Specification, Design & Verification of Networked Control Systems

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California Institute of Technology

Caltech/AFRL Short Course

24-26 April 2012

Goals for the course:

- Review recent applications in "protocol-based" control systems
- Provide an overview of basic tools from computer science and control theory that can be used as a basis for further studies
- Review recent results in formal methods, logic synthesis, hybrid systems and receding horizon, temporal logic planning (RHTLP)
- Discuss open research problems and emerging control applications

Course Instructors

Richard M. Murray
Caltech

Education
- BS, Caltech, EE
- PhD UC Berkeley, EECS
- Professor, Caltech

Research interests
- Networked control
- Verification of distributed control systems
- Biological circuit design

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Education
- MS, UC Irvine, MAE
- PhD UC Berkeley, ME
- Postdoc, Caltech

Research interests
- Distributed embedded systems
- Uncertainty quantification and management
- Optimization/control of multiscale networked systems

Tichakorn (Nok) Wongpiromsarn

MIT/Singapore

Education
- BS, Cornell, ME
- PhD, Caltech, ME
- Postdoc, MIT/Singapore

Research interests
- Verification and synthesis of hybrid control systems

Comments on Style and Approach

Protocol-based control is an emerging research area

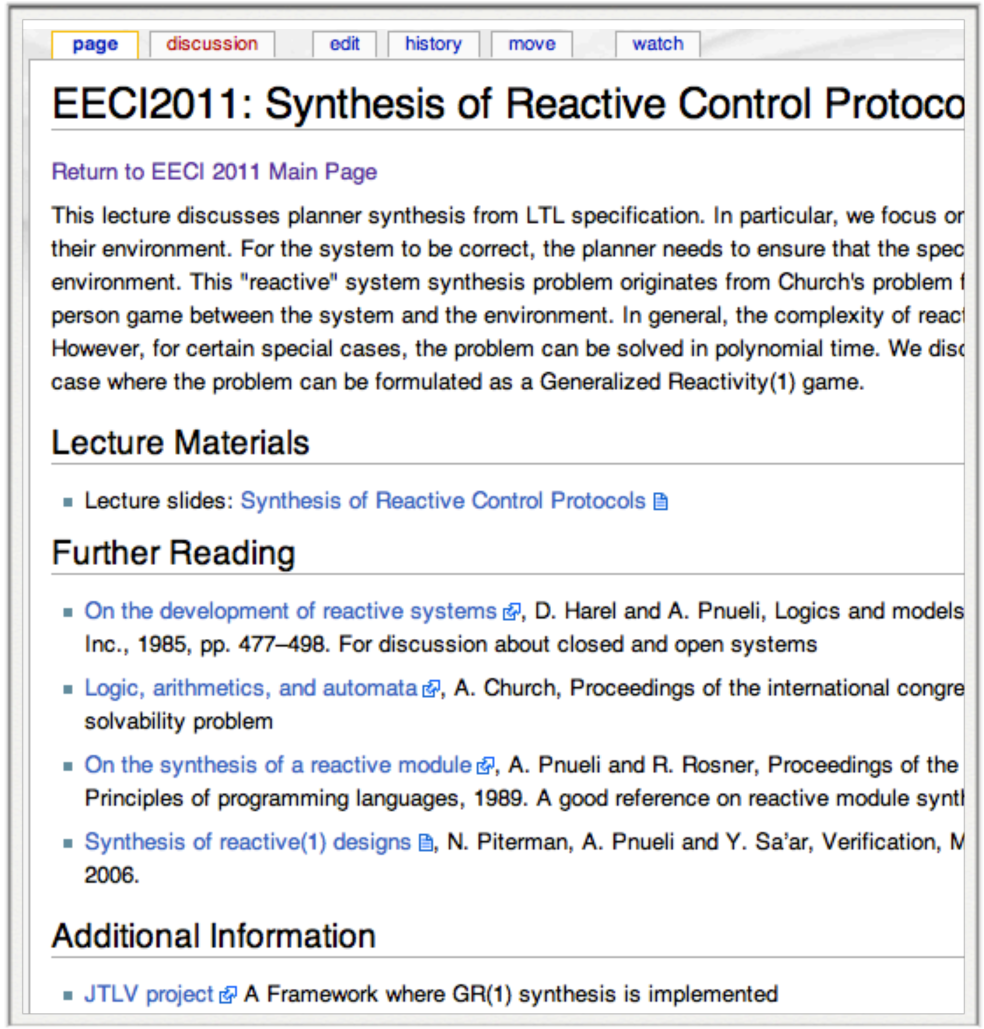
- Many results are new (in the last 5 years) and haven't yet been standardized
- Integration between different aspects of the research are a work in progress

Course uses new language and concepts

- Basic ideas will be familiar to control researchers: stability, reachability, simulations vs proofs, etc
- Much of the terminology will be strange (“$TS \models \Box(\neg b \rightarrow \Box(a \wedge \neg b))$”) => ask questions if you get lost

Lots of additional material online

- Additional references, web pages, etc are posted on the wiki pages
- Copies of slides/lecture notes available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EECI2011: Synthesis of Reactive Control Protoco

Return to EECI 2011 Main Page

This lecture discusses planner synthesis from LTL specification. In particular, we focus or
their environment. For the system to be correct, the planner needs to ensure that the spec
environment. This "reactive" system synthesis problem originates from Church's problem f
person game between the system and the environment. In general, the complexity of reac
However, for certain special cases, the problem can be solved in polynomial time. We disc
case where the problem can be formulated as a Generalized Reactivity(1) game.

Lecture Materials

- Lecture slides: Synthesis of Reactive Control Protocols

Further Reading

- On the development of reactive systems, D. Harel and A. Pnueli, Logics and models Inc., 1985, pp. 477–498. For discussion about closed and open systems
- Logic, arithmetics, and automata, A. Church, Proceedings of the international congre solvability problem
- On the synthesis of a reactive module, A. Pnueli and R. Rosner, Proceedings of the Principles of programming languages, 1989. A good reference on reactive module syntl
- Synthesis of reactive(1) designs, N. Piterman, A. Pnueli and Y. Sa'ar, Verification, M 2006.

