The Caltech Multi-Vehicle Wireless Testbed: Initial Implementation

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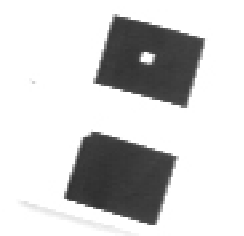
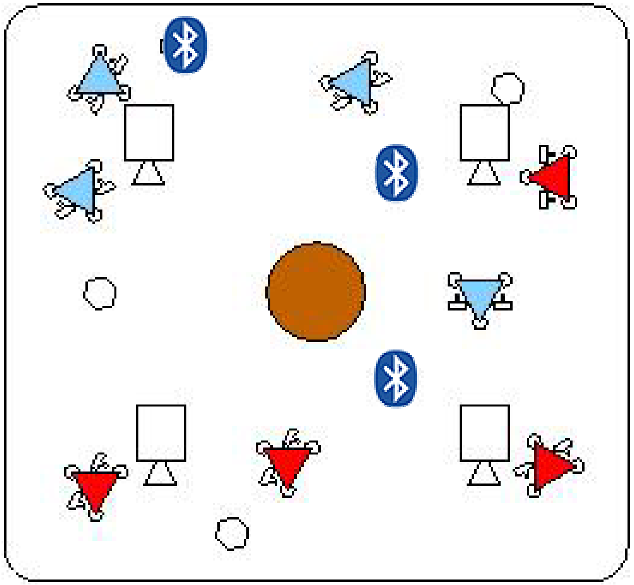
Outline

- What is the Multi-Vehicle Wireless Testbed (MVWT)?
- Implementation of closed-loop vehicle control
- Preliminary control results
- Extension to multiple vehicles
- Conclusions and future work



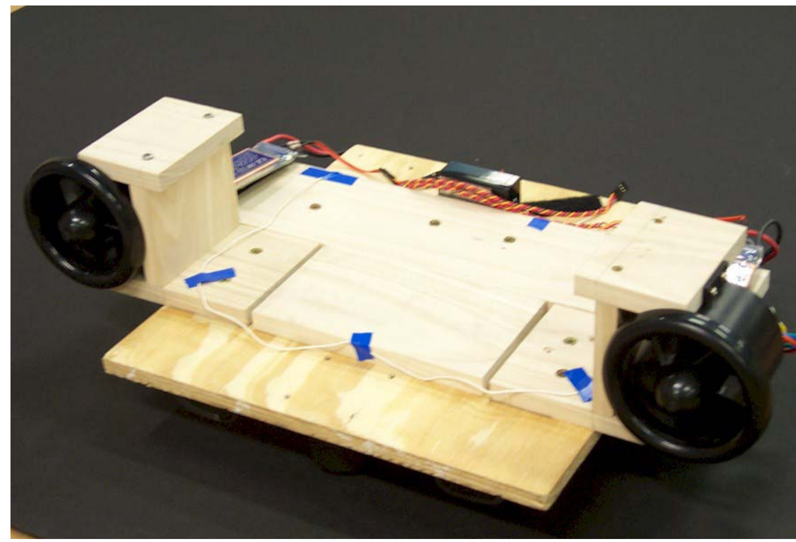
What is the MVWT?

- Experimental platform for investigating the intersection of control, computation and communications
- Consists of:
  - A number of wireless vehicles
  - Vision system (emulates GPS)
  - Command system
  - Inter-vehicle communication



<u>Prototype</u> Vehicle Design

- Actuation: Two high-power unidirectional ducted fans
- No onboard sensing
- Receive fan input signals via radio link



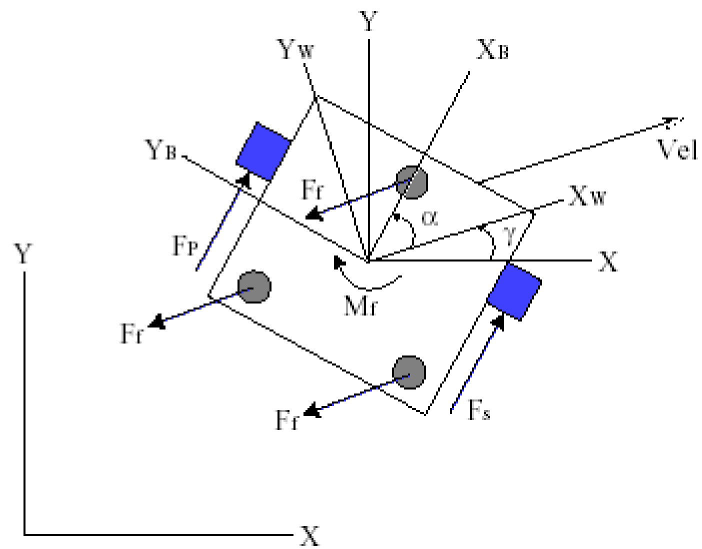
Video – Manual Control

Vehicle Dynamics

- Assuming linear friction acting at CoM ⇒ vehicle is linear in state, nonlinear in input

