Lecture 14: Future Research in Networked Control Systems

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Goals:

- Summarize (semi-) recent reports on future directions in control
- Discuss open areas of research in networked control systems

Reading:

- http://www.cds.caltech.edu/~murray/cdspanel
- http://www.cds.caltech.edu/~murray/topten

Control in an Information Rich World

1. Executive Summary

2. Overview of the Field

- What is Control?
- Control System Examples
- Increasing Role of Information-Based Systems
- Opportunities and Challenges

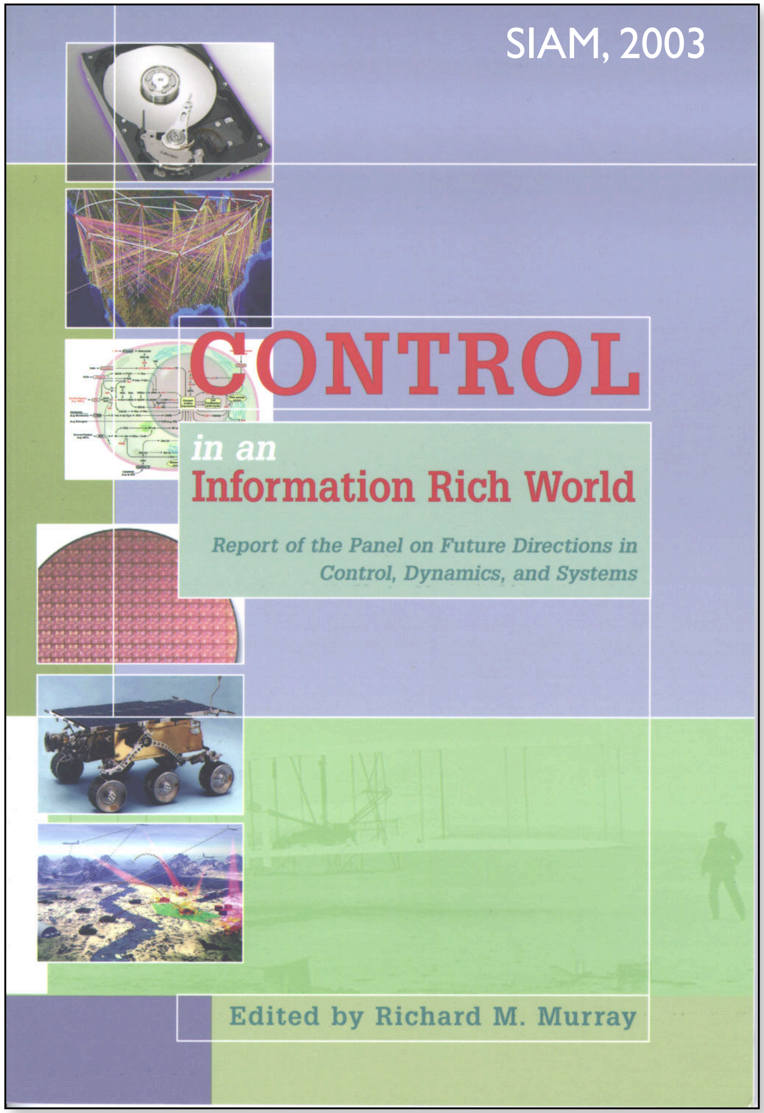
3. Applications, Opportunities & Challenges

- Aerospace and Transportation
- Information and Networks
- Robotics and Intelligent Machines
- Biology and Medicine
- Materials and Processing
- Other Applications

4. Education and Outreach

5. Recommendations

SIAM, 2003



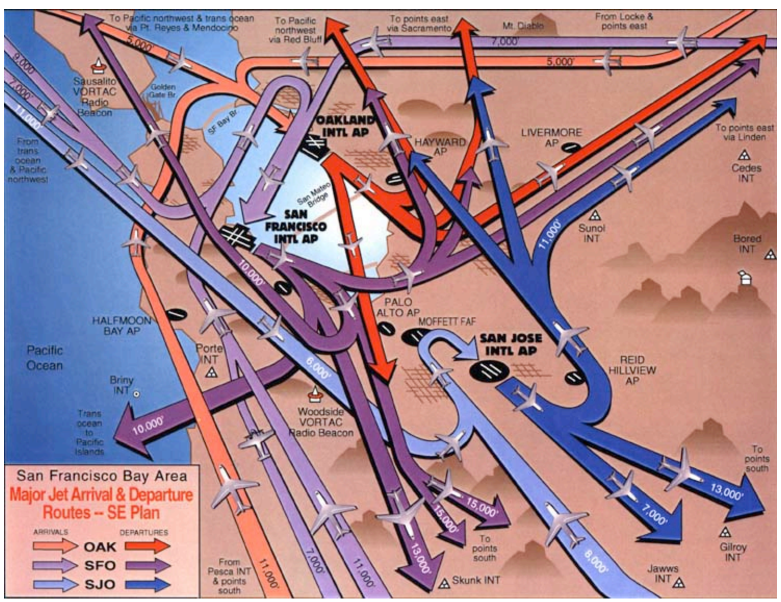
Transportation and Aerospace

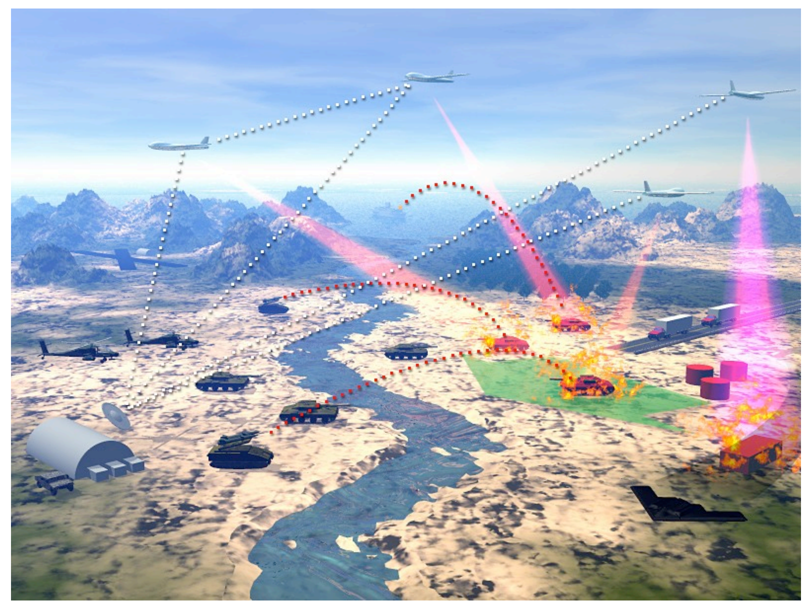
Themes

- Autonomy
- Real-time, global, dynamic networks
- Ultra-reliable embedded systems
- Multi-disciplinary teams
- Modeling for control
  - more than just $\dot{x} = f(x, u, p, w)$
  - analyzable accurate hybrid models