Additional Information

- JTLV project A Framework where GR(1) synthesis is implemented

http://www.cds.caltech.edu/~murray/wiki/afrlcourse2012

Lecture Schedule

	Tue	Wed	Thu
8:30	L1: Intro to Protocol-Based Control Systems	**Computer Lab 1** Spin	L8: Receding Horizon Temporal Logic Planning
10:30	L2: Automata Theory	L5: Verification of Control Protocols	**Computer Lab 2** TuLiP
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Lecture 1: Introduction to Protocol-Based Control Systems

Richard M. Murray
Caltech Control and Dynamical Systems
24 April 2012

Goals:

- Describe current and emerging applications of networked control systems
- Discuss the role that control “protocols” play in NCS
- Provide an overview into what we will learn in the course

Reading:

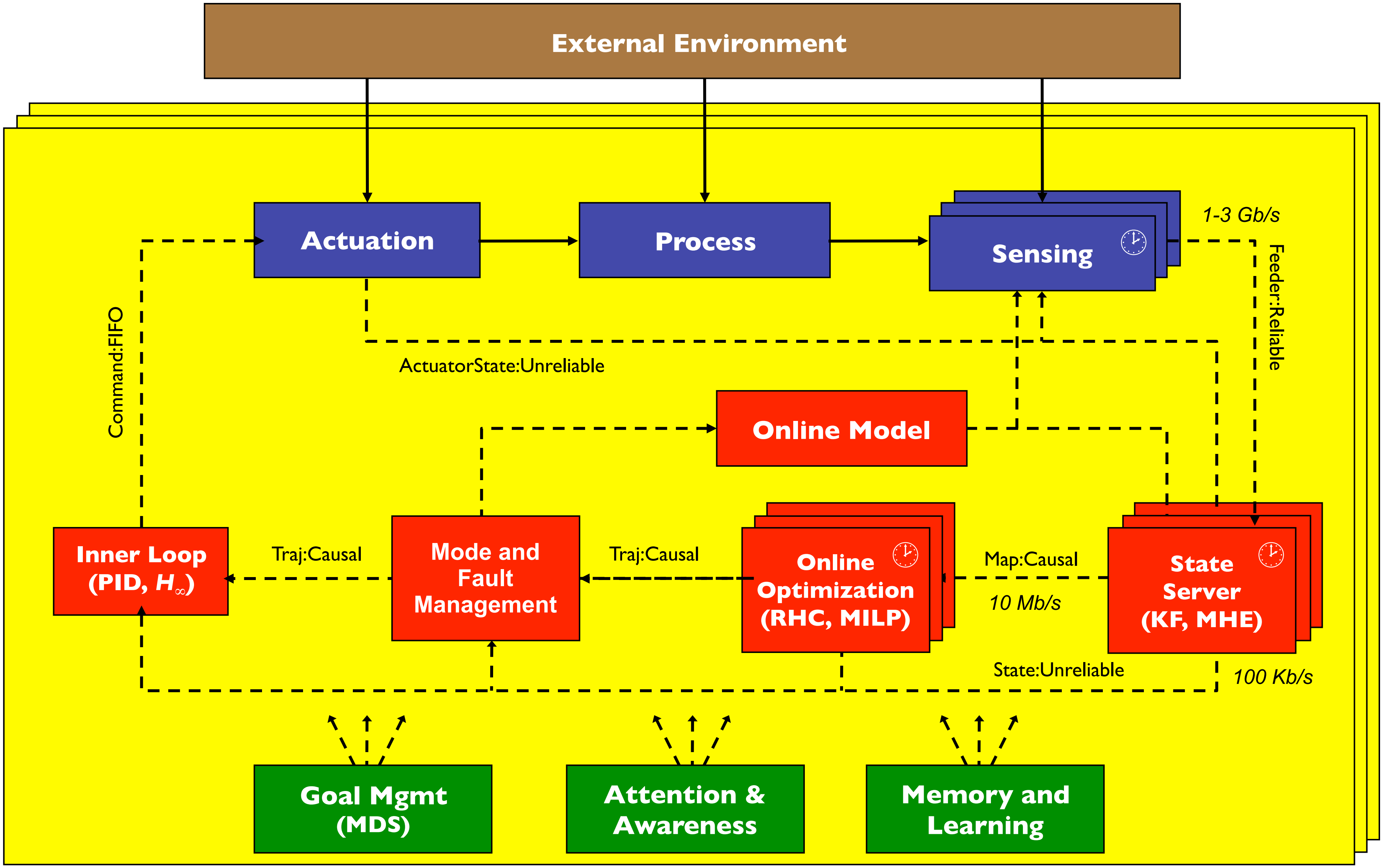
- Control in an Information Rich World, Sections 1, 3.2 and 3.3
- Sensing, Navigation and Reasoning Technologies for the DARPA Urban Challenge, 2007