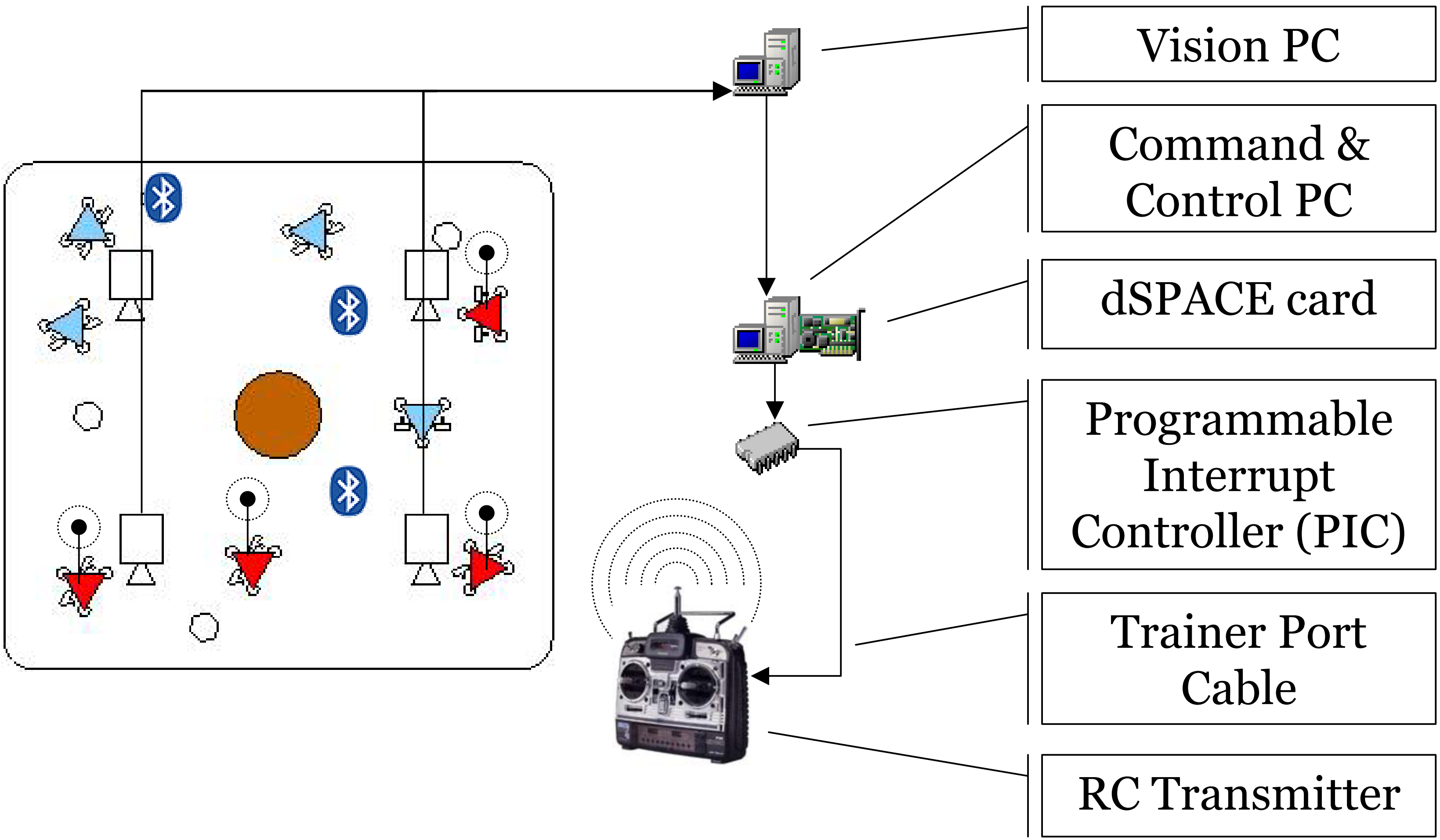
$$\dot{\underline{x}} = A\underline{x} + B(\underline{x})u$$

- Input-constrained, underactuated ($0 \leq F_{S/P} \leq F_{max}$)

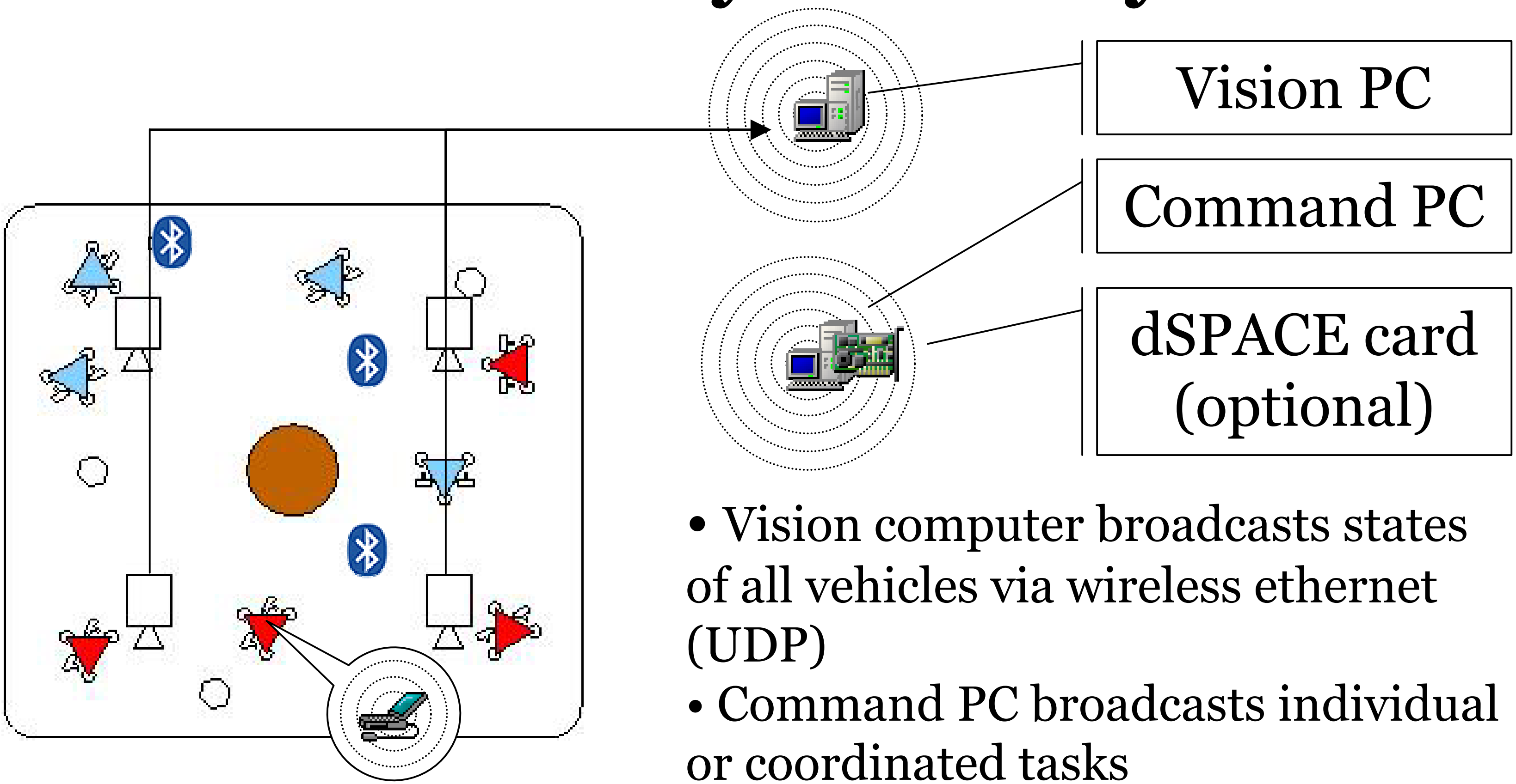


$$\begin{aligned} m\ddot{x} &= -\mu\dot{x} + (F_S + F_P)\cos(\theta) \\ m\ddot{y} &= -\mu\dot{y} + (F_S + F_P)\sin(\theta) \\ J\ddot{\theta} &= -\mu r_c^2\dot{\theta} + (F_S - F_P)r_f \end{aligned}$$