Technology Areas

- Air traffic control, vehicle management
- Mission/multi-vehicle management
- Command & control, human in the loop
- Ground traffic control (air & ground)
- Automotive vehicle & engine control
- Space vehicle clusters
- Autonomous control for deep space





Information and Networks

Pervasive, ubiquitous, convergent networking

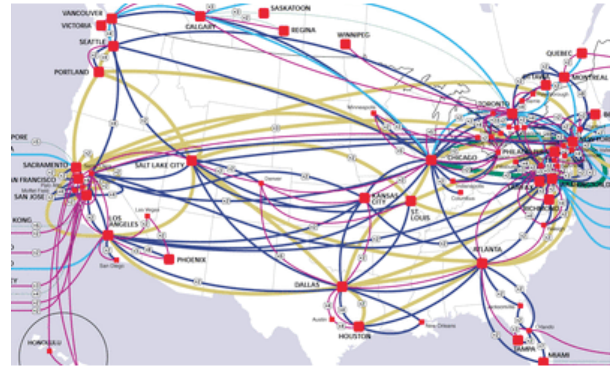
- Heterogeneous networks merging communications, computing, transportation, finance, utilities, manufacturing, health, entertainment, ...
- Robustness/reliability are dominant challenges
- Need “unified field theory” of communications, computing, and control

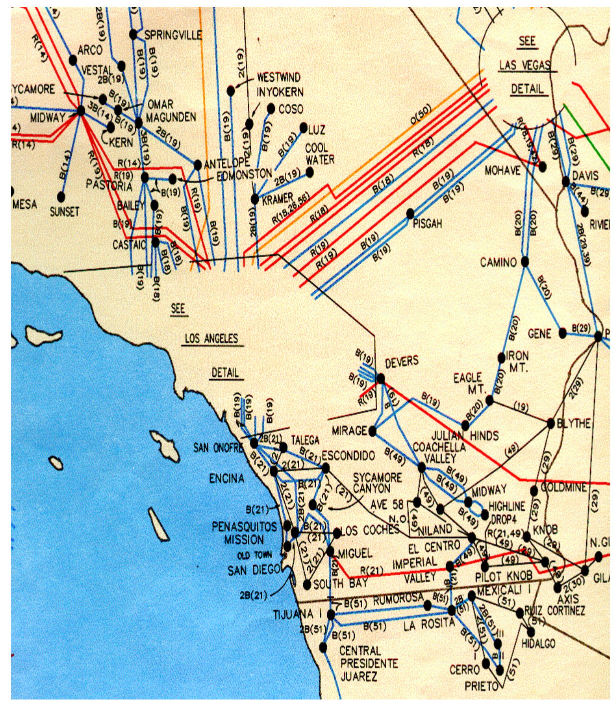
Many applications

- Congestion control on the internet
- Power and transportation systems
- Financial and economic systems
- Quantum networks and computation
- Biological regulatory networks and evolution
- Ecosystems and global change

Control <u>of</u> the network

Control <u>over</u> the network





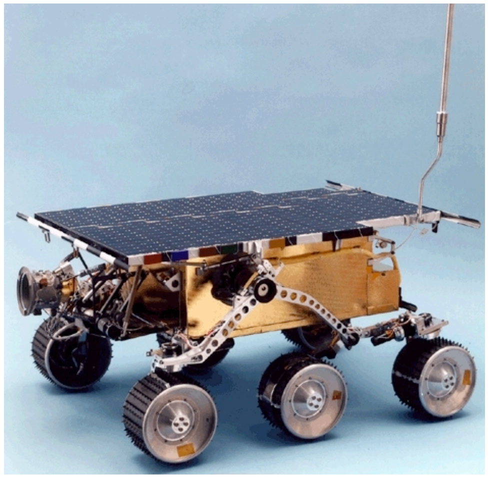
Robotics and Intelligent Machines

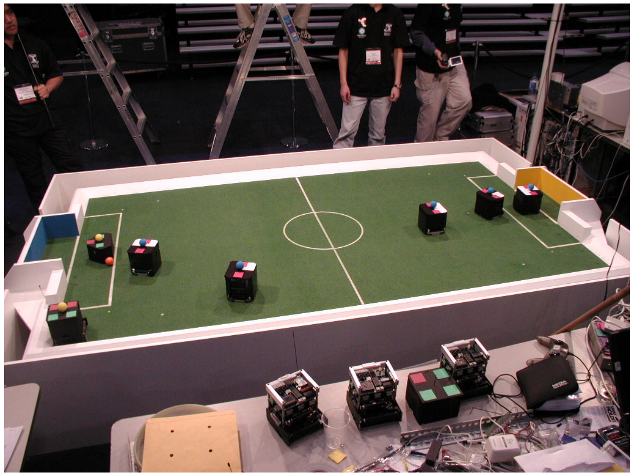
Wiener, 1948: Cybernetics

- Goal: implement systems capable of exhibiting highly flexible or ``intelligent'' responses to changing circumstances

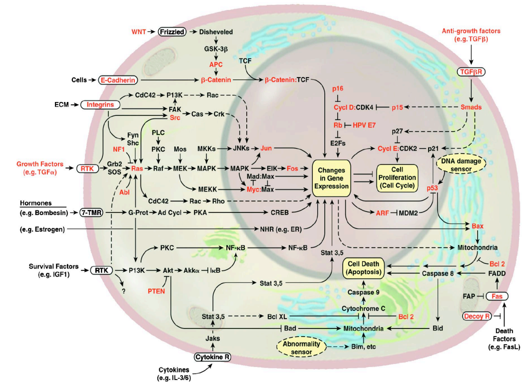
DARPA, 2003: Grand Challenge

- LA to Las Vegas (400 km) in 10 hours or less
- Goal: implement systems capable of exhibiting highly flexible or ``intelligent'' responses to changing circumstances