Available on course wiki page

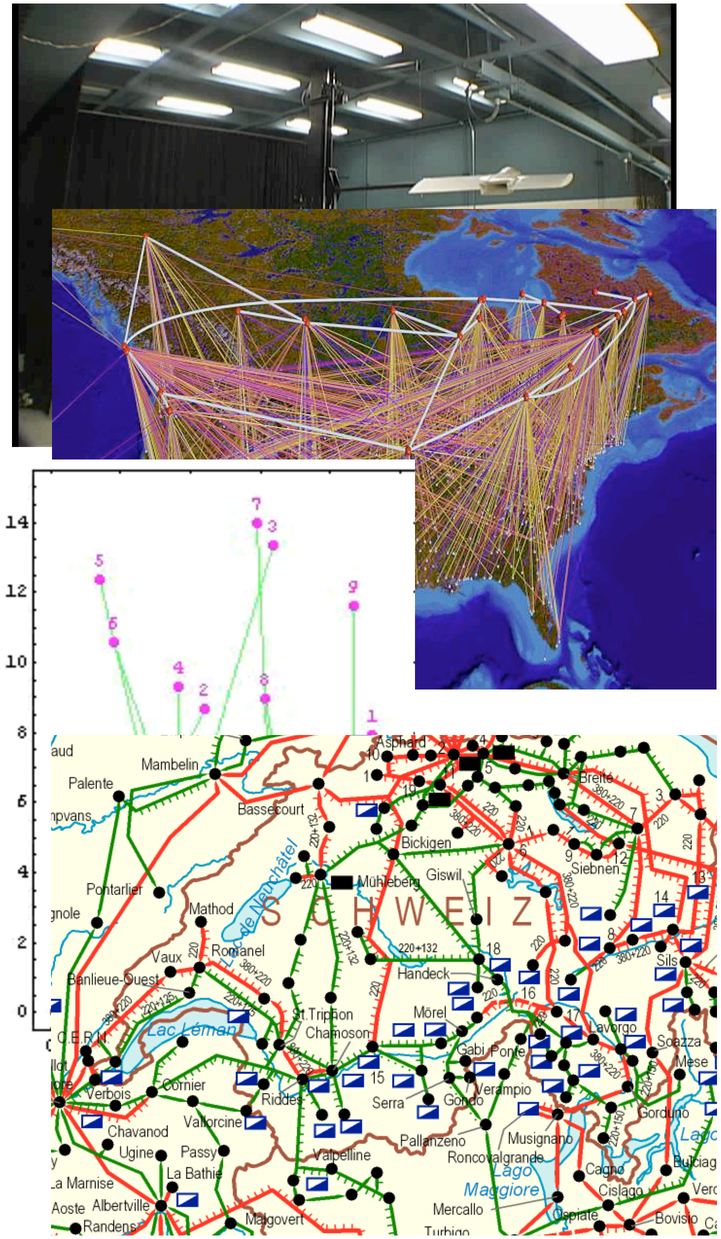
http://www.cds.caltech.edu/~murray/wiki/afrlcourse2012

Networked Control Systems

(following P. R. Kumar)



Some Important Trends in Control in the Last Decade



(Online) Optimization-based control

- Increased use of online optimization (MPC/RHC)
- Use knowledge of (current) constraints & environment to allow performance and adaptability

Layering and architectures

- Command & control at multiple levels of abstraction
- Modularity in product families via layers

Formal methods for analysis, design and synthesis

- Combinations of continuous and discrete systems
- Formal methods from computer science, adapted for hybrid systems (mixed continuous & discrete states)

Components → Systems → Enterprise

- Movement of control techniques from “inner loop” to “outer loop” to entire enterprise (eg, supply chains)
- Use of *systematic* modeling, analysis and synthesis techniques at all levels
- Integration of “software” with “controls” (Internet of things, cyber-physical systems, etc)

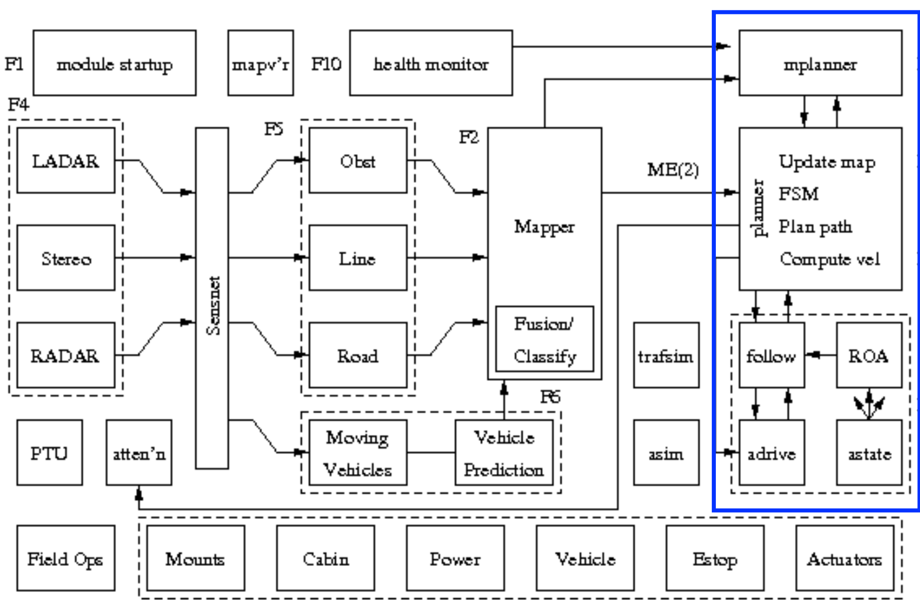
Motivating Example: Alice (DGC07)