Current Physical Layout



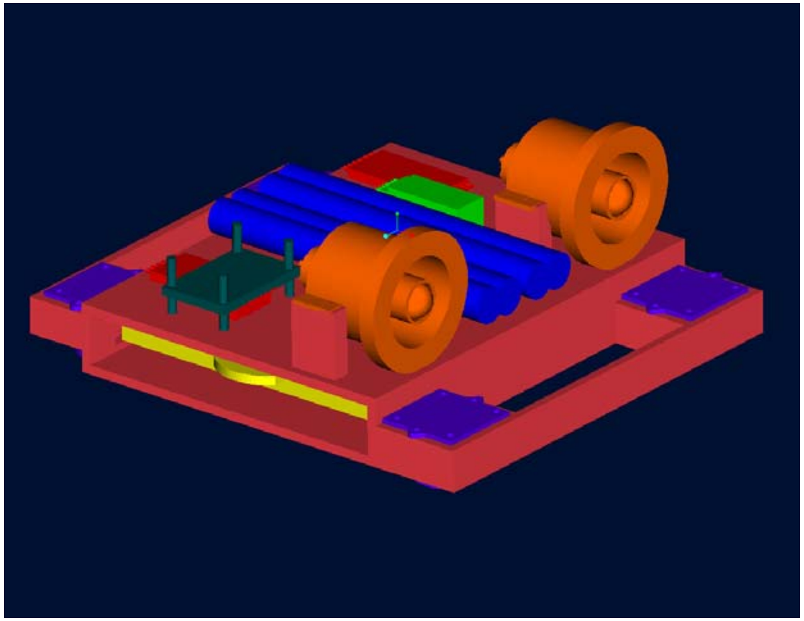
Future Physical Layout



- Vision computer broadcasts states of all vehicles via wireless ethernet (UDP)
- Command PC broadcasts individual or coordinated tasks
- Each vehicle has own control and communication

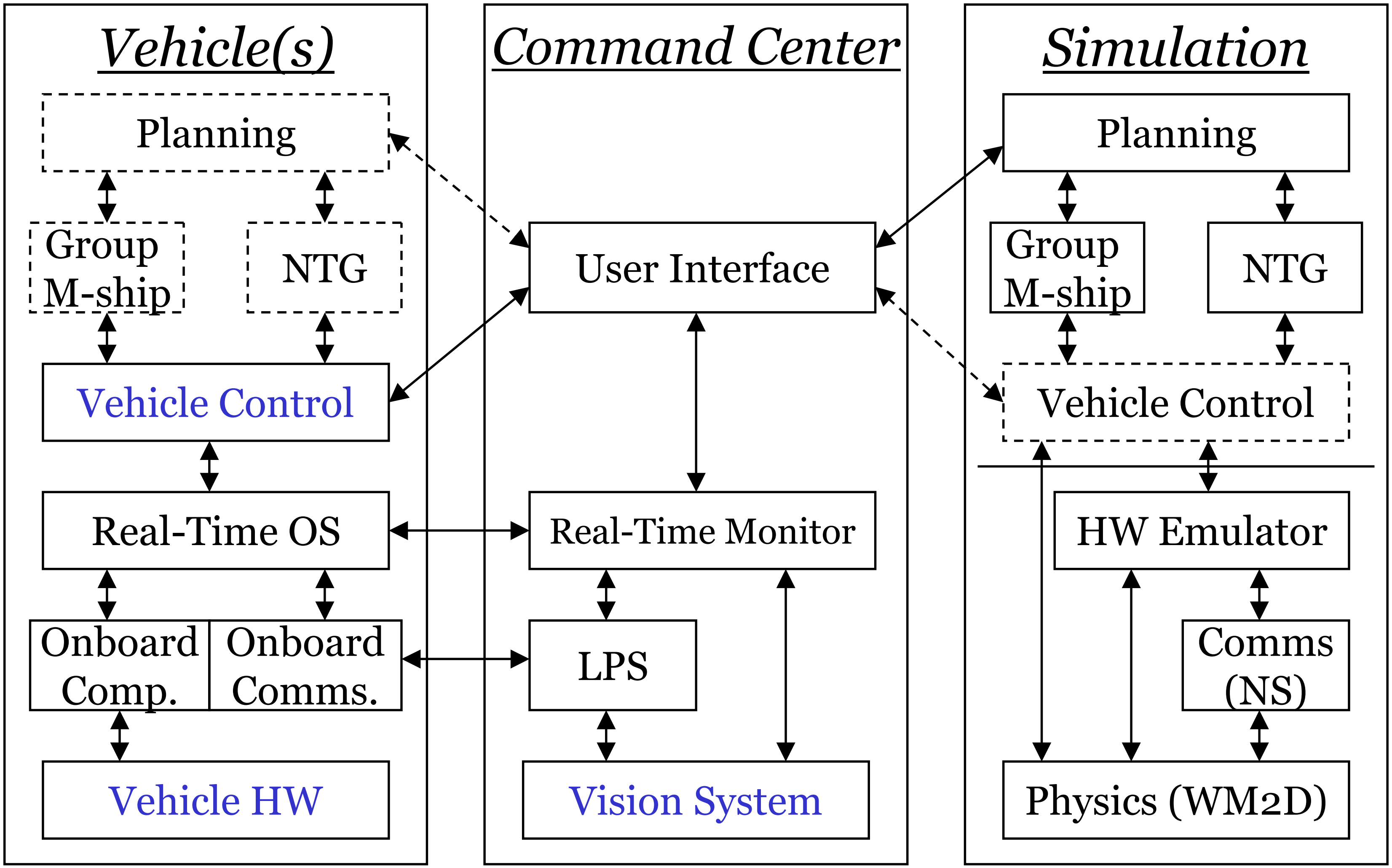
Next Generation Vehicle Design

- Smaller, lighter
- Remove radio control dependency
- On-board laptop processing for each vehicle
- Receive position data via wireless 802.11