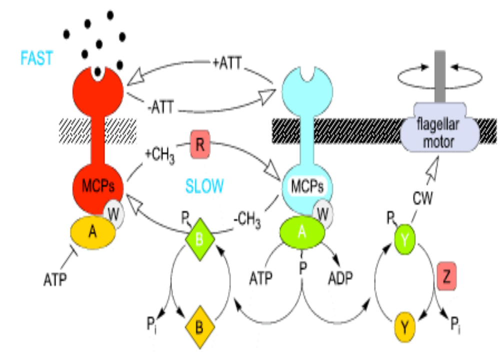


Biology and Medicine



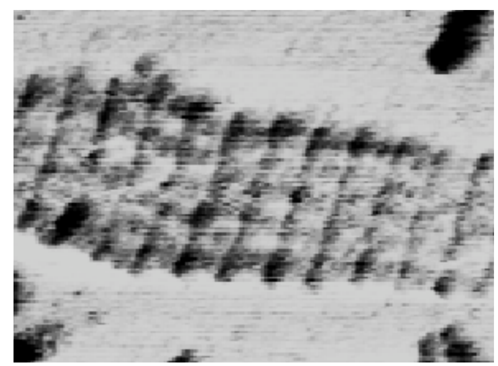
"Systems Biology"

- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical, fluid, and structural elements



Key features of biological systems

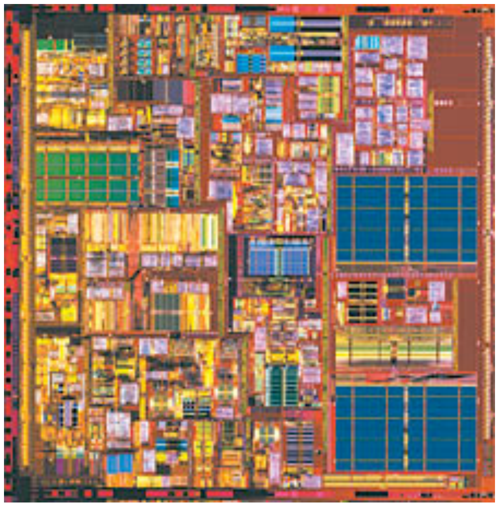
- Integrated control, communications, computing
- Reconfigurable, distributed control, at *molecular* level



Design and analysis of biological systems

- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow of information is key

Materials and Processing

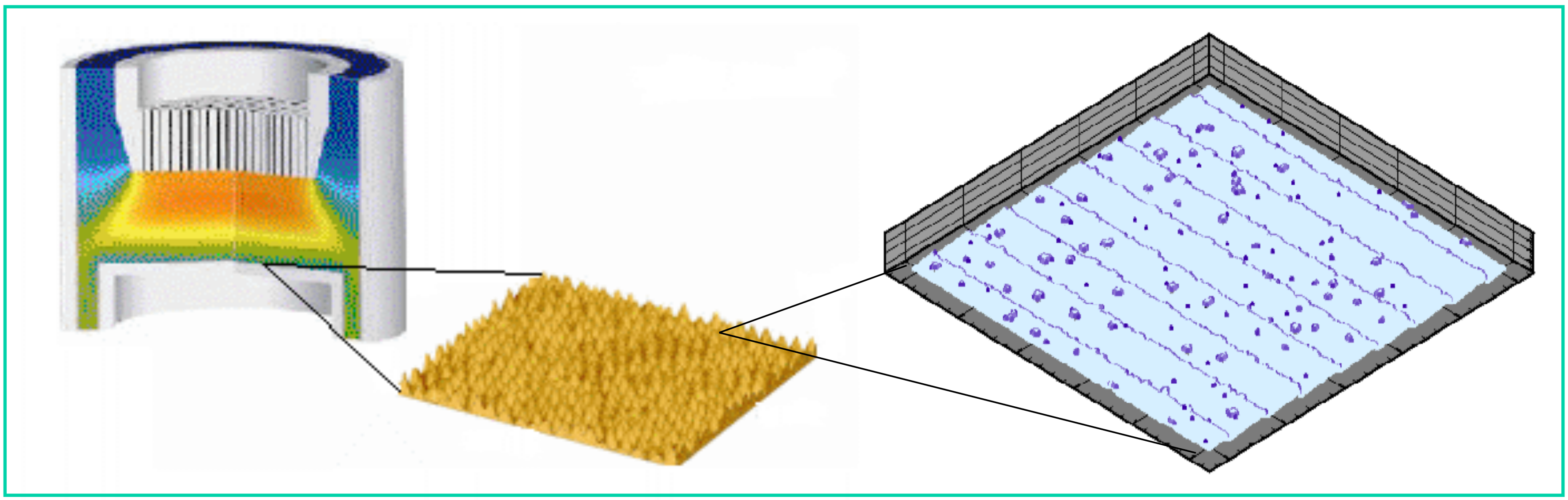


Multi-scale, multi-disciplinary modeling and simulation

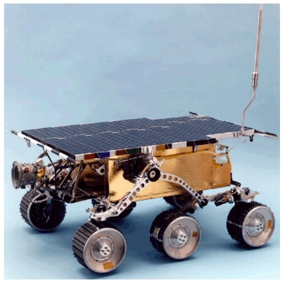
- Coupling between macro-scale actuation and micro-scale physics
- Models suitable for control analysis and design

Increased use of in situ measurements

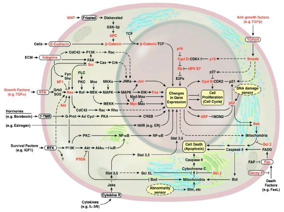
- Many new sensors available that generate real-time data about microstructural properties



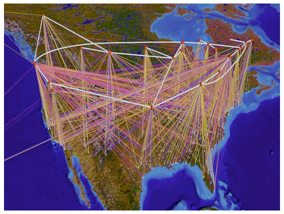
CDS Panel Recommendations



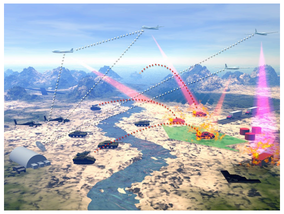
1. **Substantially increase research aimed at the integration of control, computer science, communications, and networking.**



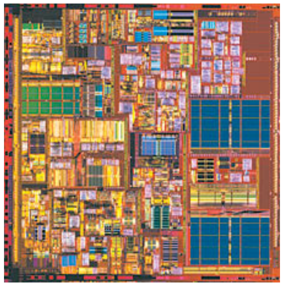
2. **Substantially increase research in control at higher levels of decision making, moving toward enterprise level systems.**



3. **Explore high-risk, long-range applications of control to areas such as nanotechnology, quantum mechanics, electromagnetics, biology, and environmental science.**



4. **Maintain support for theory and interaction with mathematics, broadly interpreted.**



5. **Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences.**

Grand Challenges

Mixed Initiative Control of Semi-Autonomous Teams (RoboFlag)