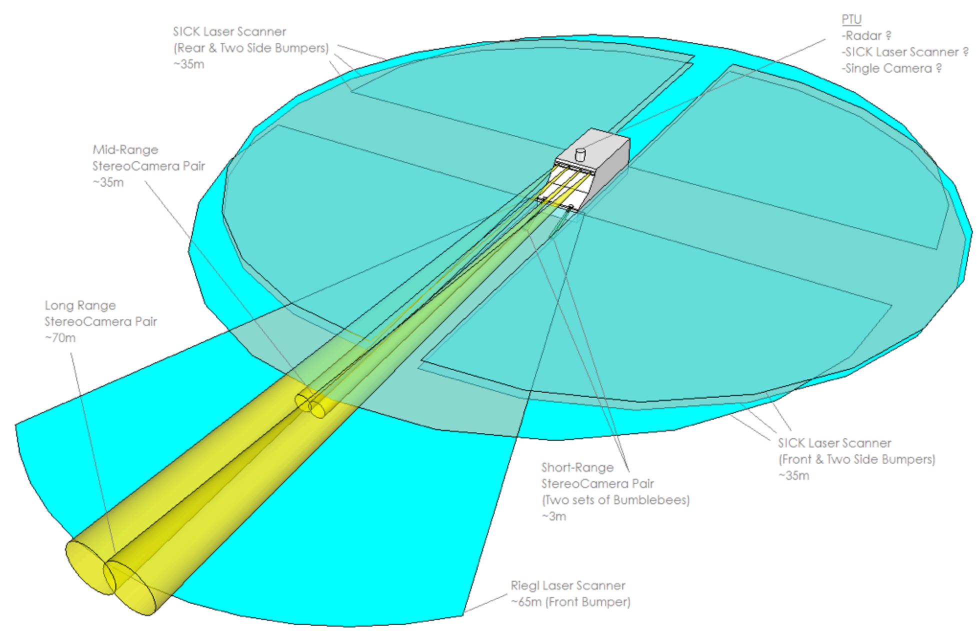
Alice

- 300+ miles of fully autonomous driving
- 8 cameras, 8 LADAR, 2 RADAR
- 12 Core 2 Duo CPUs + Quad Core
- ~75 person team over 18 months

Software

- 25 programs with ~200 exec threads
- 237,467 lines of executable code





Planner Stack

Burdick et al, 2007

Mission Planner performs high level decision-making

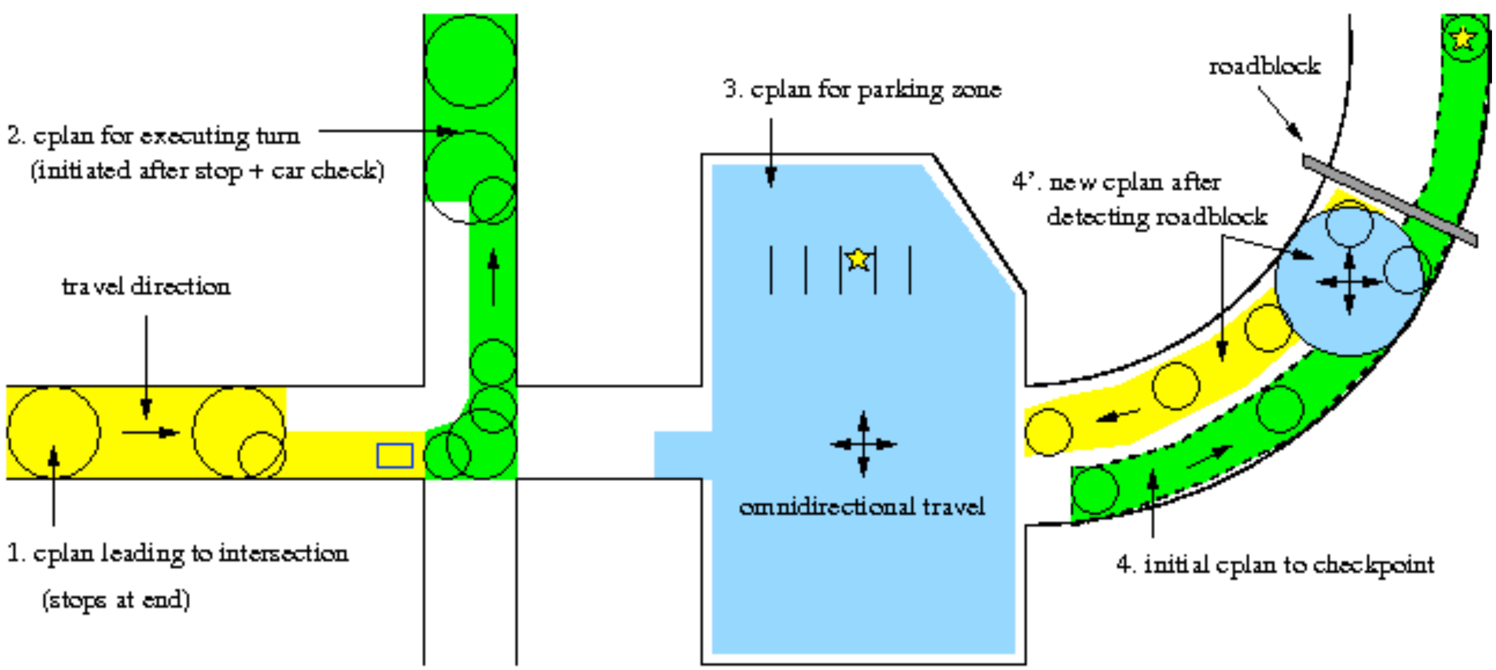
- Graph search for best routes; replan if routes are blocked

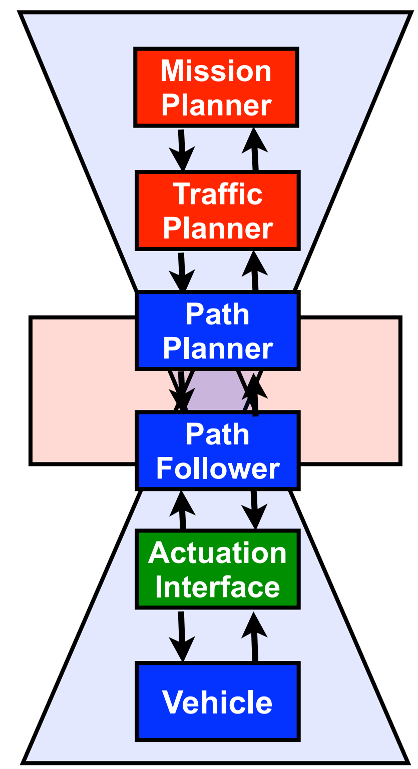
Traffic Planner handles rules of the road

- Control execution of path following & planning (multi-point turns)
- Encode traffic rules - when can we change lanes, proceed thru intersection, etc

