Challenges in Cyber-physical Systems

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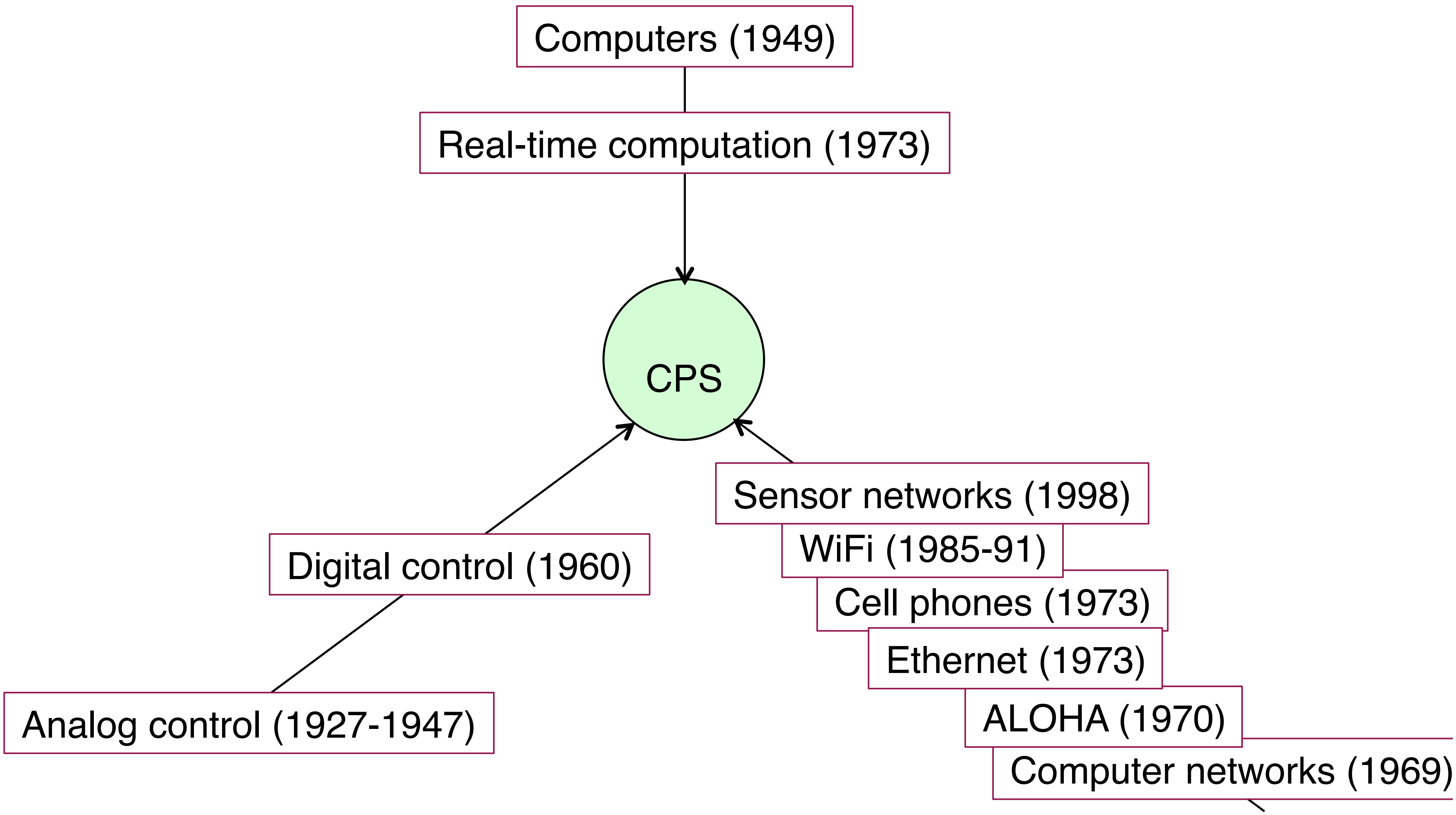
Push: The technological enablers of CPS



