Networked Control Systems for Robotics and Autonomy

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Goals

- Important trends in control over the last decade
- Networked control systems for robotics and autonomy
- Potential challenges for autonomy in civilian aviation

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
- Platform-based design; contract-based design

Cyber-physical systems (CPS)

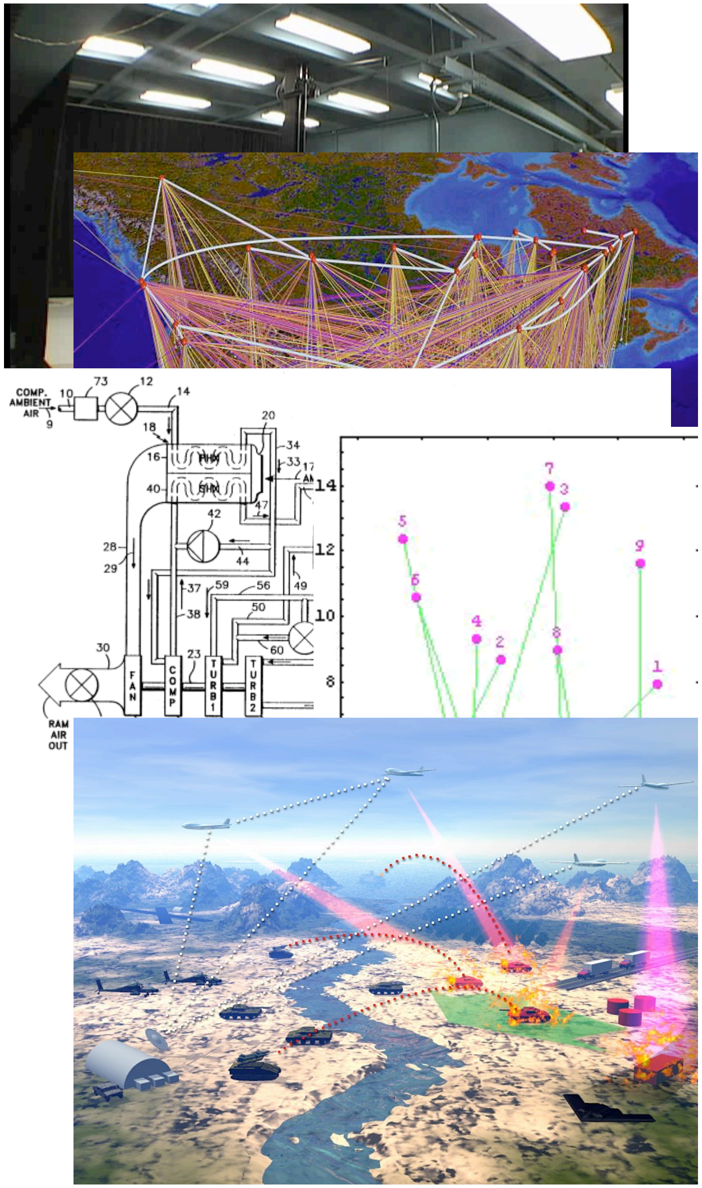
- Systems that combine information systems/physics
- Better coupling between computer science, controls, communications and networking

Formal methods for analysis, design and synthesis

- Formal methods from computer science, adapted for cyberphysical systems
- Horizontal & vertical contracts for layering, modularity