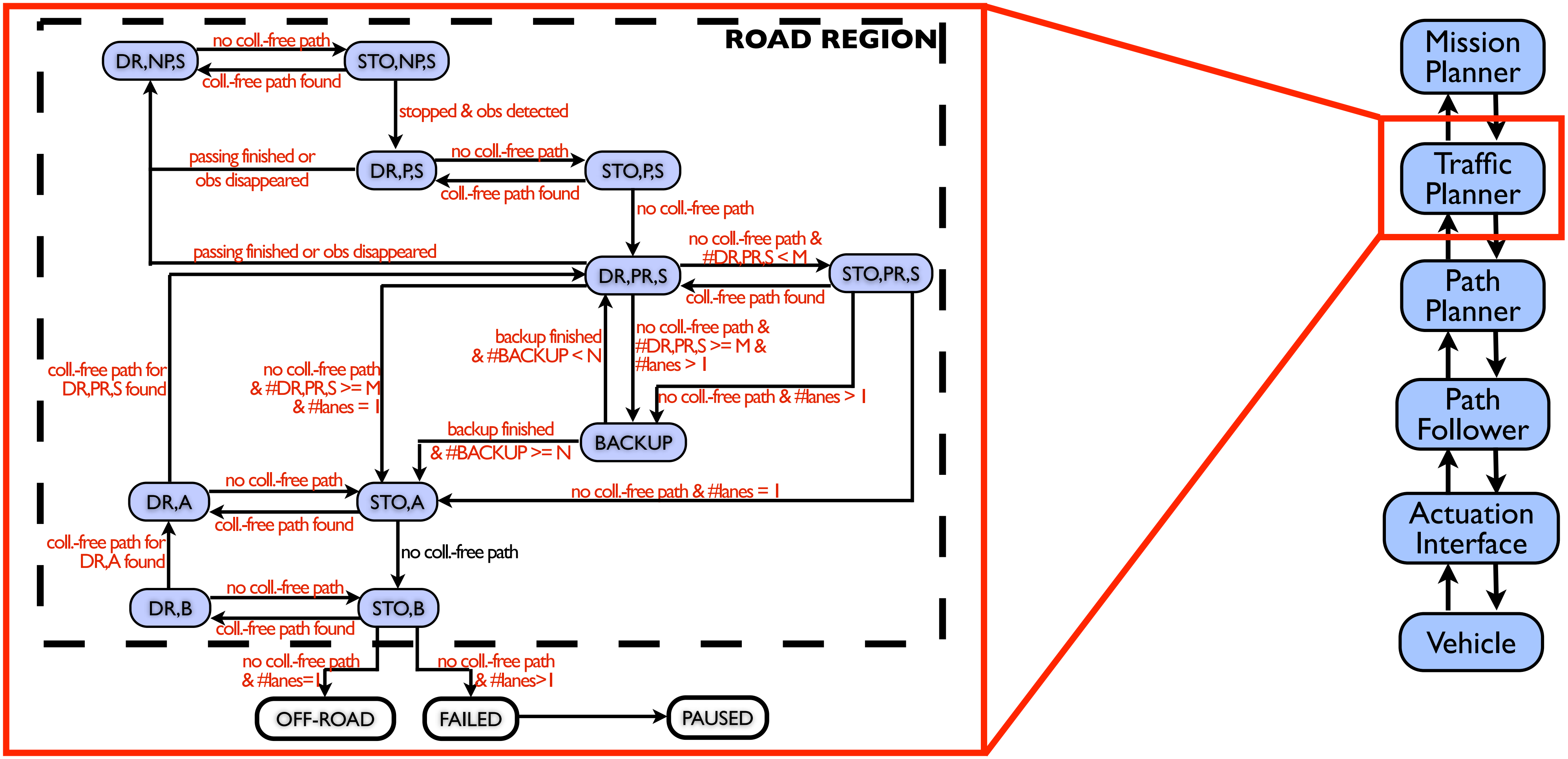
Path Planner/Path Follower generate trajectories and track them

- Optimized trajectory generation + PID control (w/ anti-windup)
- Substantial control logic to handle failures, command interface, etc