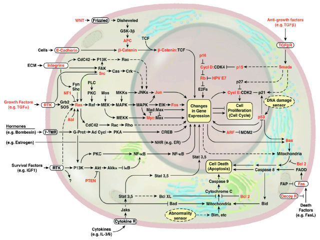
- Capture the flag with 10 robots, 2 people per team
- Limited sensing and communications; packet-based environment

Autonomous Driving in Urban Environments

- 60 miles of driving in regular traffic, completely autonomously
- DGC07 demonstrated feasibility, but many open research problems remain

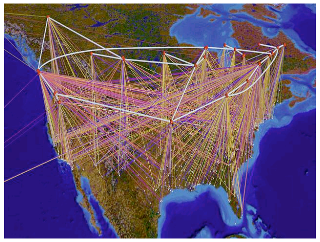
Synthetic Biology: Redesign the Feedback Control System of a Bacteria

- Redesign "circuitry" to change behavior in response to external stimuli
- Applications: new medical treatments, *in vivo* sensing systems

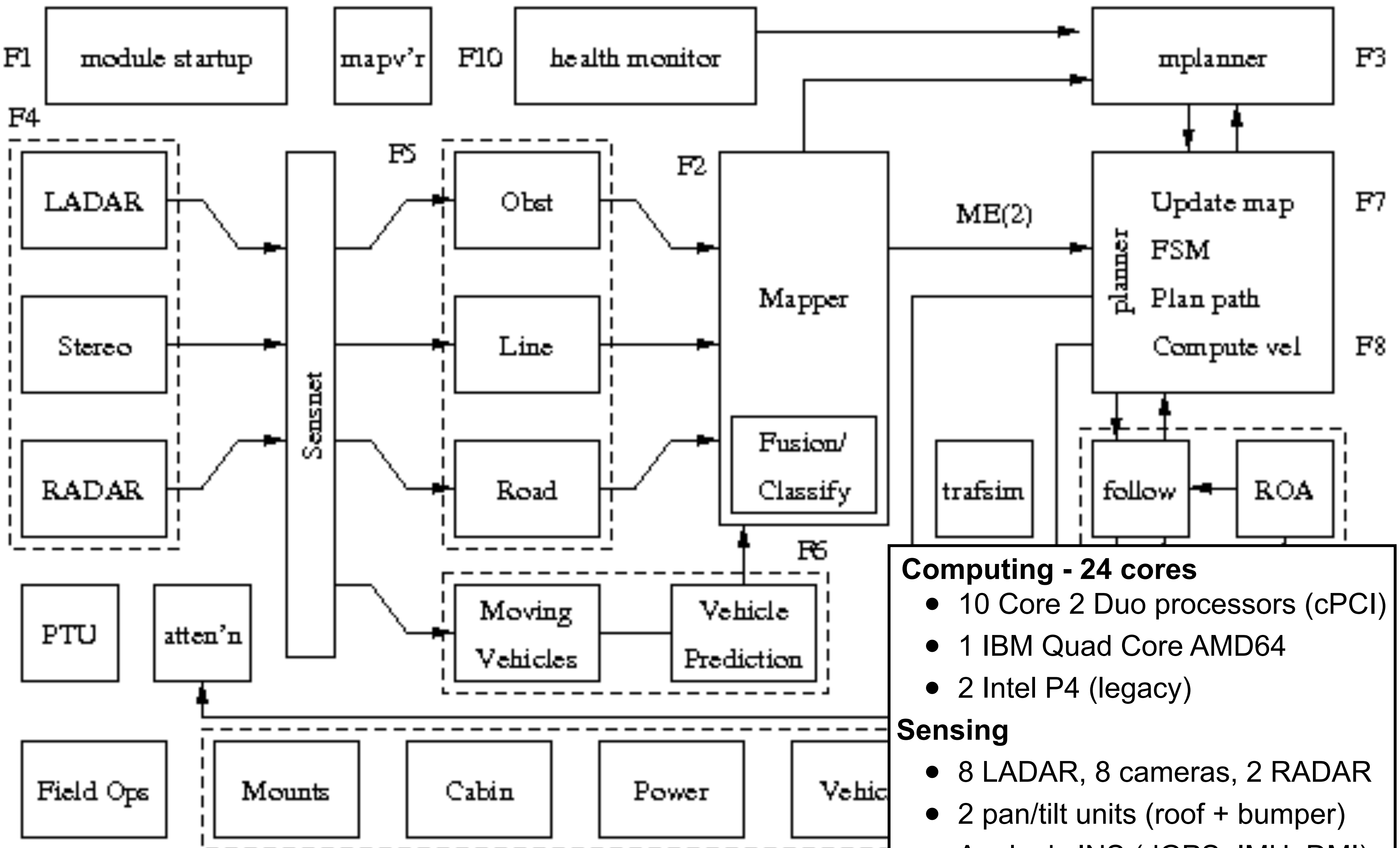


Specification, Design and Verification of Distributed Embedded Systems

- How do we specify complex behaviors for (hybrid/networked) systems
- What design tools are required to satisfy performance specifications?
- What analysis tools are required to verify safety specifications?