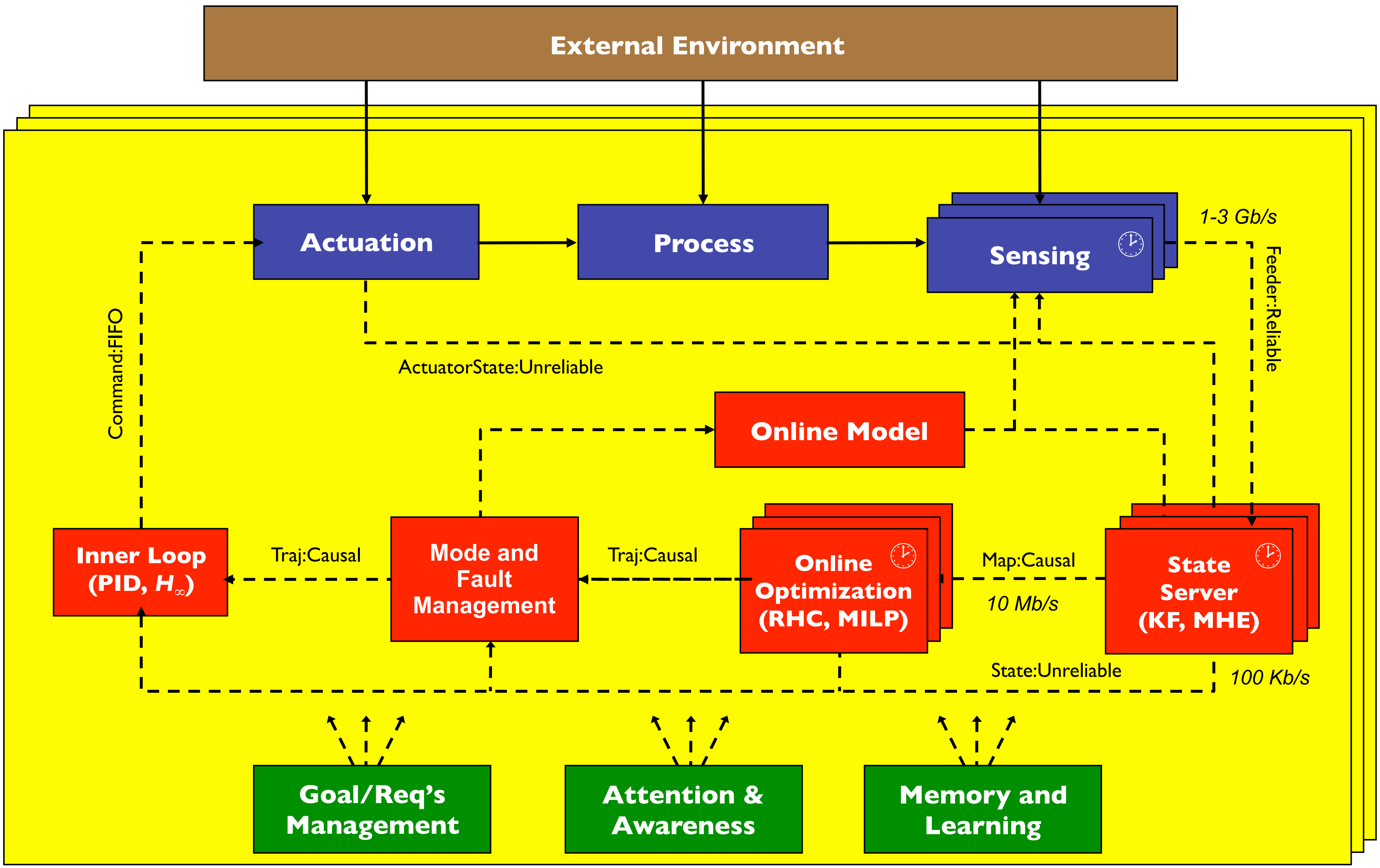
Components → Systems → Enterprise

- Movement of control techniques from “inner loop” to “outer loop” to entire enterprise (eg, supply chains)



Modern Networked Control System Architecture

(following P. R. Kumar, UIUC/Texas A&M)



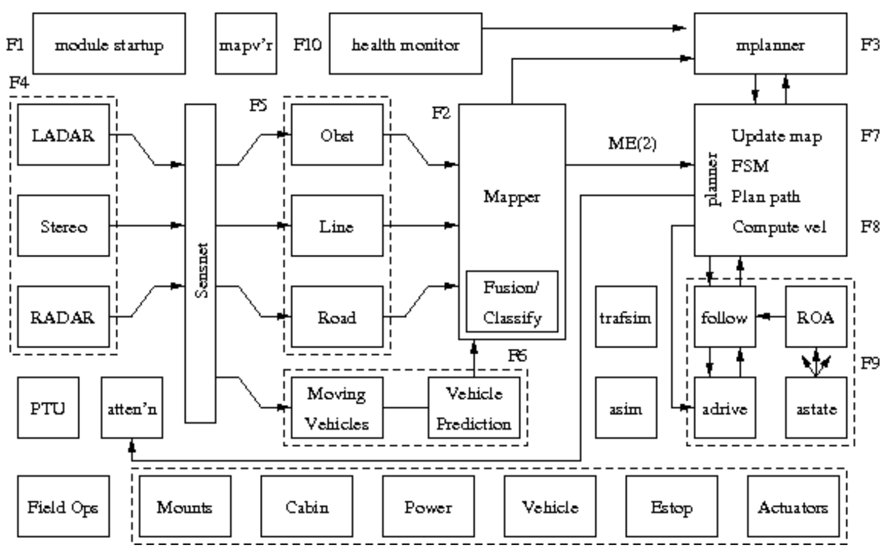
Recent Example: Alice (DGC07)