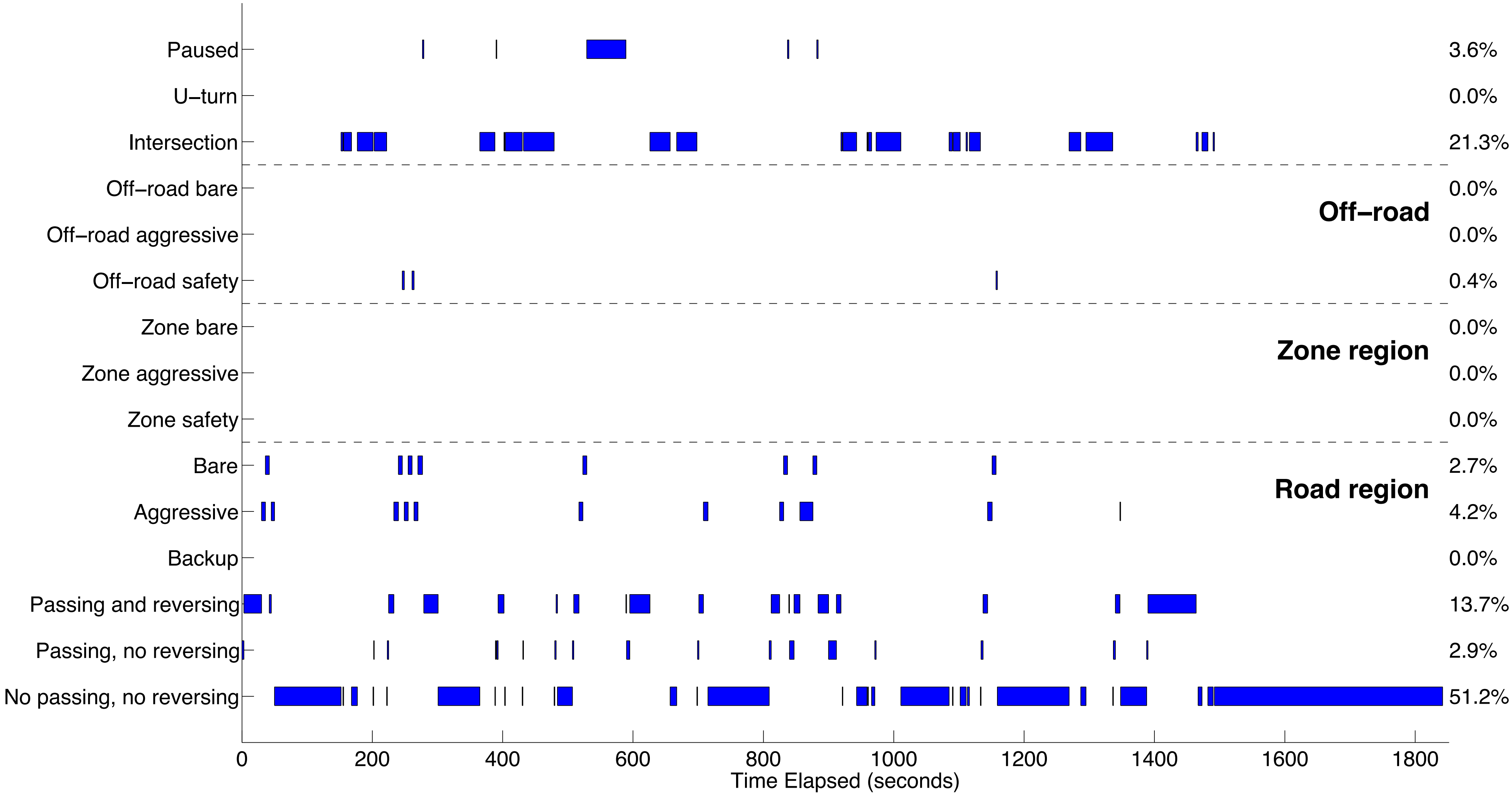
Traffic Planner Logic



Goal: move from verification of human-designed FSA (hard!) to synthesis

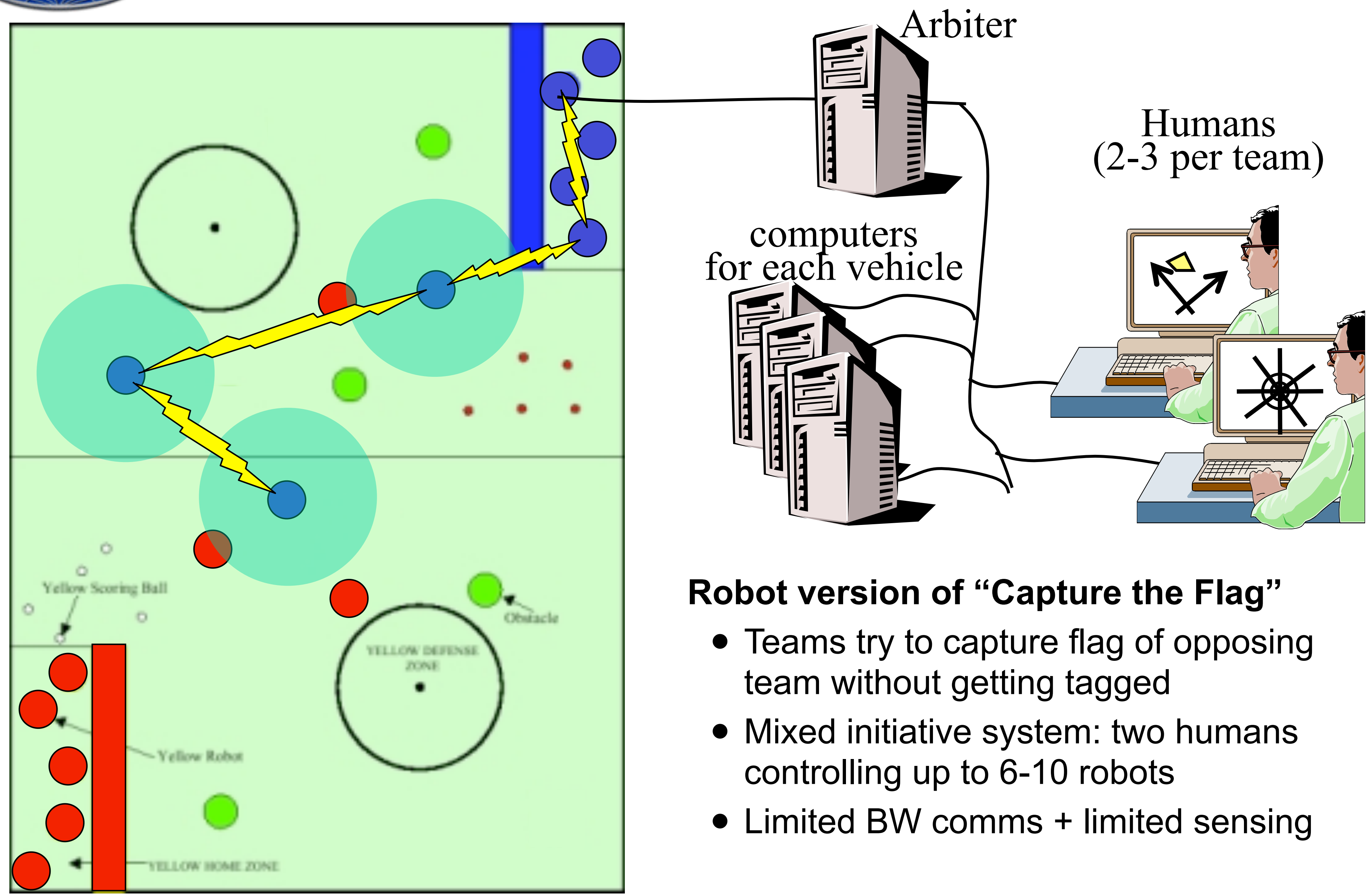
- Given specification + model of the environment, can we produce the FSA?
- Key enabler: new tools in logic synthesis (eg, Kress-Gazit & Pappas, Sa'ar)

