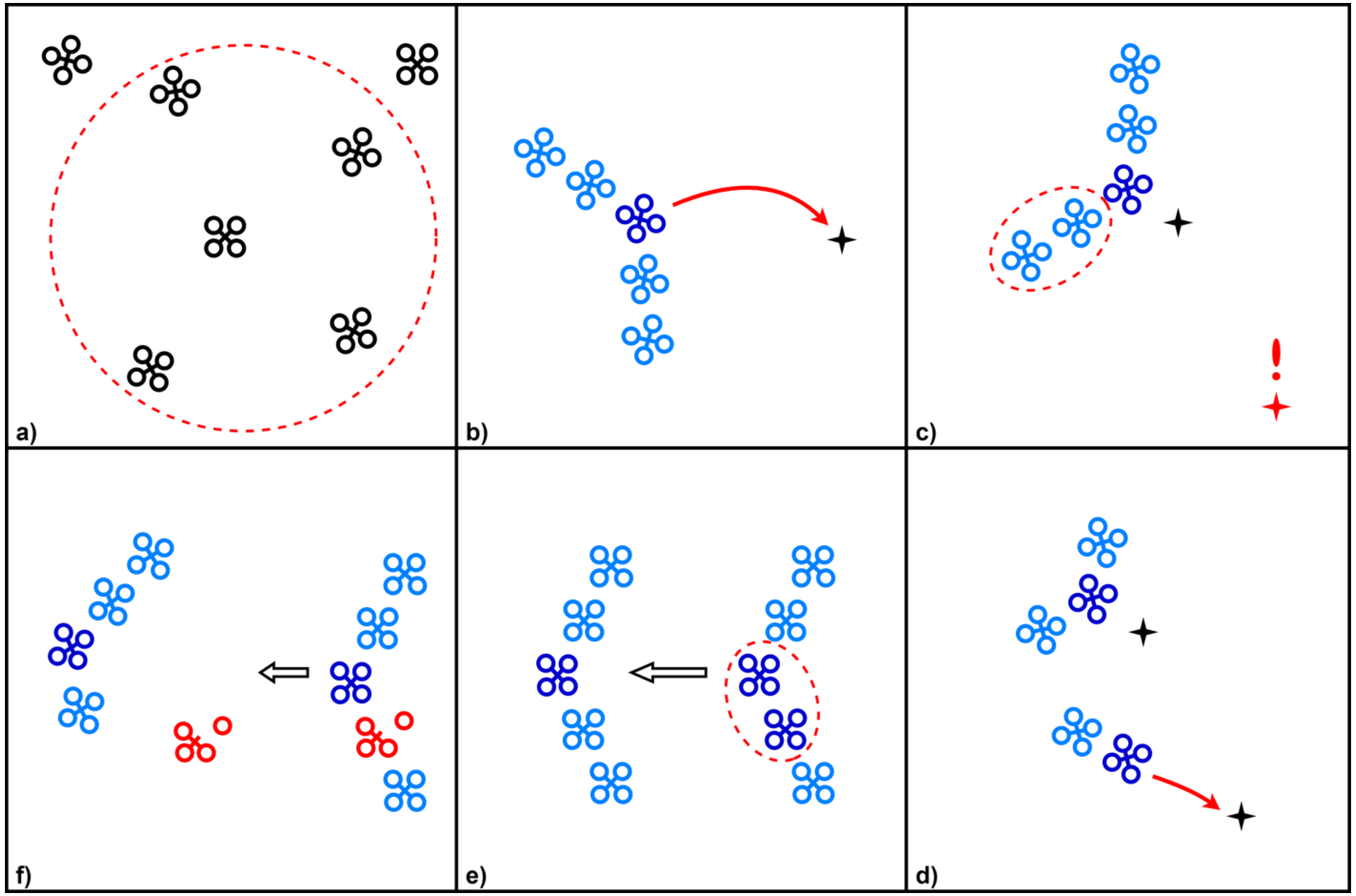
Multi-Agent System

- Bidirectional communications among all agents and the GCS
  - Restricted by mesh interface
- Command GUI monitors and controls the fleet
  - Cluster selection
  - Motion goals
  - Situational awareness