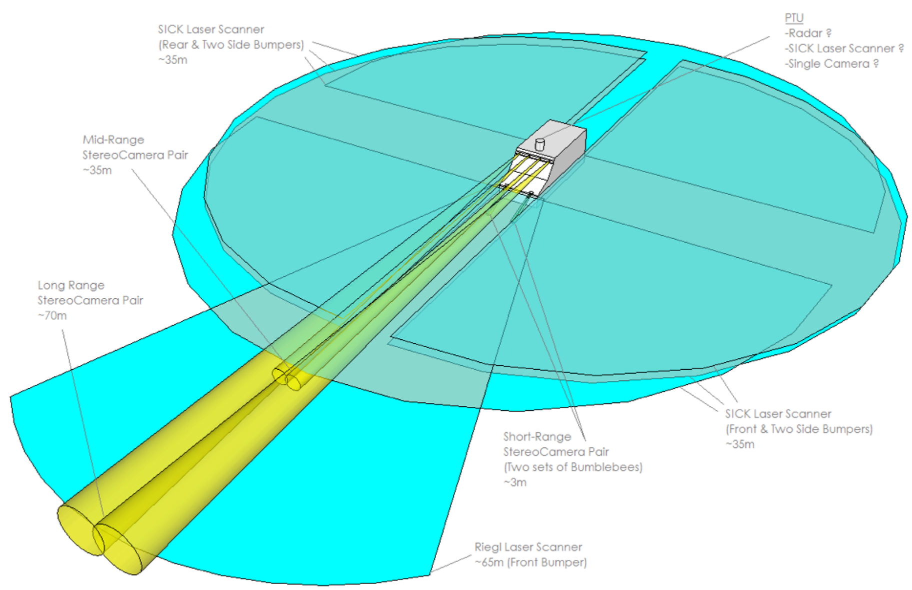
Alice

- 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

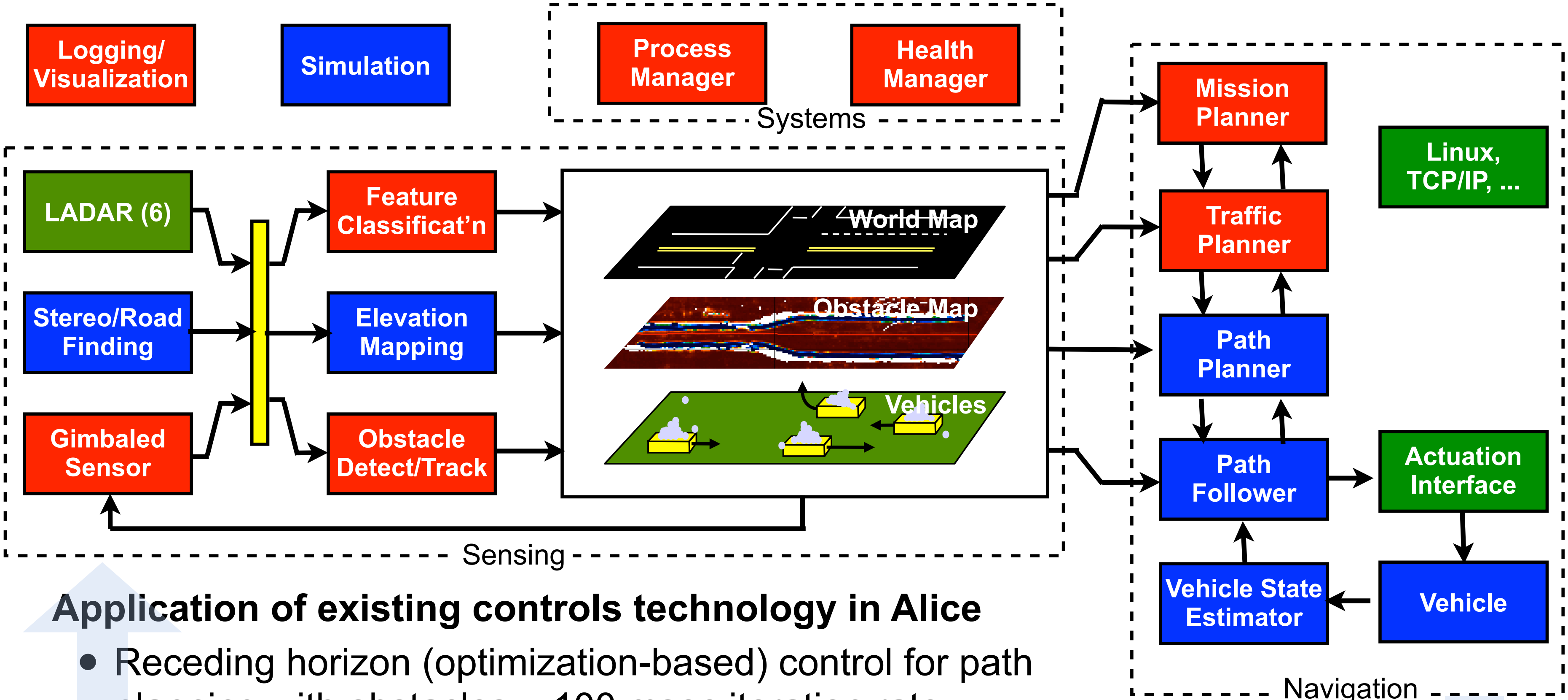
Software

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





DGC07 System Architecture



Application of existing controls technology in Alice

- Receding horizon (optimization-based) control for path planning with obstacles; ~100 msec iteration rate
- Multi-layer sensor fusion: sensor "bus" allows different combinations of sensors to be used for perceptors + fusion at "map" level
- Low level (inner loop) controls: PID w/ anti-windup (but based on a feasible trajectory from RHC controller)

Properties

- Highly modular
- Rapidly adaptable
- Constantly viable
- Robust ???

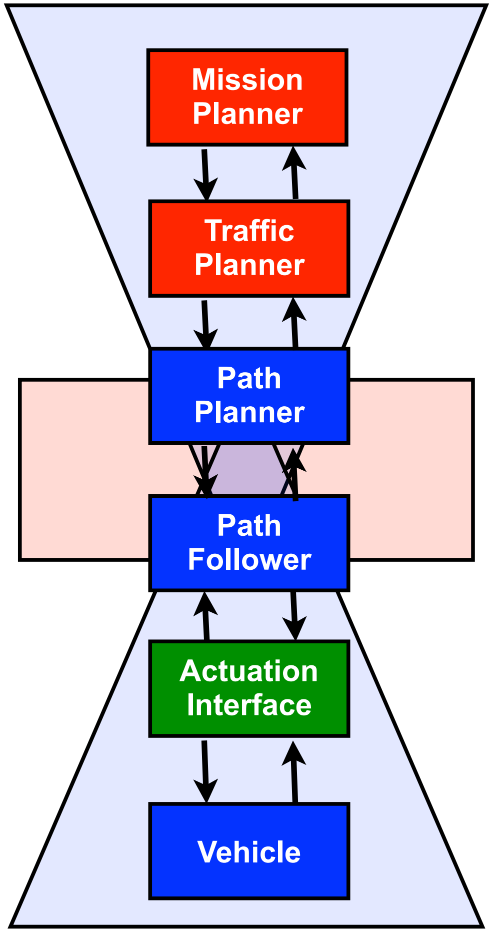
Planning Hourglass

Protocol stack based architecture

- Planners uses directives/responses to communicate
- Each layer is isolated from the ones above and below
- Had 4 different path planners under development, two different traffic planners.