From real-time and hybrid systems

Computers were developed for computation (1949)

Real-time computation (1973)

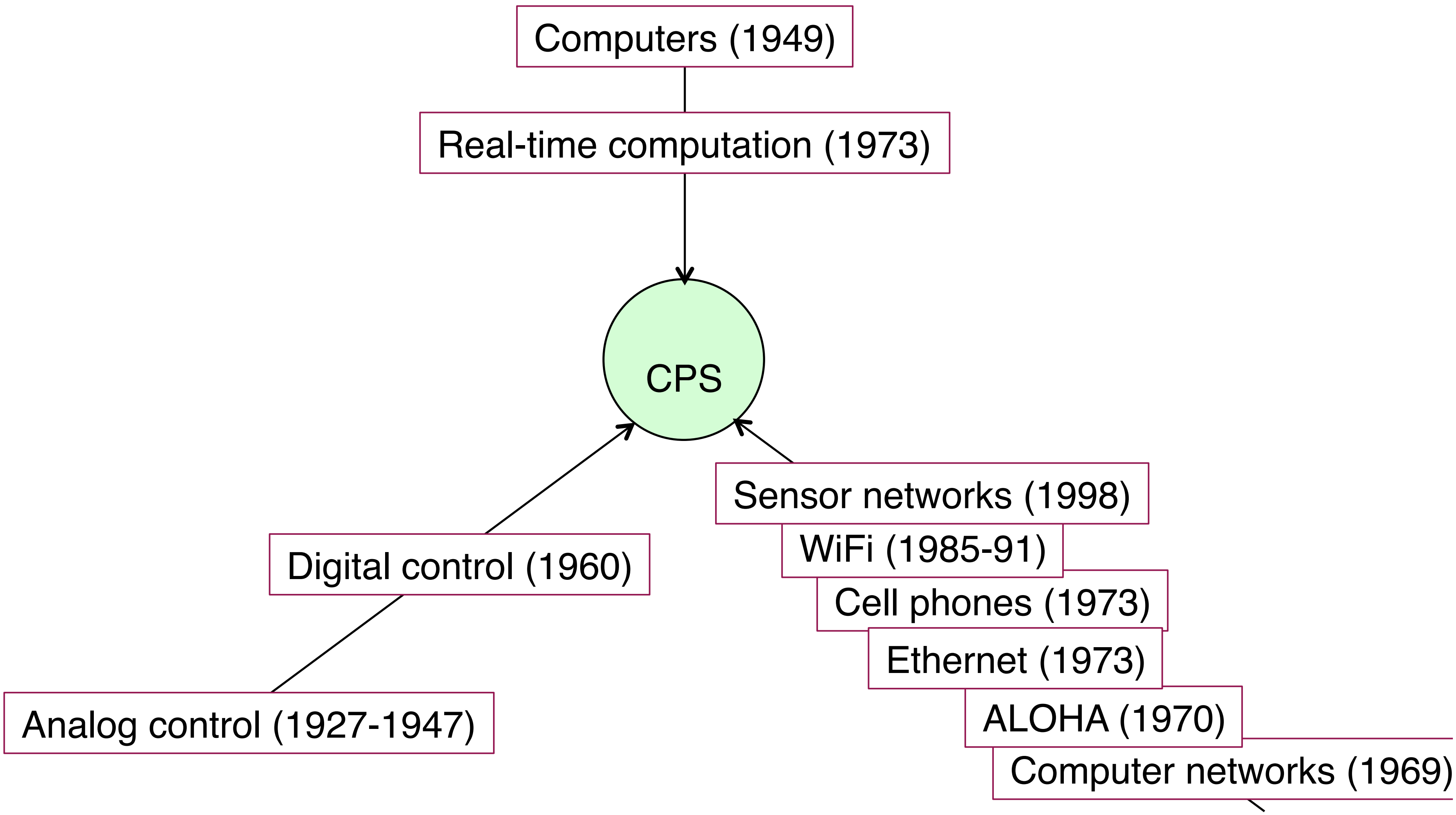
Hybrid systems (1990s)