Mode Transitions



D’Andrea & M
ACC 2003

Example: RoboFlag (D’Andrea, Cornell)

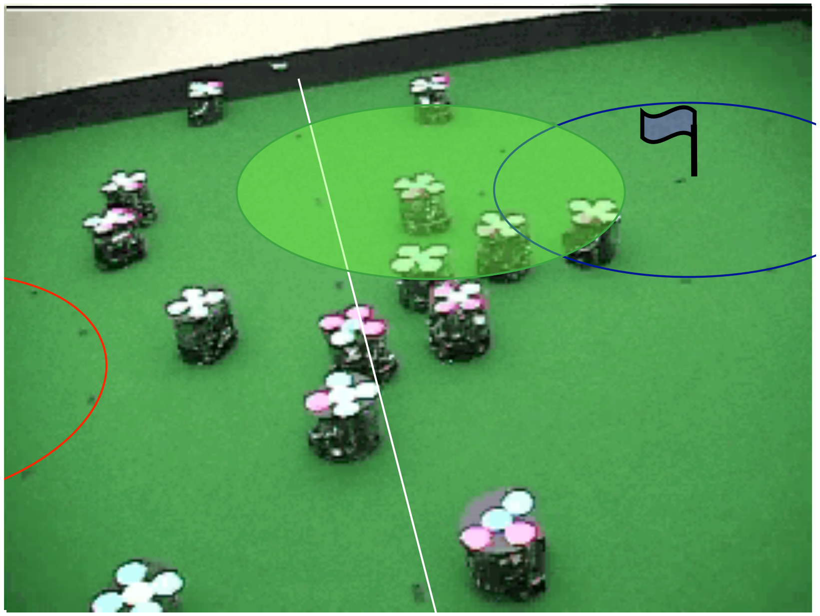


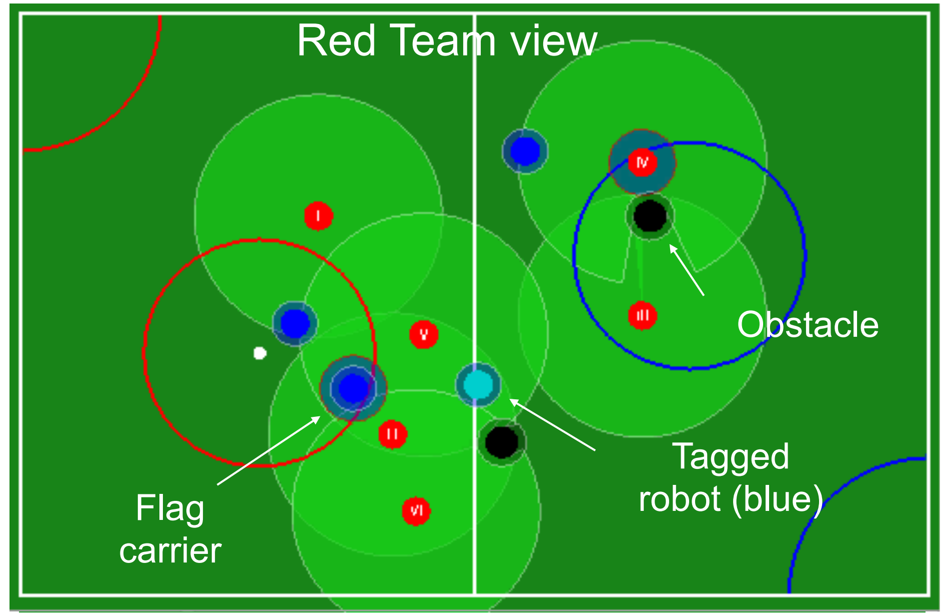
Robot version of “Capture the Flag”

- Teams try to capture flag of opposing team without getting tagged
- Mixed initiative system: two humans controlling up to 6-10 robots
- Limited BW comms + limited sensing