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)

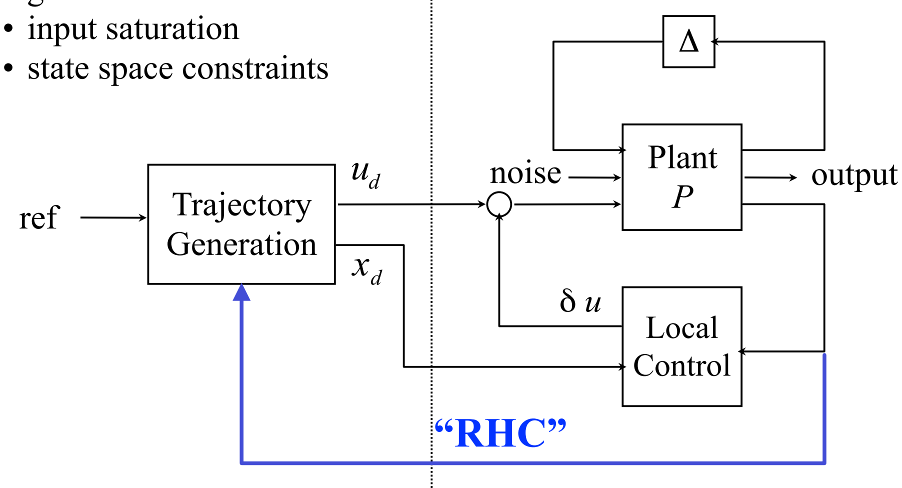


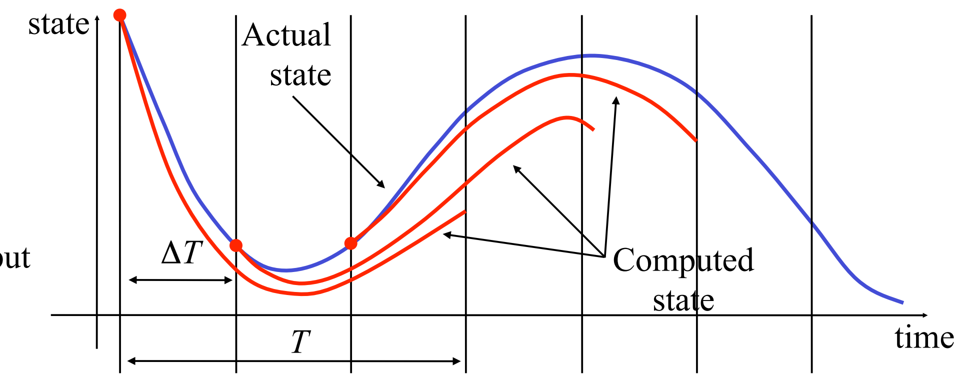
Hybrid system control methodology

- Finite state automata control interactions between layers and mode switches (intersection, off road, etc)
- Formal methods for analysis of control protocol correctness (post race)
  - Eg: make sure that you never have a situation where two layers are in conflict

Analysis vs Design: Optimization-Based Control

Nonlinear design
- global nonlinearities
- input saturation
- state space constraints





$$u_{[t,t+\Delta T]} = \arg\min \int_t^{t+T} L(x(\tau), u(\tau))\, d\tau + V(x(t+T))$$

$$x_0 = x(t) \quad x_f = x_d(t+T)$$

$$\dot{x} = f(x,u) \quad g(x,u) \le 0$$

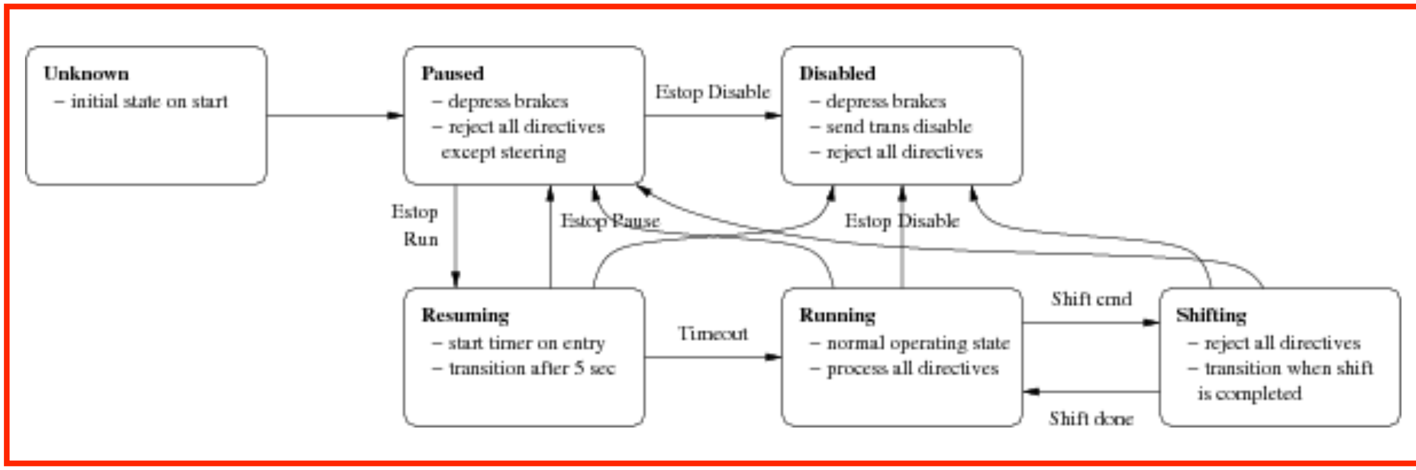
Offline design + analysis → online design

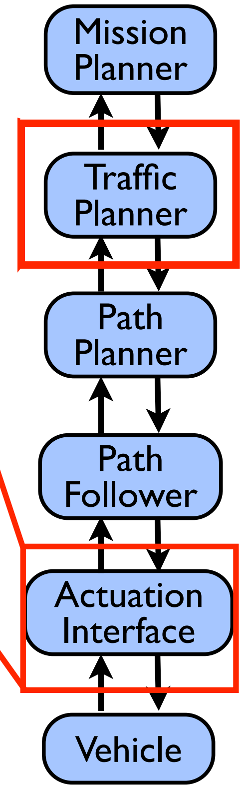
- Traditional: design (simple) controller, analyze performance, check with constraints
- Modern: specify performance and constraints, design trajectory/control to satisfy
- Problem: overall space too large; *online* optimization allows simplification
- Example of a "correct by construction" technique. Cost function = Lyapunov function