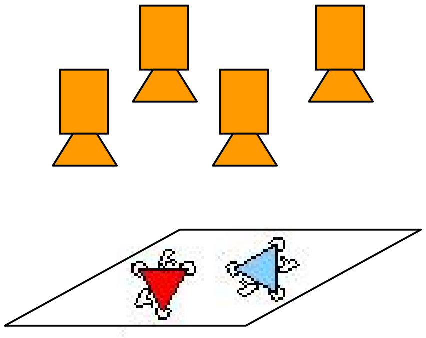


CAD courtesy of Kelly Klima

Project Structure

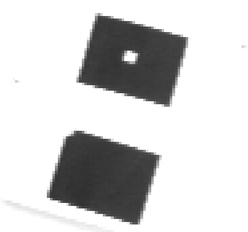


Vision System

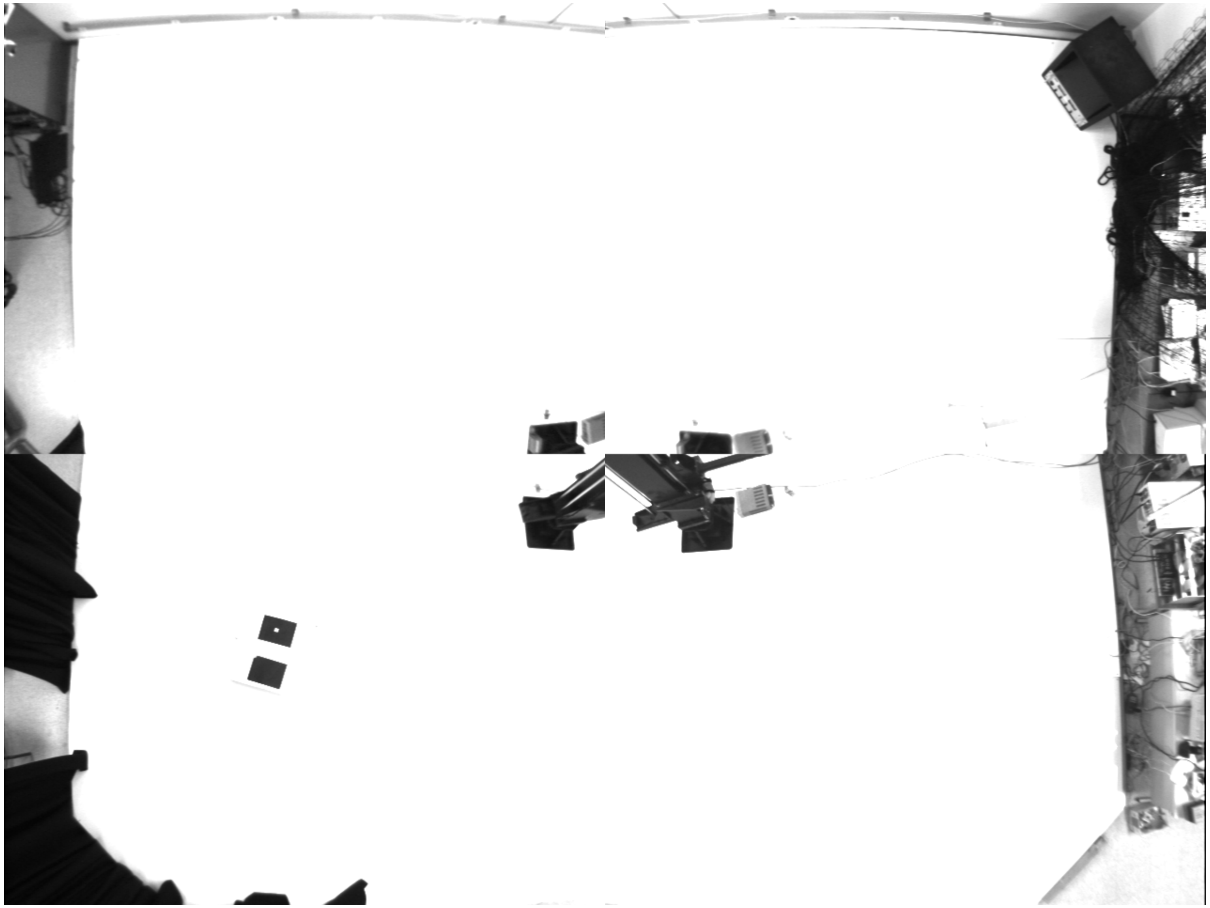


- Four monochrome 648x484 CCD cameras mounted on ceiling
- Four Matrox Genesis vision processing boards
- C++ code for processing, calibration and data broadcast via UDP
- Vehicles identified via blob analysis
- Calibration: J.Y. Bouguet's Calibration