Design Reference Mission

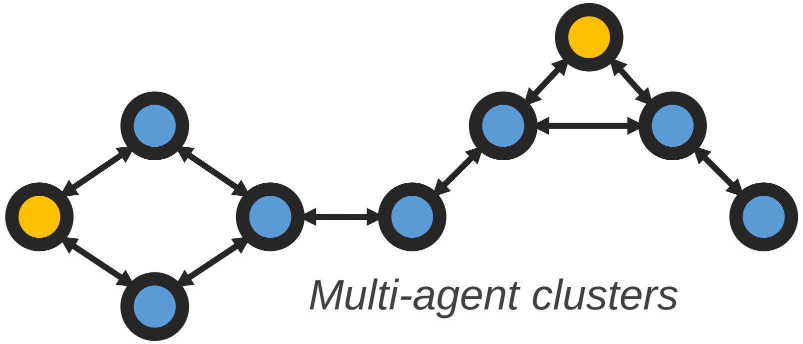
- Reference mission
  - a) Formation creation and command
  - b) Coordinated trajectory generation and execution
  - c) Area of interest discovery
  - d) Formation splitting and re-tasking
  - e) Formation merging
  - f) Fault handling



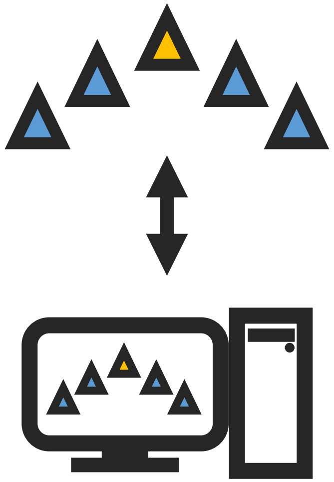
- Subsystem and integration demos highlighting individual elements

Conclusion

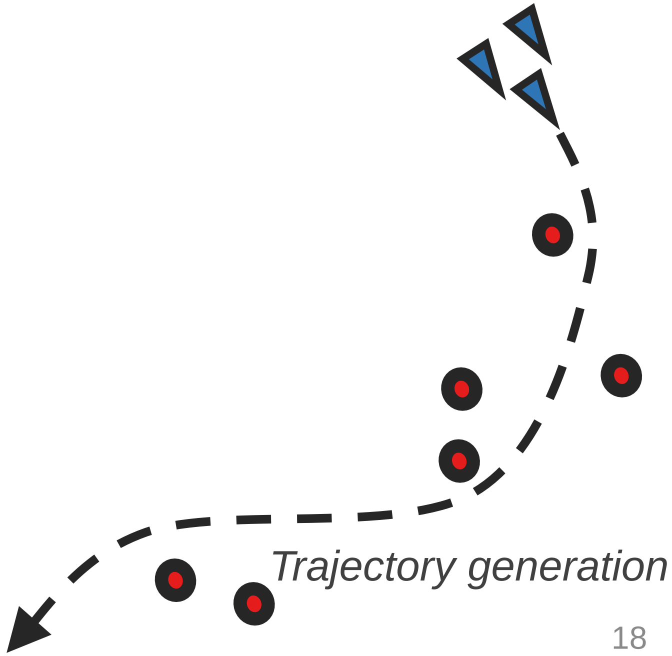
- Ongoing algorithm development will establish a foundation for autonomous formation flying
- Modular, extensible architecture paves the way for complementary future work
  - Data-driven mission planning
  - Distributed sensing algorithms
  - Increasing technology maturity
- Collaborative mobile robots can transform space and surface in-situ assembly
  - Enhanced situational awareness
  - Dynamic infrastructure support



Multi-agent clusters



Sim-to-flight pipeline



Trajectory generation

Thank you!