Hayes et al
ACC 2003

RoboFlag Demonstration





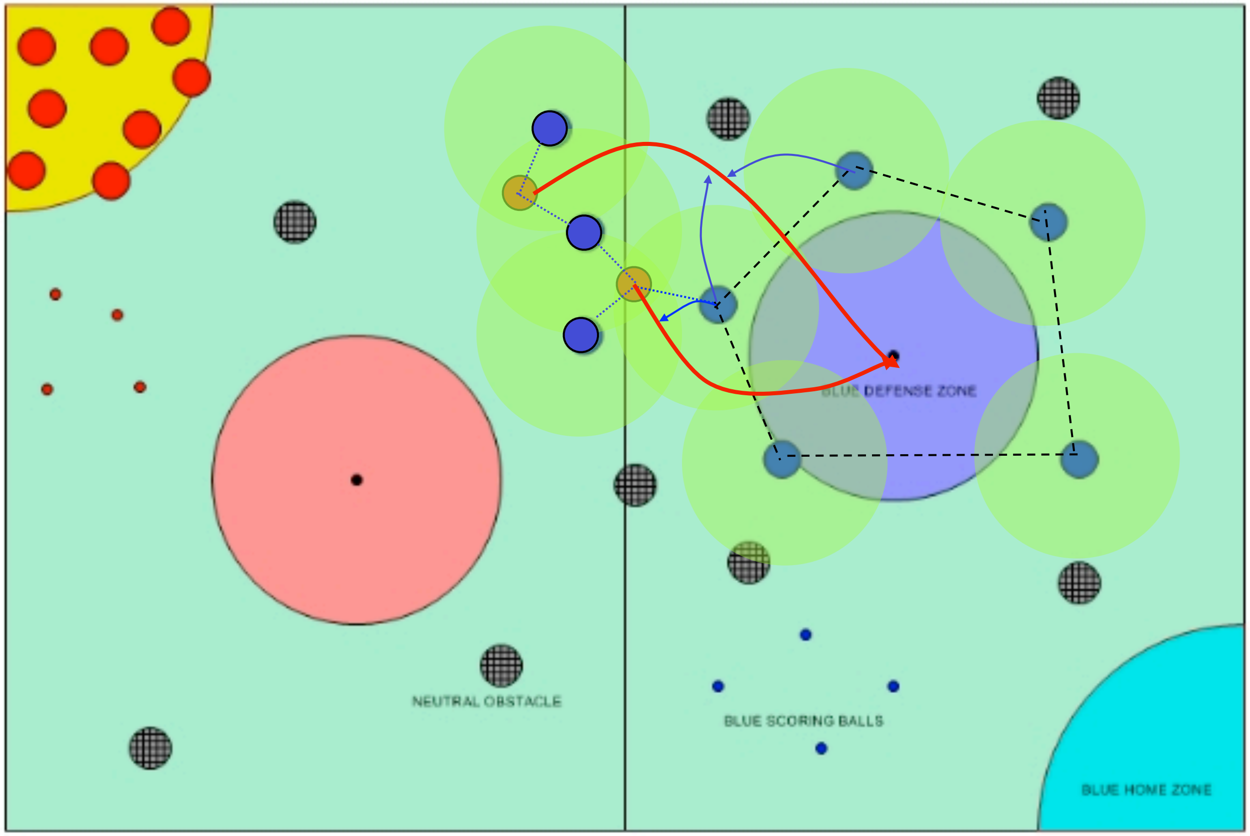
Integration of computer science, communications, and control

- Time scales don't allow standard abstractions to isolate disciplines
- Example: how do we maintain a consistent, shared view of the field?

Higher levels of decision making and mixed initiative systems

- Where do we put the humans in the loop? what do we present to them?
- Example: predict "plays" by the other team, predict next step, and react

RoboFlag Subproblems



1. Formation control

- Maintain positions to guard defense zone

2. Distributed estimation

- Fuse sensor data to determine opponent location

3. Distributed consensus

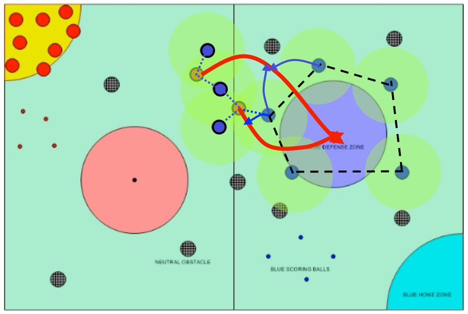
- Assign individuals to tag incoming vehicles

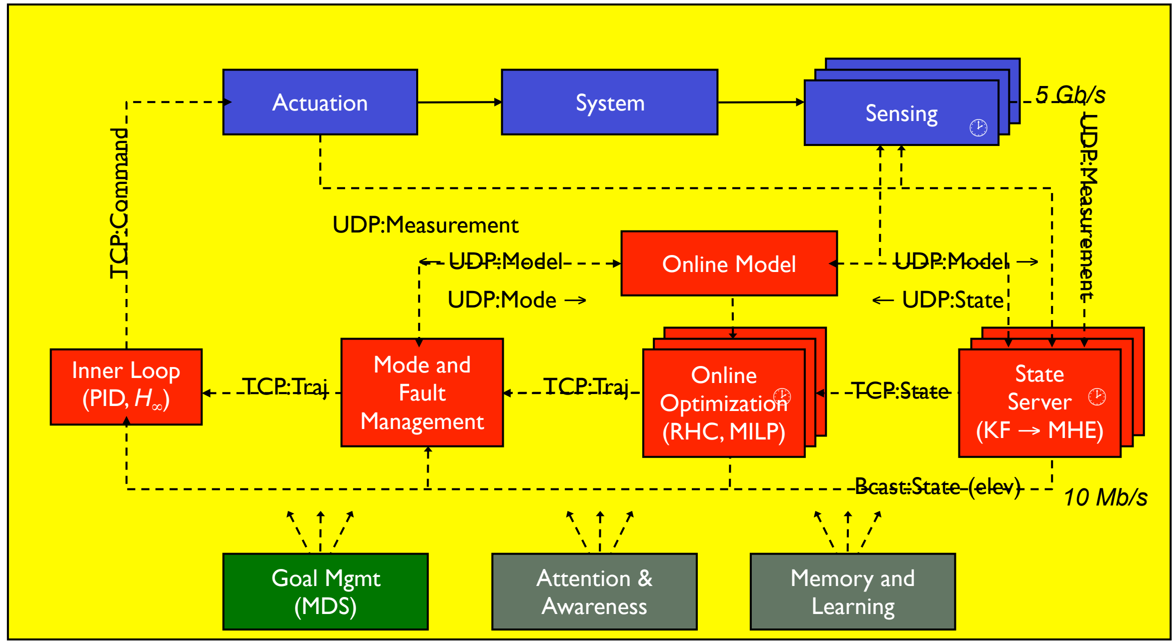
Goal: develop systematic techniques for solving subproblems

- Cooperative control and graph Laplacians
- Distributed estimation and sensor fusion
- Distributed receding horizon control
- Packet-based estimation and control
- Verifiable protocols for consensus and control

→ Implement and test as part of annual RoboFlag competition

Summary: Protocol-Based Control Systems





Control Challenges

- How should we distribute computing load burden between computers?
- How should we handle communication limits and dropped packets?
- How do multiple computers cooperate in a shared task (with common view)?
- What types of protocols should we use for making correct (safe) decisions?

Specification

- How do we describe correct behavior?

Design

- What tools can we use to design protocols to implement that behavior?

Verification

- How do we know if it is actually correct?

Synthesis

- Can we generate protocols from specs?

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