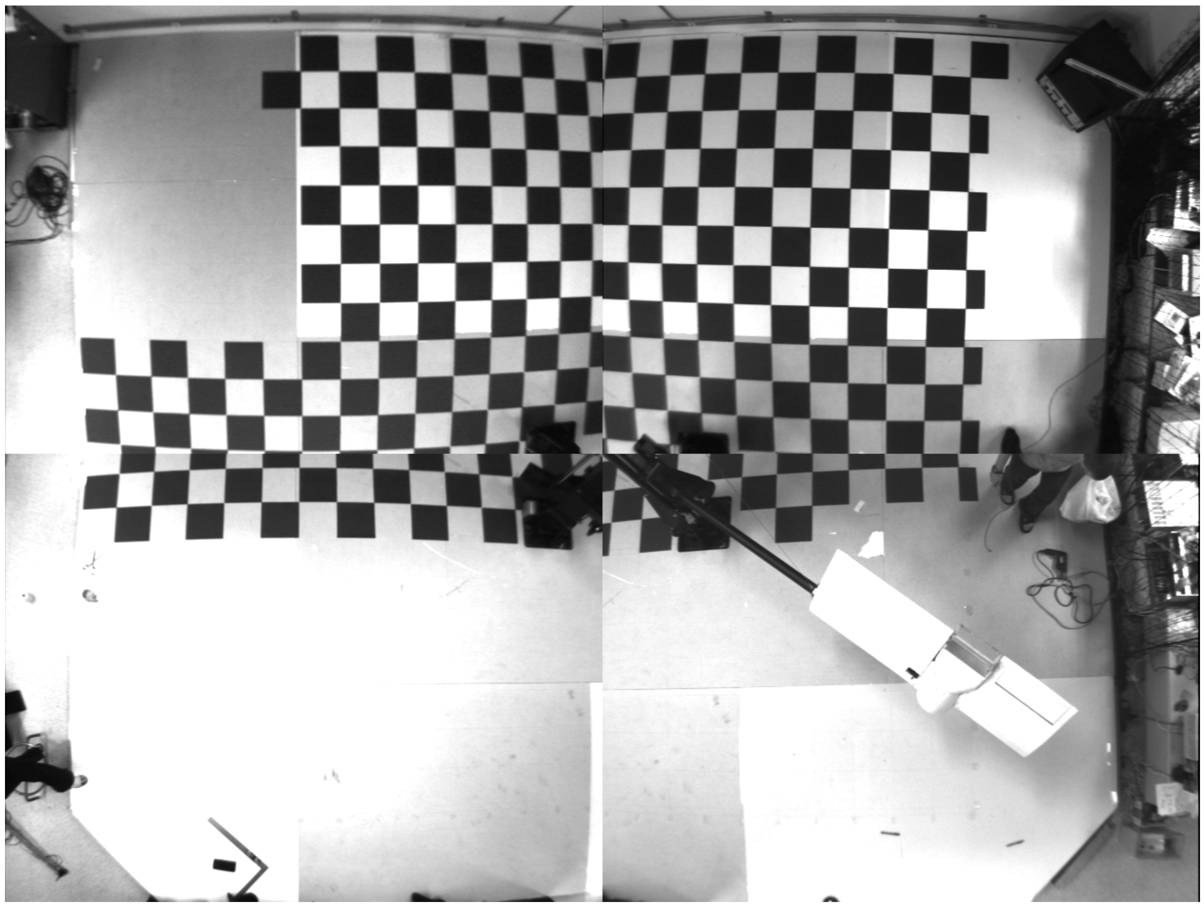
Toolbox, (Caltech vision lab)