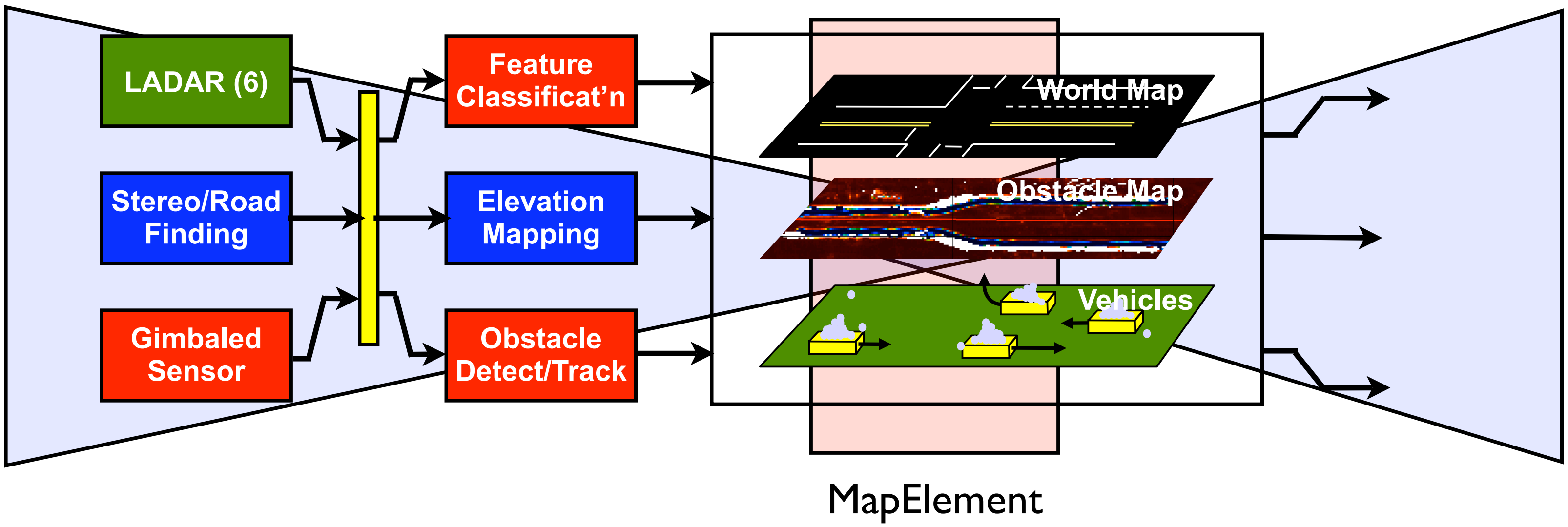
Architecture, July 2007



Computing - 24 cores
- 10 Core 2 Duo processors (cPCI)
- 1 IBM Quad Core AMD64
- 2 Intel P4 (legacy)

Sensing
- 8 LADAR, 8 cameras, 2 RADAR
- 2 pan/tilt units (roof + bumper)
- Applanix INS (dGPS, IMU, DMI)

Sensing Bowtie



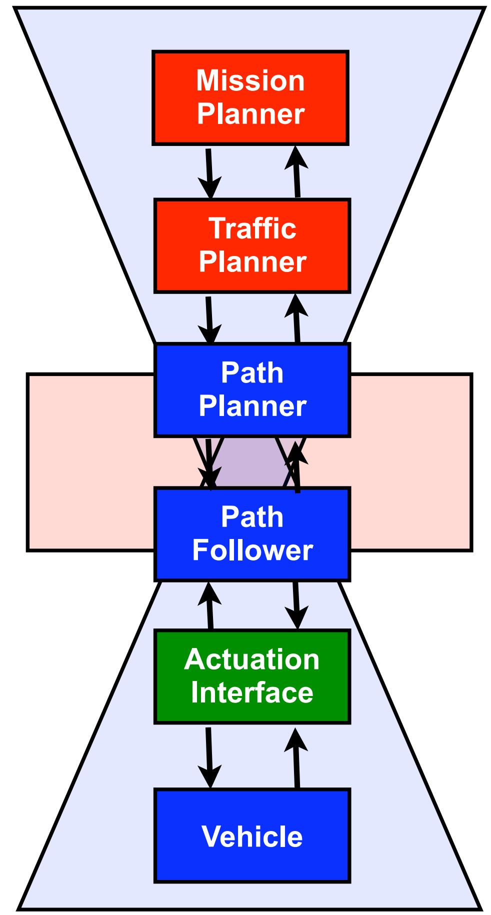
MapElement serves as "constraint that deconstrains"
- Fix the structure of the elements in the world map
- Left end: sensors → perceptors → MapElements
- Right end: MapElements → environment descriptions → planners

Engineering principle: allow parallel development (people and time) + flexibility
- Fixing the map element structure allows 15 people to work simultaneously
- We can evolve/adapt our design over time, as we get closer to the race

Planning Hourglass

Protocol stack based architecture

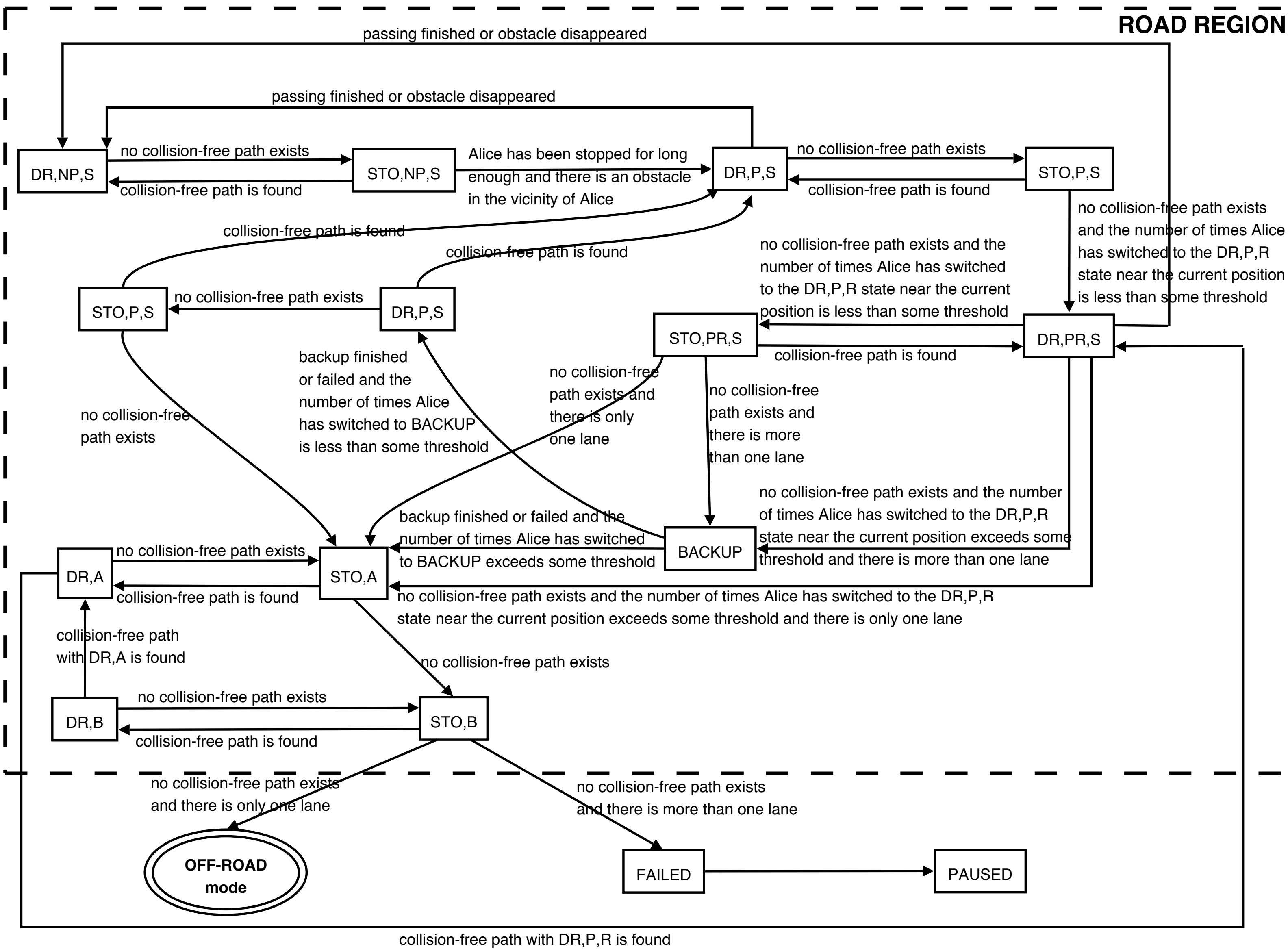
- Planners uses directives/responses to communicate
- Each layer is isolated from the ones above and below
- Have 4 different path planners under development, two different traffic planners. Rewriting the controllers as we speak (literally)