Links to complexity management

- Correct by construction allows "automatic" verification
- Still limited by our ability to formally specify behavior, computational tractability, etc

Challenge: Verification of Control Logic





Function: respond to control commands + DARPA pause/emergency stop

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

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

Lessons Learned from Alice

Online optimization solves nonlinear control problems

- Modern computation allows constrained optimization problems to be solved online
- Solutions exist for situations with more limited computation (multi-parametric optimization)

Layered control architectures allow more efficient design

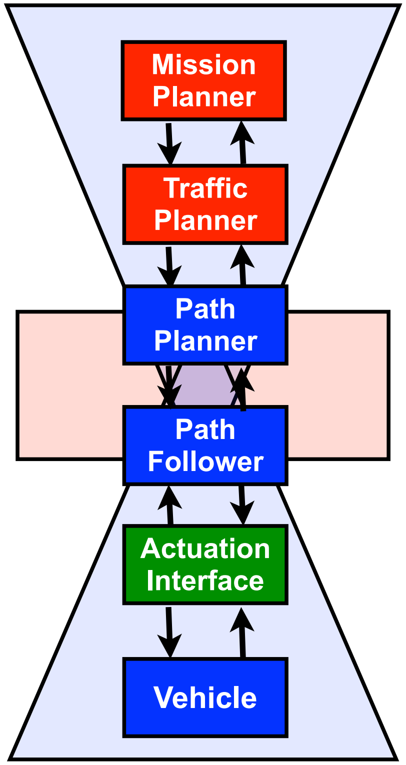
- Allows for "separation of concerns" between subsystems
- Provided a very modular design, capable of rapid (human-controlled) adaptation

Verification of control protocols is necessary, but hard

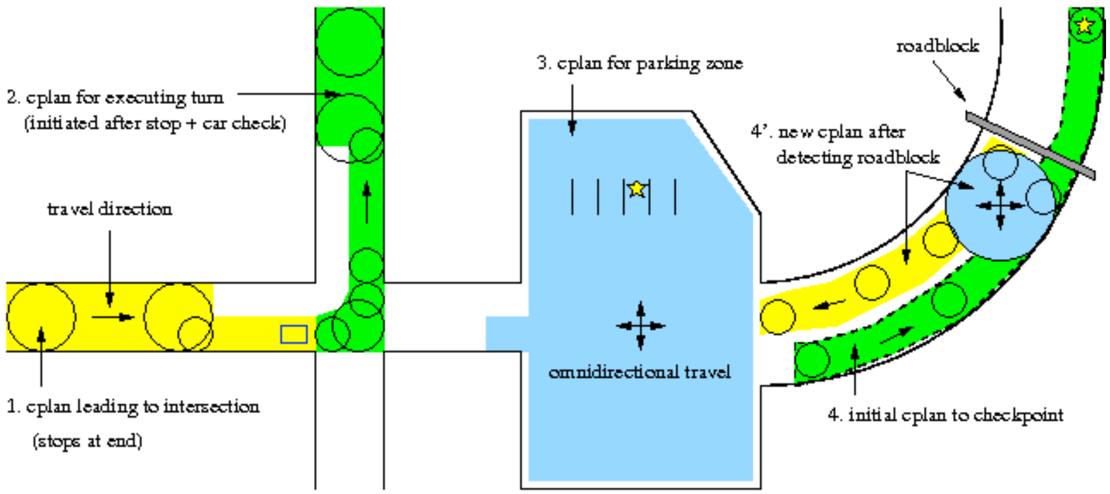
- Traditional methods of simulation and testing not sufficient
- Formal methods not easily applied to "hand designed" control protocols

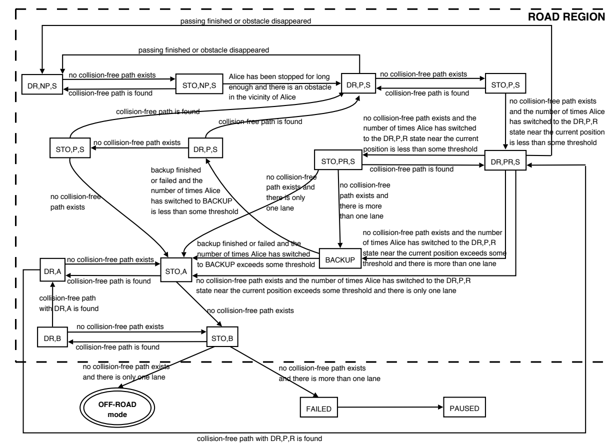
New tools for "correct by construction" design are needed

- Temporal logic(s) are powerful language for specifying desired behavior (combined with traditional measures)
- New tools are becoming available, but not yet ready for prime time



Current Work: Design of Control Protocols



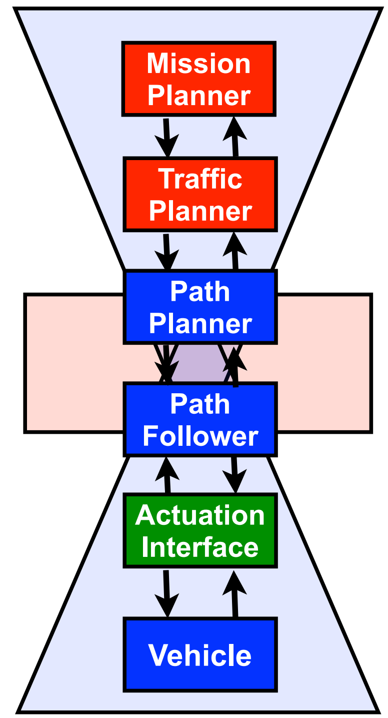


How do we *design* control protocols that manage behavior

- Mixture of discrete and continuous decision making
- Insure proper response external events, with unknown timing
- Design input = specification + model (system + environment)
- Design output = finite state machine implementing logic