Camera Image

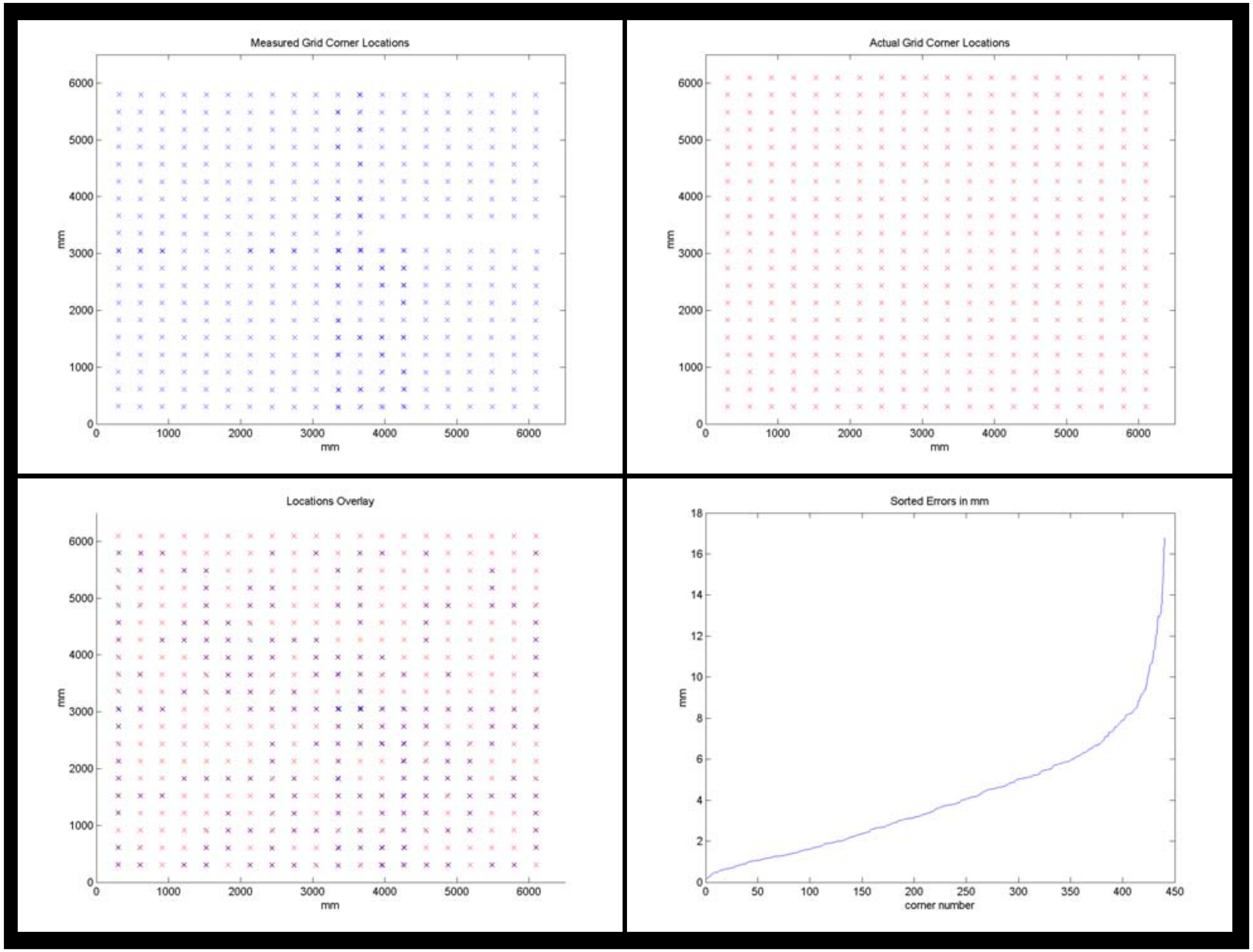


Vision Calibration



Vision Performance Specs

- 60 Hz
- 16.8mm max. calibration error
- 90% ≤ 8mm
- ~16msec latency

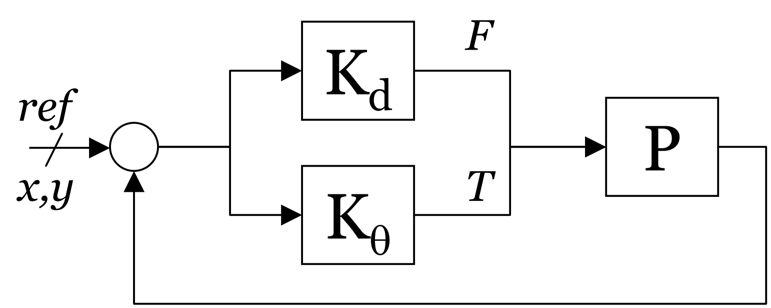


Simulation Environment

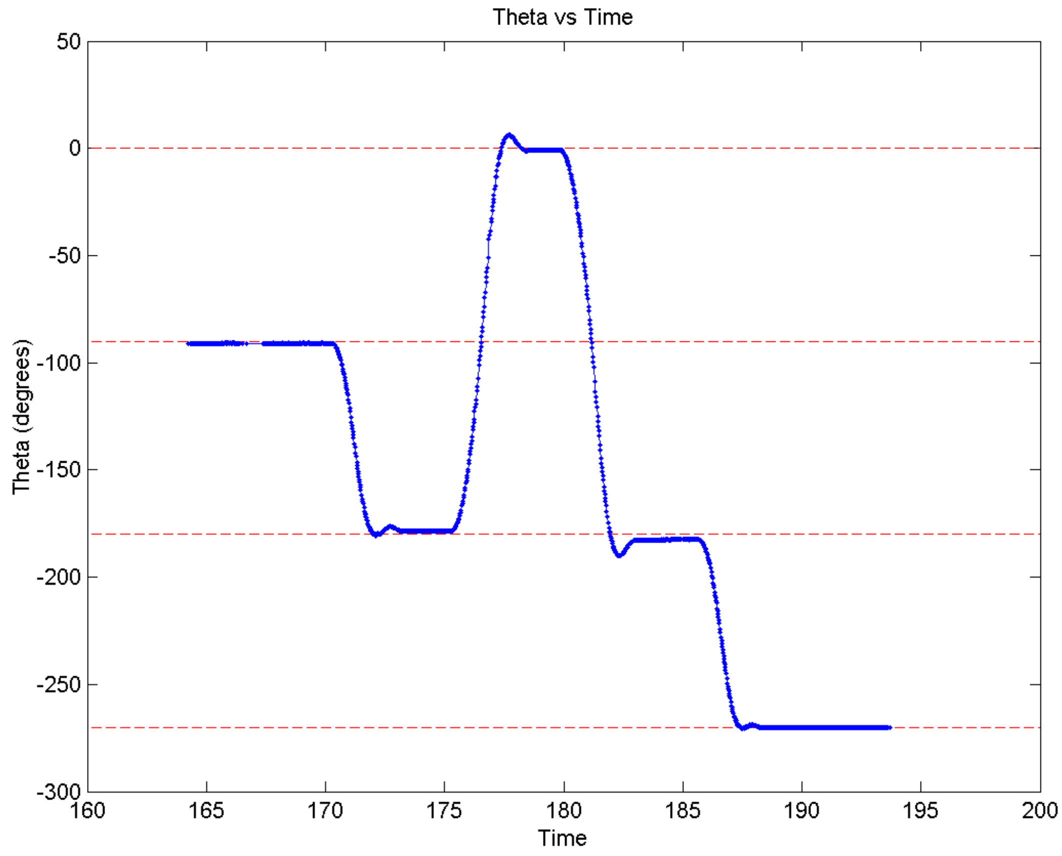
- Dynamic simulation by Working Model 2D
- DDE interface to MATLAB (and C/C++) for control design
- Collision detection/ handling

Initial Controller Design

- Two PID loops based on deconstructed state
- "Inner" loop preserves angle to target
- "Outer" loop attempts to regulate distance to target to zero
- Gain applied to outer loop depends on inner loop performance

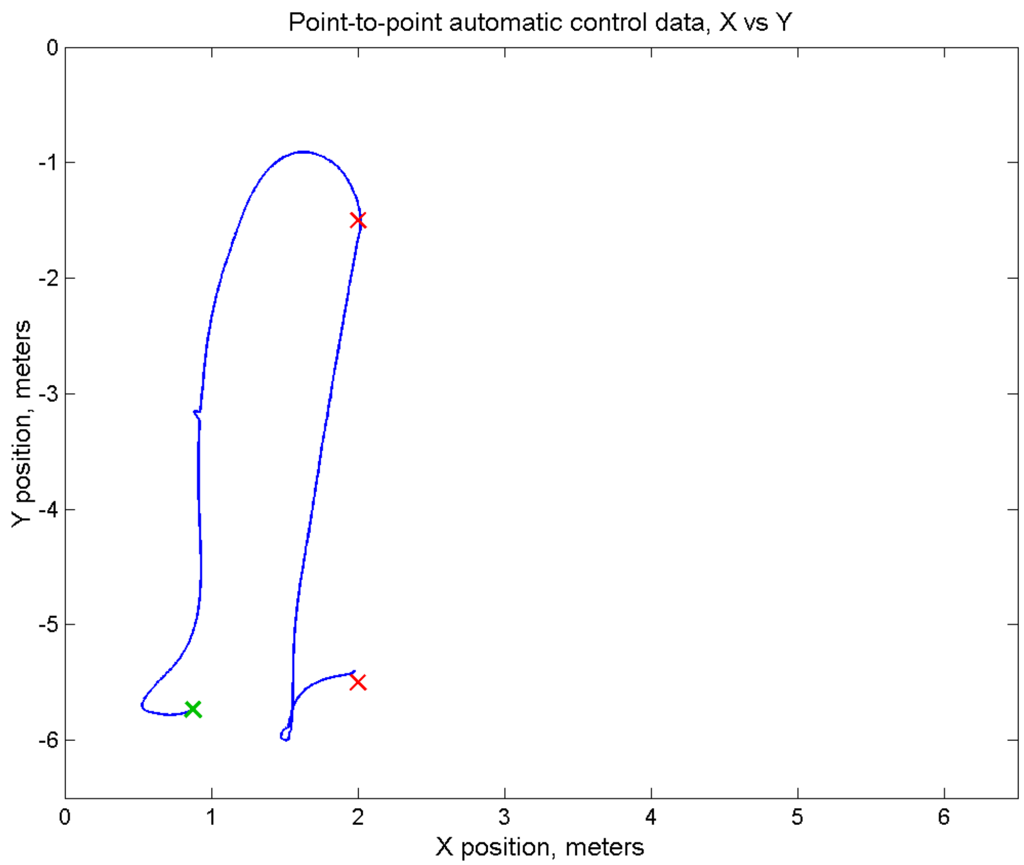
""