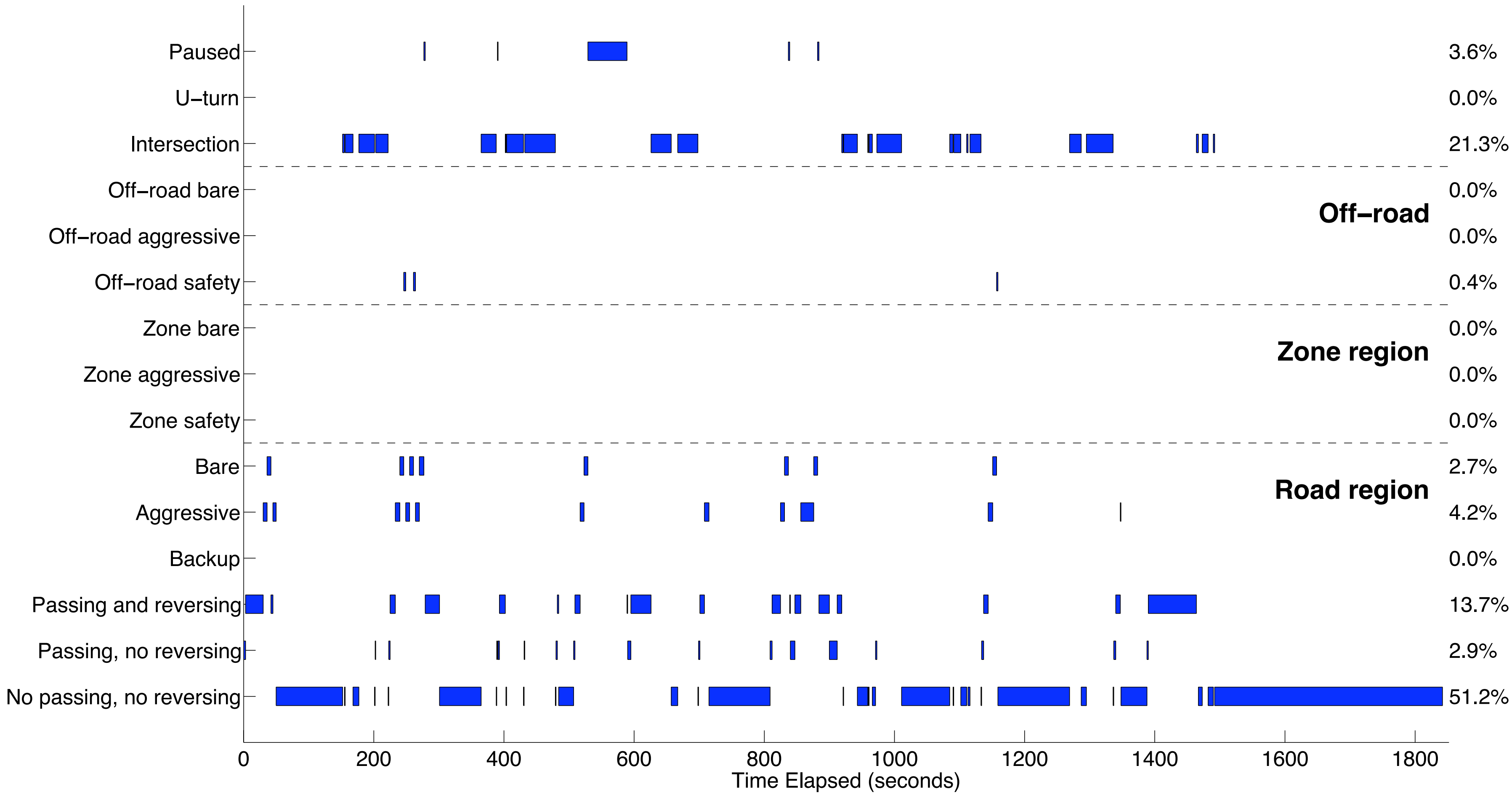
Engineering principle: layered protocols isolate interactions

- Define each layer to have a specific purpose; don't rely on knowledge of lower level details
- Important to pass information back and forth through the layers; a fairly in an actuator just generate a change in the path (and perhaps the mission)
- Higher layers (not shown) monitor health and can act as "hormones" (affecting multiple subsystems)

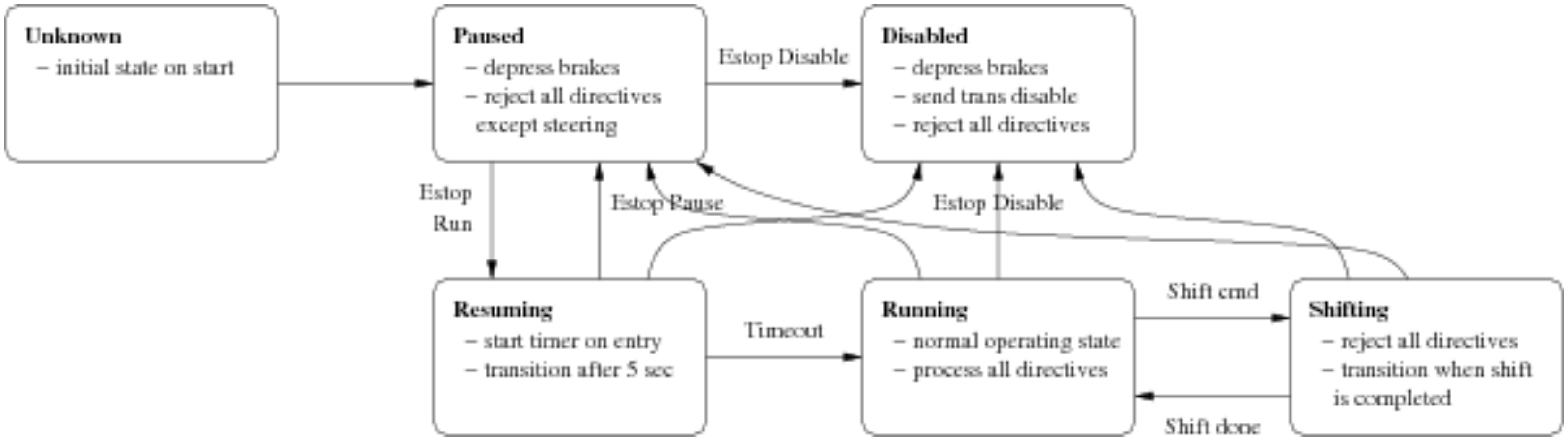
Logic Planner



Mode Transitions



GCDrive FSM Verification



Verification using temporal logic (Lamport's TLC, TLA+)