Around 2006

"Instigators": Gill, Krogh, K, Lee, Midkiff, Mok, Rajkumar, Sastry, Sha, Shin, Stankovic, Sztipanovits, …

Cyber-physical systems

The technological enablers of CPS



The third generation of control systems

- First generation: Analog Control
  - Technology: Feedback amplifiers
  - Theory: Frequency domain analysis
    Evans, Nyquist, Bode

- Second generation: Digital Control
  - Technology: Digital computers
  - Theory: State-space design
  - Real-Time Scheduling

- Third generation: Networked Control
  - Embedded computers
  - Wireless and wireline networks
  - Software

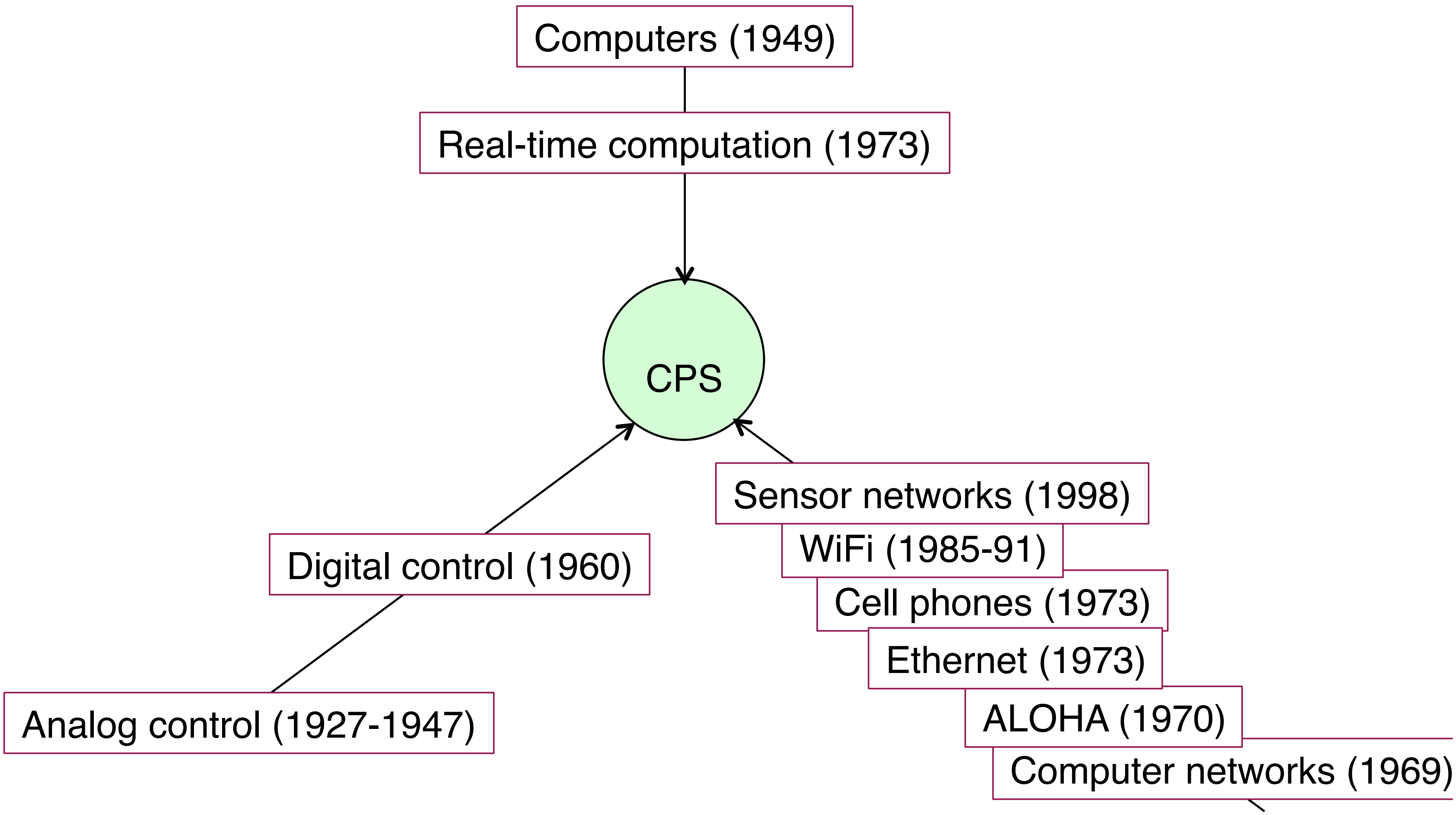
- Platform revolution

Foundation of system theory

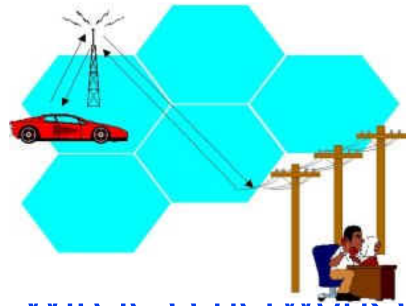
- Linear systems
- Nonlinear systems
- Estimation
- Optimal control
- System identification
- Adaptive control
- Robust control
- Discrete event systems
- Hybrid systems

Bouquet of books

The technological enablers of CPS

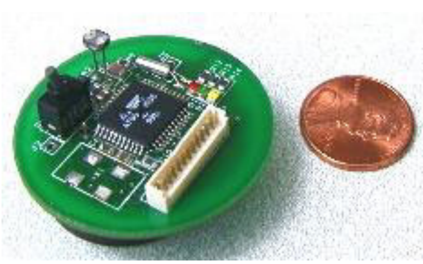


From communicating to sensing to acting



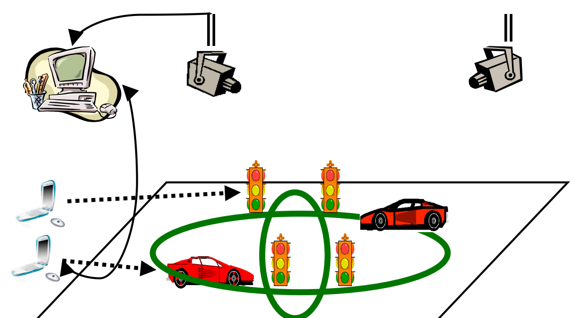
Cellular systems

Convergence of communication, computation and control

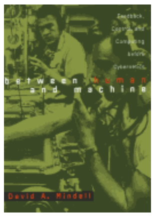


Sensor Networks

Networked Embedded Control



Re-convergence of control, communication and computation