Initial data – Theta control



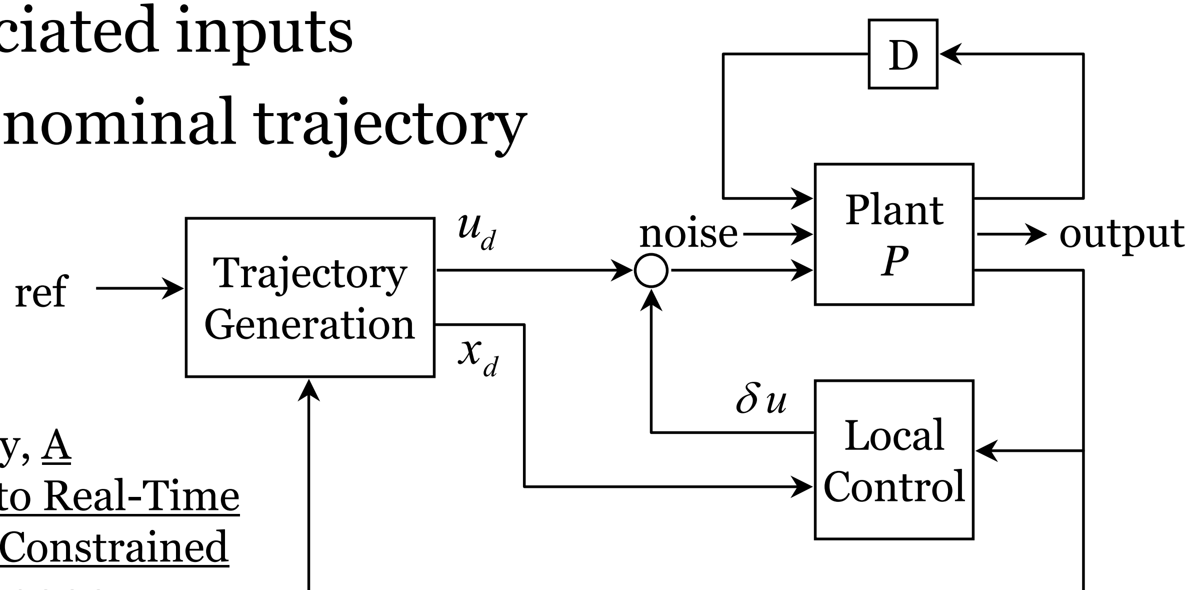
Movie – Point-to-point automatic control

Data – Point-to-point automatic control



Trajectory Tracking - Methodology

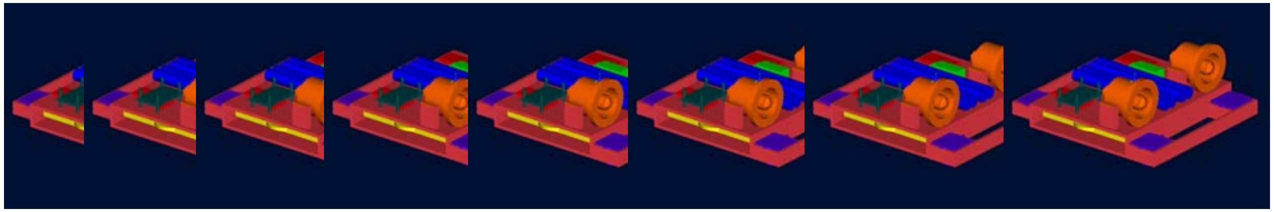
- More general framework for control
- Compute feasible trajectory in real-time
- Compute associated inputs
- Control about nominal trajectory



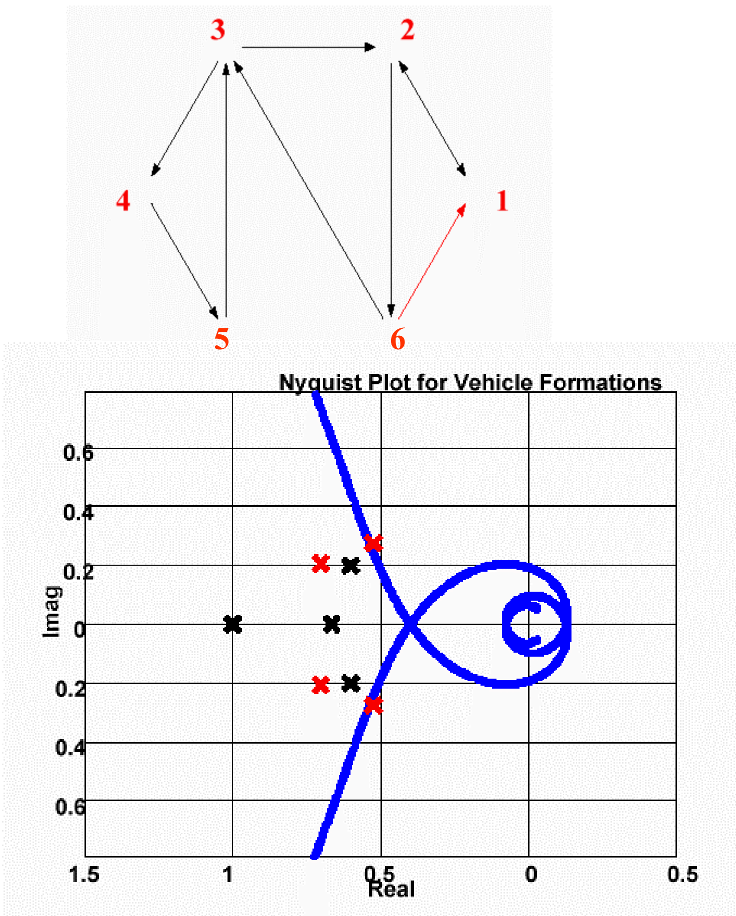
Reference:
Milam, Mushambi, Murray, A Computational Approach to Real-Time Trajectory Generation for Constrained Mechanical Systems, CDC 2000