- Model follower, Actuation Interface, DARPA, accModule, transModule in TLC
- Shared variables: *state, estop, acc, acc_command, trans, trans_command*

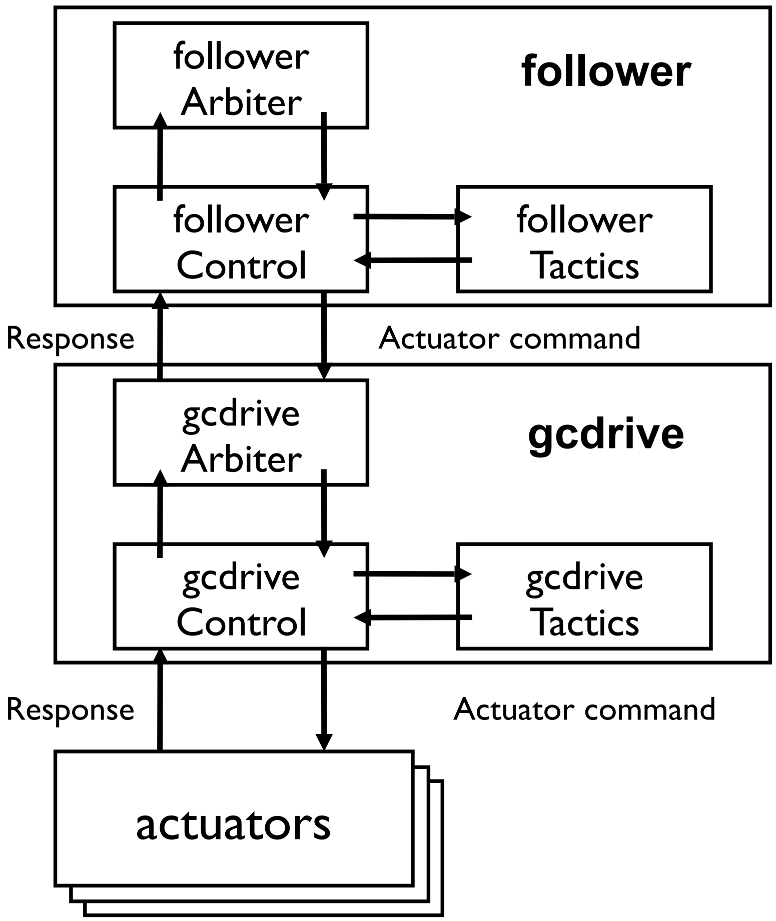
Verify the following properties

- $\Box((estop = \mathrm{DISABLE}) \Rightarrow \Diamond\Box(state = \mathrm{DISABLED} \wedge acc = -1))$
- $\Box((estop = \mathrm{PAUSE}) \Rightarrow \Diamond(state = \mathrm{PAUSED} \vee estop = \mathrm{DISABLE}))$
- $\Box((estop = \mathrm{RUN}) \Rightarrow \Diamond(state = \mathrm{RUNNING} \vee state = \mathrm{RESUMING}))$
- $\Box((state = \mathrm{RESUMING}) \Rightarrow \Diamond(state = \mathrm{RUNNING} \vee estop = \mathrm{DISABLE} \vee estop = \mathrm{PAUSE}))$
- $\Box((\mathrm{state} \in \{\mathrm{DISABLE, PAUSED, RESUMING, SHIFTING}\} \Rightarrow \mathrm{acc} = -1)$

DGC Example: Changing Gear

Verify that we can't drive while shifting or drive in the wrong gear

- Five component: follower Control, gcdrive Arbiter, gcdrive Control, actuators and network
- Construct temporal logic models for each component (including network)



Asynchronous operation

- Notation: Message$_{mod,dir}$ - message to/from a module; Len = length of message queue

- Verify: follower has the right knowledge of the gear that we are currently in, or it commands a full brake.
  - $\Box$ $((Len(TransResp_{f,r}) = Len(Trans_{f,s}))$ $\wedge$ $TransResp_{f,r}[Len(TransResp_{f,r})] =$ COMPLETED $\Rightarrow$ $Trans_f = Trans))$
  - $\Box$ $(Trans_f = Trans \vee Acc_{f,s} = -1)$

- Verify: at infinitely many instants, follower has the right knowledge of the gear that we are currently in, or we have hardware failure.
  - $\Box\Diamond$ $(Trans_f = Trans = Trans_{f,s}[Len(Trans_{f,s})] \;\vee\; HW\ failure)$

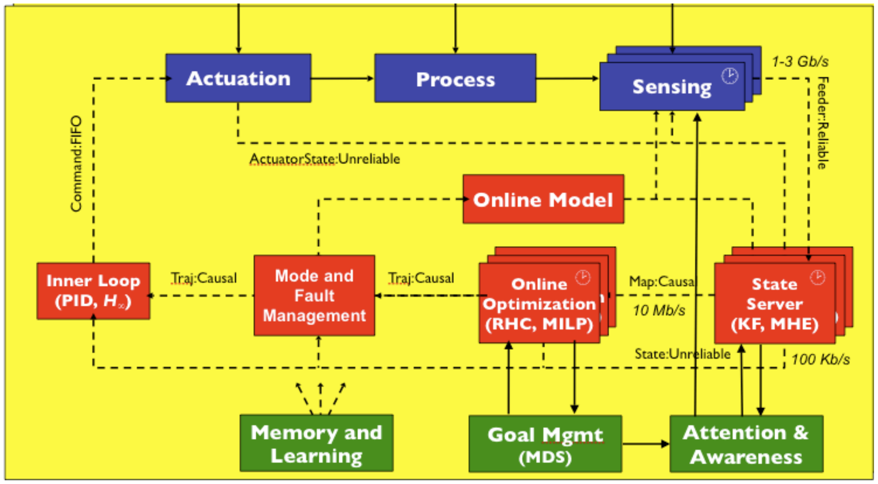
Open Challenge: Verification of NCS Designs