"…the era of cyberspace and the Internet, with its emphasis on the computer as a communications device and as a vehicle for human interaction connects to a longer history of control systems that generated computers as networked communications devices."

– D. Mindell in "Feedback, Control and Computing before Cybernetics," 2002

- 1950 — 2000 and continuing
  - Computation: ENIAC (1946), von Neumann (1944), Turing,..
  - Sensing and inference: Fisher, Wiener (1949),…
  - Actuation/Control: Bode, Kalman (1960),…
  - Communication: Shannon (1948), Nyquist,…
  - Signal Processing: FFT, Cooley-Tukey (1965),…

- 2000 — onwards: Age of system building
  - Nodes that can communicate, control, compute
  - Larger grand re-unification of control, communication and computation
  - Pedagogical challenges: Knowledge of all these fields may be important
  - Undergraduate education? Graduate education?
  - Research challenges

The Pull: System building era of 21st century

- Satisfying greater demand for infrastructure and services with resource constraints
  - Transportation systems
  - Energy systems
  - Medical systems
  - Water systems

- Ongoing resource-aware system building era of the 21st century
- CPS with sensing, communication, computation, actuation needs to play a key role

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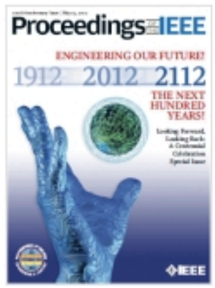
Centennial special issue