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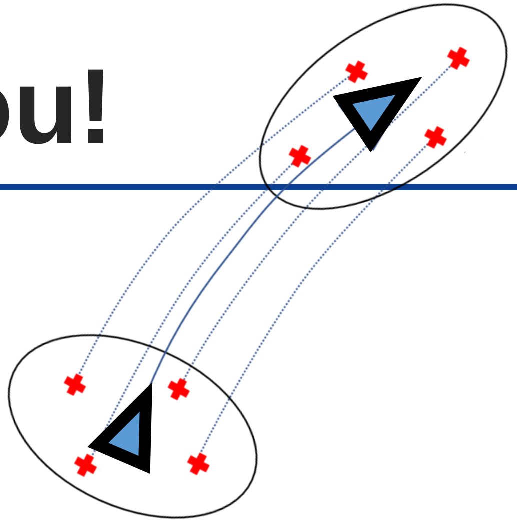
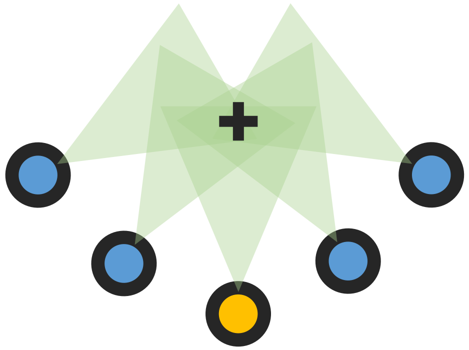
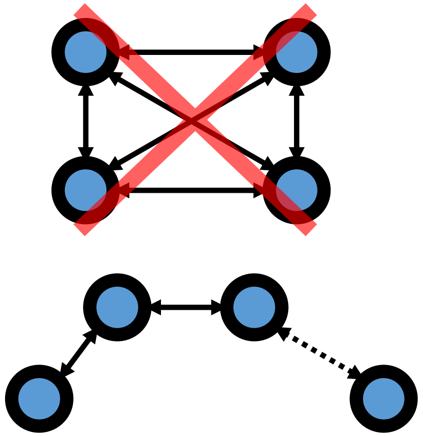
- Sherif Shazly
- Robert Slick
- Loc Tran
- Walter Waltz
- Ralph Williams



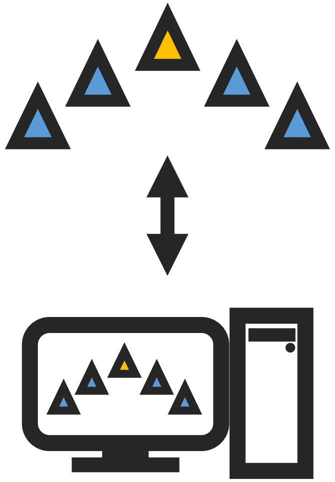
Uncertainty propagation



State estimation



Mesh networking



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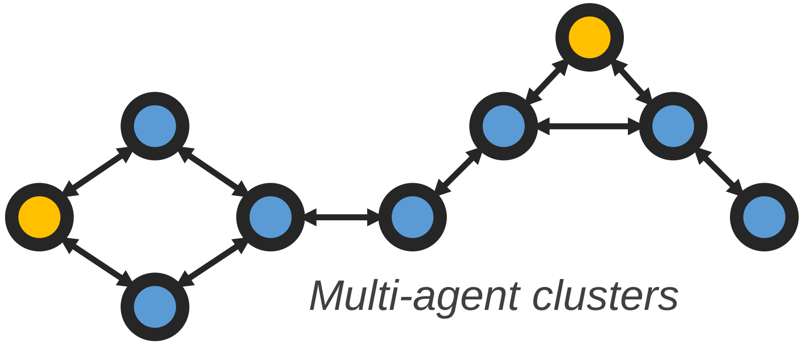

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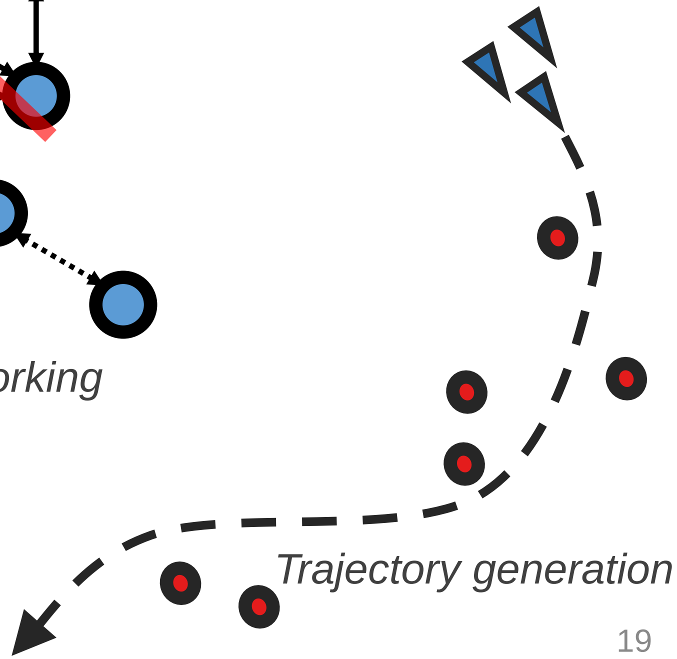

Trajectory generation