Approach: rapidly explore all trajectories satisfying specs

- Search through all possible actions and events, discarding executions that violate a set of (LTL) specifications
- Issue: state space explosion (especially due to environment)
- Good news: recent results in model checking for class of specs

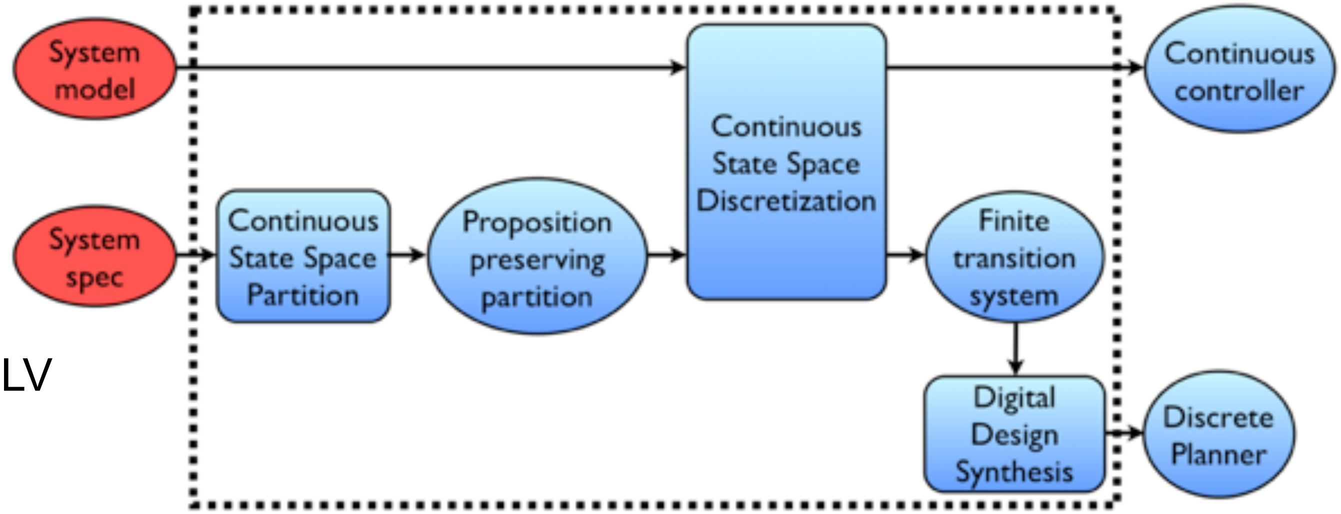


Temporal Logic Planning (TuLiP) toolbox

http://tulip-control.sourceforge.net

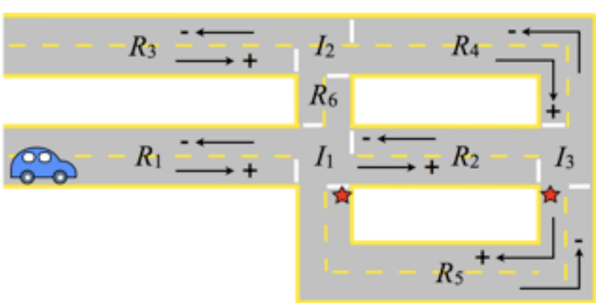
Python Toolbox

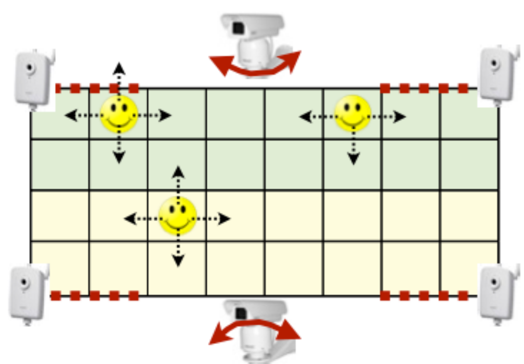
- GR(1), LTL specs
- Nonlin dynamics
- Supports discret-ization via MPT
- Control protocol designed using JTLV
- Receding horizon compatible

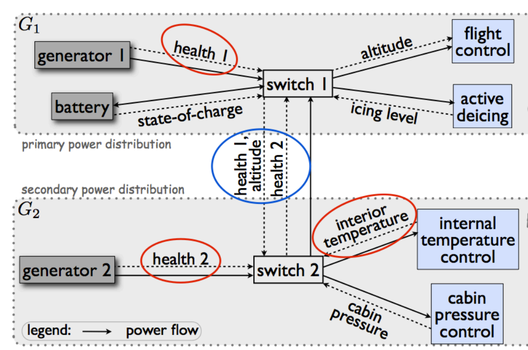


Applications of TuLiP in the last year

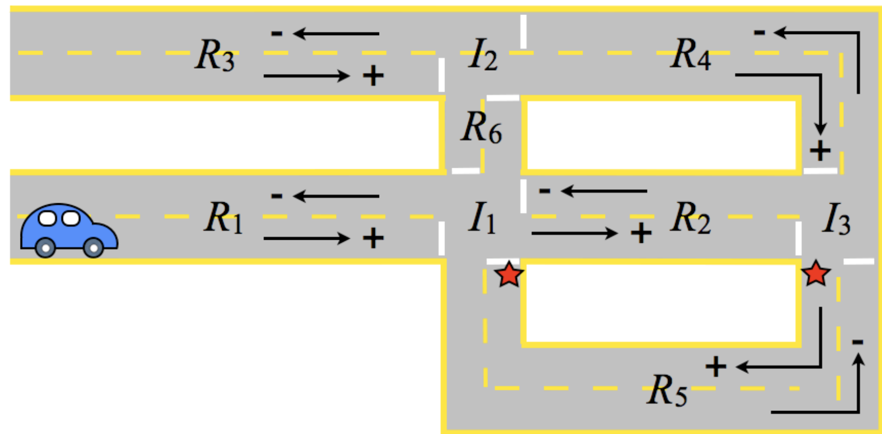
- Autonomous vehicles - traffic planner (intersections and roads, with other vehicles)
- Distributed camera networks - cooperating cameras to track people in region
- Electric power transfer - fault-tolerant control of generator + switches + loads