A special 13 May centennial issue will be published as the thirteenth issue of 2012, which will review 19 key technologies from three perspectives: the past, the present, and prospects for developments in the future. Technical topics include:

1. cyber-physical systems;
2. electric power and energy engineering;
3. engineering education;
4. entertainment technologies;
5. hjardware/software co-design;
6. mass storage and data retrieval;
7. materials for electronics, photonics & energy storage;
8. medical devices and electronics;
9. neurotechnological systems: the brain-computer interfac
10. optics and photonics;
11. personal and home electronics;
12. privacy and cybersecurity;
13. radio spectrum access;
14. the search for life: SETI;
15. science and engineering beyond Moore's Law;
16. social implications of technology;
17. space exploration and science;
18. transportation and navigation technology;
19. wireless communications technology.



Centennial Celebration

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Proceedings of the IEEE

Proceedings of the IEEE is celebrating its centennial year of publication during 2012. Many exciting features and events are being planned to mark this wonderful occasion!

On this Page:
- Historical perspectives
- Centennial special issue
- Engineering Innovation Forum
- Future technology predictions

A moment of celebration

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◆ May 2012: Special 13th issue

INVITED PAPER

Cyber–Physical Systems: A Perspective at the Centennial

This paper surveys cyber–physical systems and the potential benefits of the convergence of computing, communications, and control technologies for developing next-generation engineered systems.

By Kyoung-Dae Kim and P. R. Kumar, *Fellow IEEE*

Platform and system building revolution

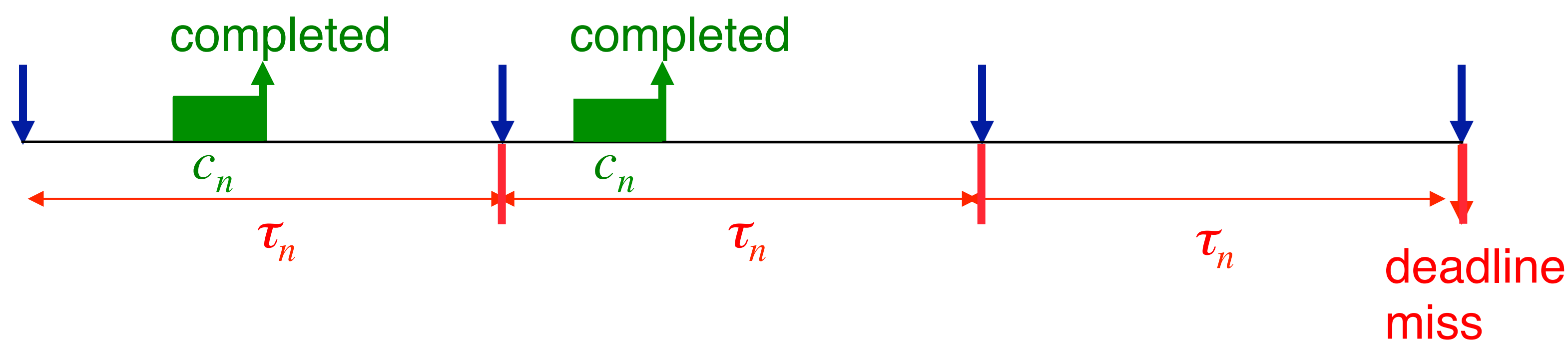
- Mechanisms
  - *How to implement?*
- Policies
  - *What to implement?*
- Confluence
  - *Hybrid*
    - *Discrete and continuous*
    - *Protocol and algorithm*

What performance guarantees can be provided?