Extension to Multiple Vehicles

- Currently two prototype vehicles built
  Eight next-generation vehicles planned
- Each vehicle, in general, will have knowledge of the states of itself and some subset of all other vehicles



Preliminary Graph Theory Results

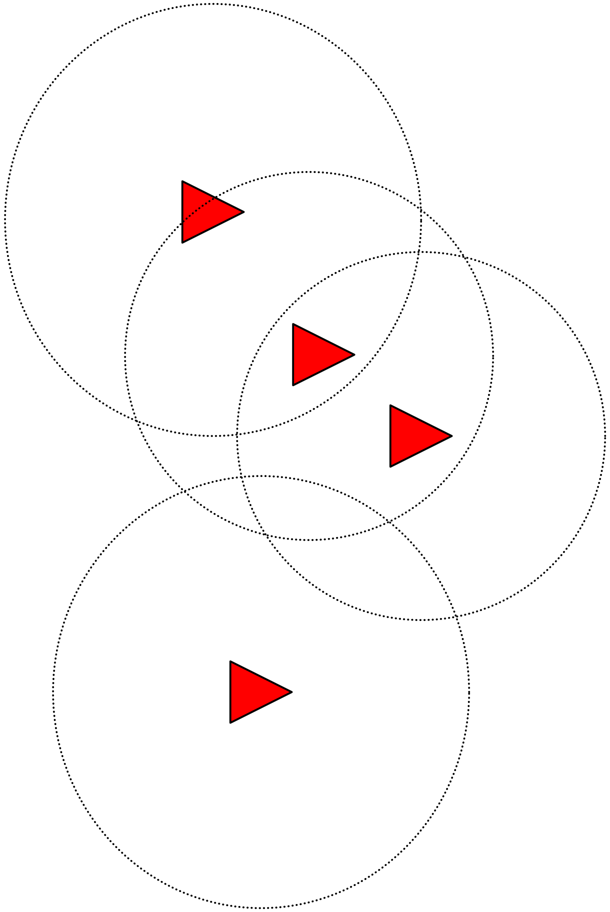


- Model information topology as a directed graph
- Changes in interconnection affect stability of configuration
- Nyquist-based criterion for formation stability

Reference: Fax, Murray; Information Flow and Cooperative Control of Vehicle Formations, IFAC 2002 submitted

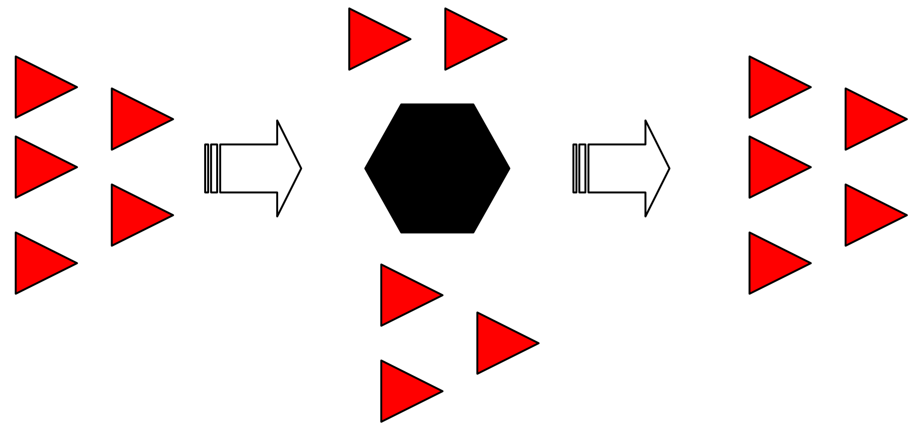
Inter-vehicle Communication

- Protocols for inter-vehicle communication in development
- Potential for use of both 802.11 and Bluetooth wireless communication
- Graph theoretic aspects extend to communicated information as well as sensed information

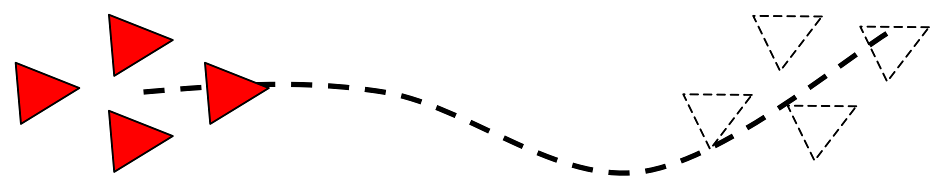


Benchmark Multi-Vehicle Tasks

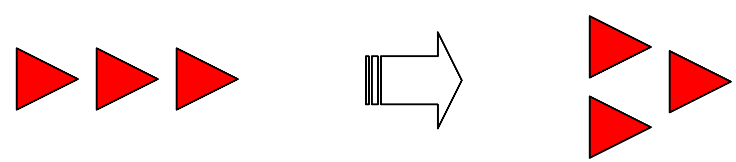
- Split/rejoin maneuvers



- Formation keeping while tracking a common trajectory



- Formation changing



Conclusions

- Have implemented reliable closed-loop control infrastructure for coordinated control of multiple vehicles…

…and Future Work

- advanced controller design
- next generation vehicle design
- trajectory generation/following
- multiple vehicle implementation for limited sensing network
- network protocol design for inter-vehicle communication
- testing new algorithms/strategies/theory