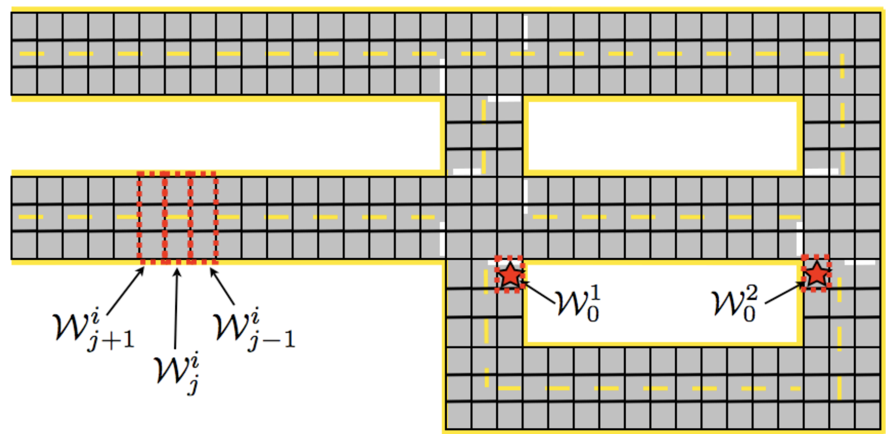






Example: Autonomous Navigation in Urban Environment





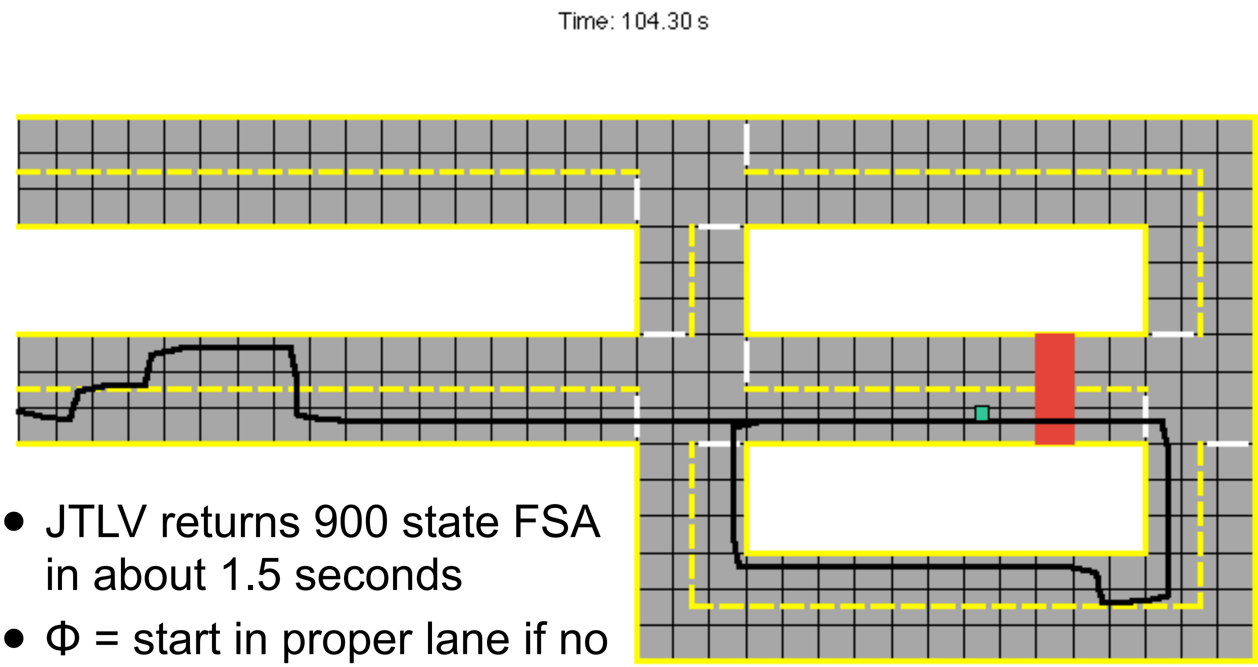
Traffic rules

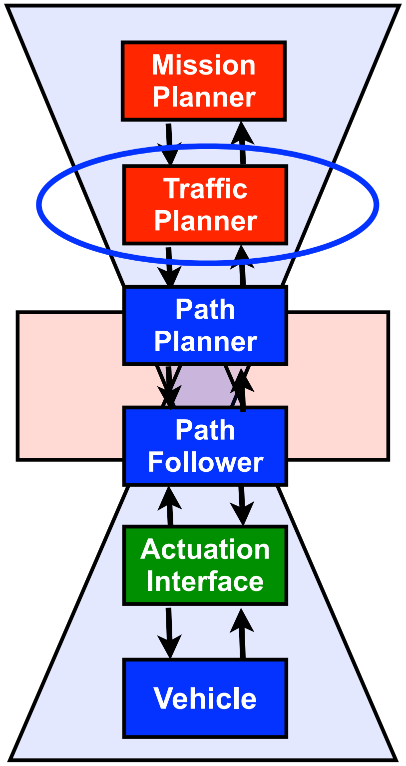
- No collisions with other vehicles
- Stay in the travel lane unless there is an obstacle blocking the lane
- Only proceed through an intersection when it is clear