- How can we guarantee that systems will perform correctly and be safe?
- Ultimate goals: Correctness, safety, reliability

The importance of time

Real-time scheduling: (Liu and Layland `73)

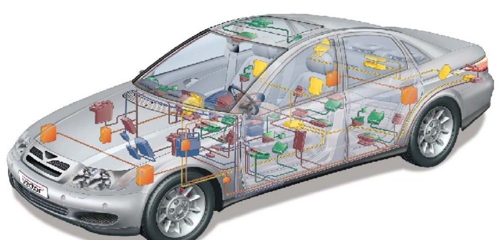


- N tasks
  - Jobs of Task n arrive with period τ_n
  - Deadline is end of period
  - Worst case execution time c_n
- Rate monotone scheduling: Priority to smallest period task
- All deadlines met if $\sum_{n=1}^{N} \frac{c_n}{\tau_n} \leq N(2^{1/N} - 1)$ $\quad(\rightarrow \ln 2 = 0.69$ as $N \rightarrow \infty)$

What kind of guarantees can be provided over an unreliable medium like wireless?

In-Vehicle Networks

Wire harnesses are:
Costly (>$1000.00)
Complex (>4,000 parts)
Heavy (>40kg)
Warranty issues (>65 IPTV)



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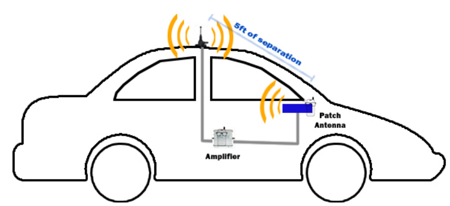
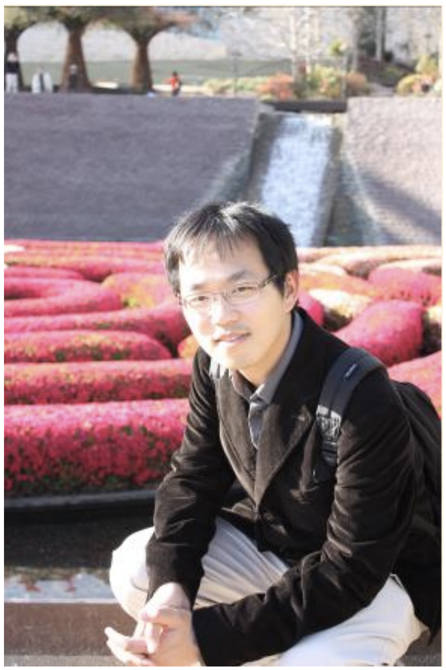
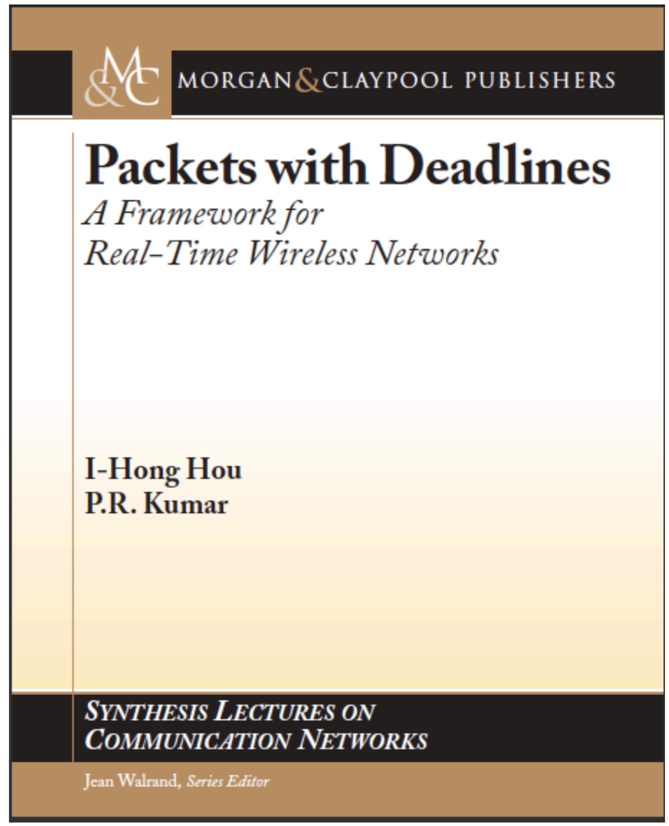