Missing: V&V based design environment

- Specification: how do we describe what the (sub) systems must do?
- Design: how do we design protocols, interfaces, modules, controllers?
- Verification: how to do we make sure the design satisfies the specification

Alice example: safe vehicle operation in multithreaded environment

- Vehicle operation controlled by net-worked interface; responsible for fail safe operation
- Requires careful reasoning about message passing, external events, internal failures
- Asynchronous operations (message passing, failures, environment) complicate verification
- Experience shows this is where we are weakest



Approach: temporal logic + SOS

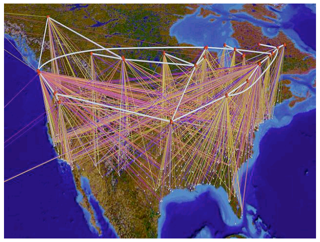
- Formulate control goal using temporal logic specs w/ continuous+ discrete vars
- Use Lyapunov functions to reason about dynamics and protocols

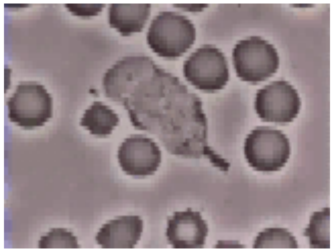
Results to date

- Specification using linear temporal logic
- Initial verification using LTC software
- Working on incorporating dynamics via SOS certificates to bound possible motion

NRC, 2005

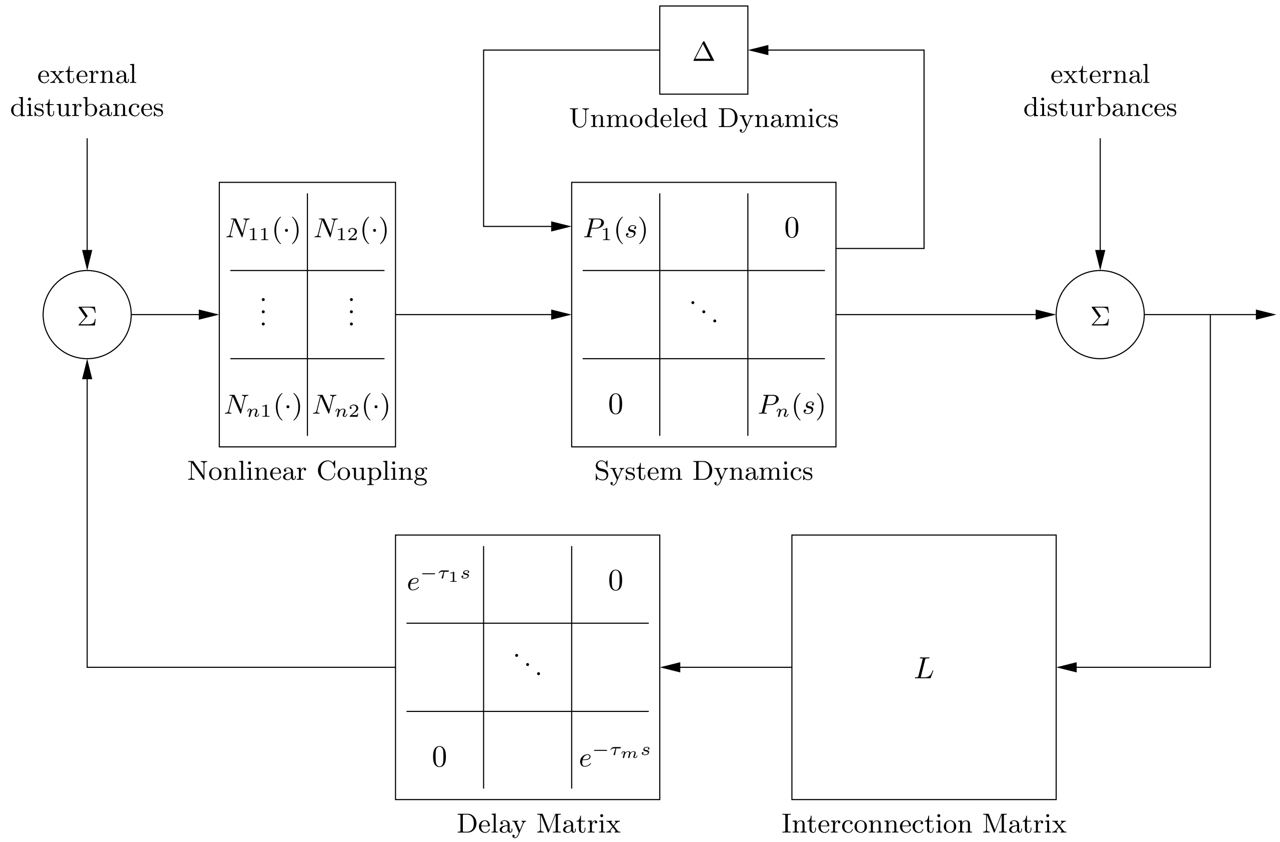
Some Future Directions in Network Science





1. **Dynamics, spatial location and information propagation in networks**
   - Integrated communications, computation and control
   - Distributed representations and coordinated operations
2. **Verification and validation of large feedback systems**
   - Proof certificates for complex embedded SW sysems
3. **Design and synthesis of networks and protocols**
   - What should the network topology look like (and why)
   - When do I use TCP vs UDP vs broadcast
4. **Increased rigor and mathematical structure**
   1. How do we model & analyze Alice? MS Word? E. coli?
5. **Abstracting common concepts across fields**
   - Bio, Ec, CS …
6. **Robustness and security of networked control systems**

Design of Biomolecular Feedback Systems



Design the easy parts

- Interconnection matrix
- Time delay matrix

Design tools exist for pairwise combinations

- Linear + uncertain = robust control theory
- Linear + nonlinear = describing functions
- Linear + network = formation stabilization
- Linear + delay = Floquet analysis

Open questions

- What is the class of feedback compensators we can obtain using L and τ ?
- How do we specify robustness and performance in highly stochastic settings?
- Can feedback be used to design robust dynamics that implements useful functionality?

Summary: Future Directions in Control

Control remains an exciting area, with *many* new applications

- Community needs to get involved in new applications (already happening!)
- Need to maintain support for control research by government, industry

Panel Recommendations

1. Increase research aimed at the integration of control, computer science, & communications
2. Increase research in control at higher levels of decision making, moving toward enterprise level systems
3. Explore high-risk, long-range applications of control in nanotechnology, quantum mechanics, electro-magnetics, biology, environmental science, etc
4. Maintain support for theory and interaction with mathematics
5. New approaches to education to disseminate con-trol concepts and tools to non-traditional audiences