Assumptions

- Obstacle may not block a road
- Obstacle is detected before the vehicle gets too close to it
- Limited sensing range
- Obstacle does not disappear when the vehicle is in its vicinity
- Obstacles may not span more than a certain number of consecutive cells in the middle of the road
- Each intersection is clear infinitely often
- Each of the cells marked by star and its adjacent cells are not occupied by an obstacle infinitely often

Example: Autonomous Navigation in Urban Environment





- JTLV returns 900 state FSA in about 1.5 seconds
- Φ = start in proper lane if no obstacle present ^ no collision

Use response mechanism to replan if no feasible solution exists

- Trajectory planner sees blockage and fails to find strategy satisfying specification
- Trajectory planner reports failure to goal generator
- Goal generator re-computes a (high level) path to the goal state

Potential challenges for autonomy in civilian aviation

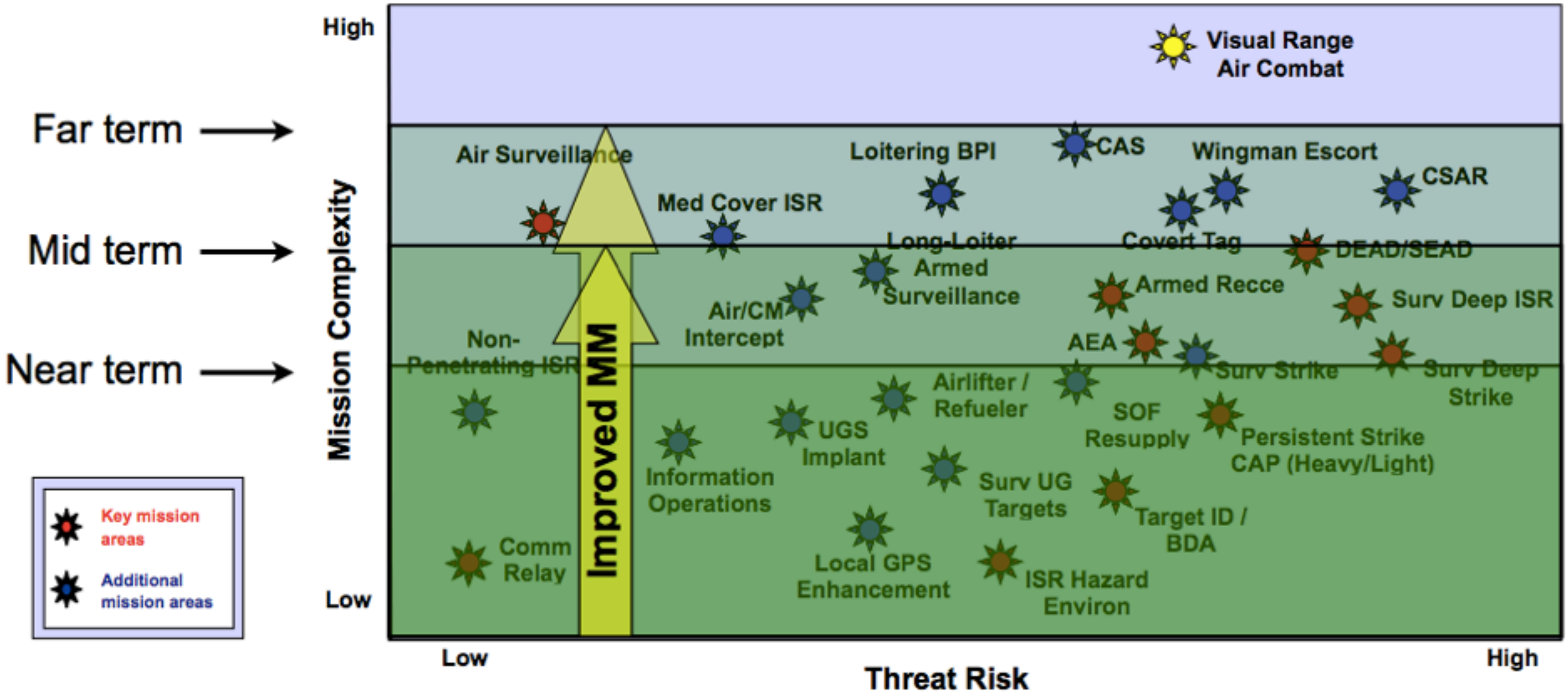
Two comparisons to previous areas of interest

- Control of UAVs in military operations (AFSAB study, 2003)
- Challenges in control of autonomous vehicles in urban environments

References

- "UAVs in Perspective," Air Force. Scientific Advisory Board Summer Study, June 2003
- M. Campbell, M. Egerstedt, J. P. How, and R. M. Murray, "Autonomous Driving in Urban Environments: Approaches, Lessons and Challenges," Philosophical Transactions of the Royal Society - A, Oct. 2009.

UAVs in Perspective (2003 Study)



- With the possible exception of air to air combat, UAVs are capable of executing all current air force missions
- Advances in autonomy and human-system integration technologies are required to conduct increasingly complex missions
- The challenge is to optimally integrate human and machine abilities

Campbell, Egerstedt, How, M
Phil Trans Roy Soc A, 2010

Challenges in Autonomous Driving

Systems integration

- Integration of complex sensing, actuation and decision-making subsystems
- Need to insure assumptions are consistent across algorithms (and teams)

Prediction and trust

- How do we anticipate the actions of other systems (autonomous or human-controlled)
- How do we make sure that autonomous systems behave in "understandable" manner

Interactions between agents

- Exploit the ability for autonomous (or semi-autonomous) systems to communicate
- Unfortunately, cannot assume that all vehicles will cooperate...

Learning

- Can autonomous systems learn from prior mistakes, other vehicles, online data?

Scaling up

- How do we "scale up" (speed, complexity) from operation in controlled environments

Verification and validation

- How do we verify and certify that the system can operate safely and robustly
- Particularly hard since we know that this cannot be done 100% of the time