Replace wires by an access point

Packets with deadlines

With I-Hong Hou





and Vivek Borkar

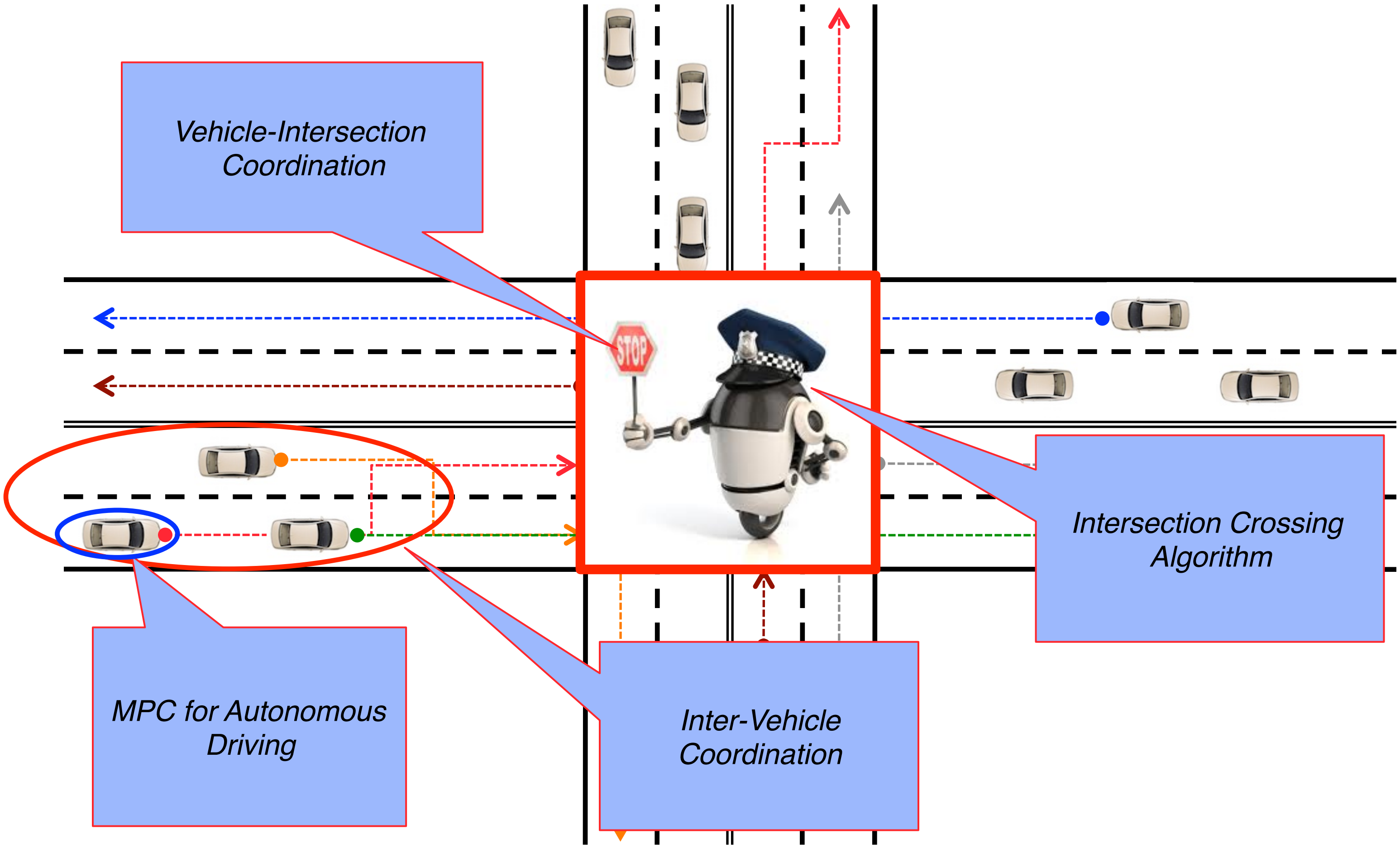
Provable Guarantees for Hybrid Systems

Autonomous ground traffic systems

Challenge of provable safety of algorithms for large systems

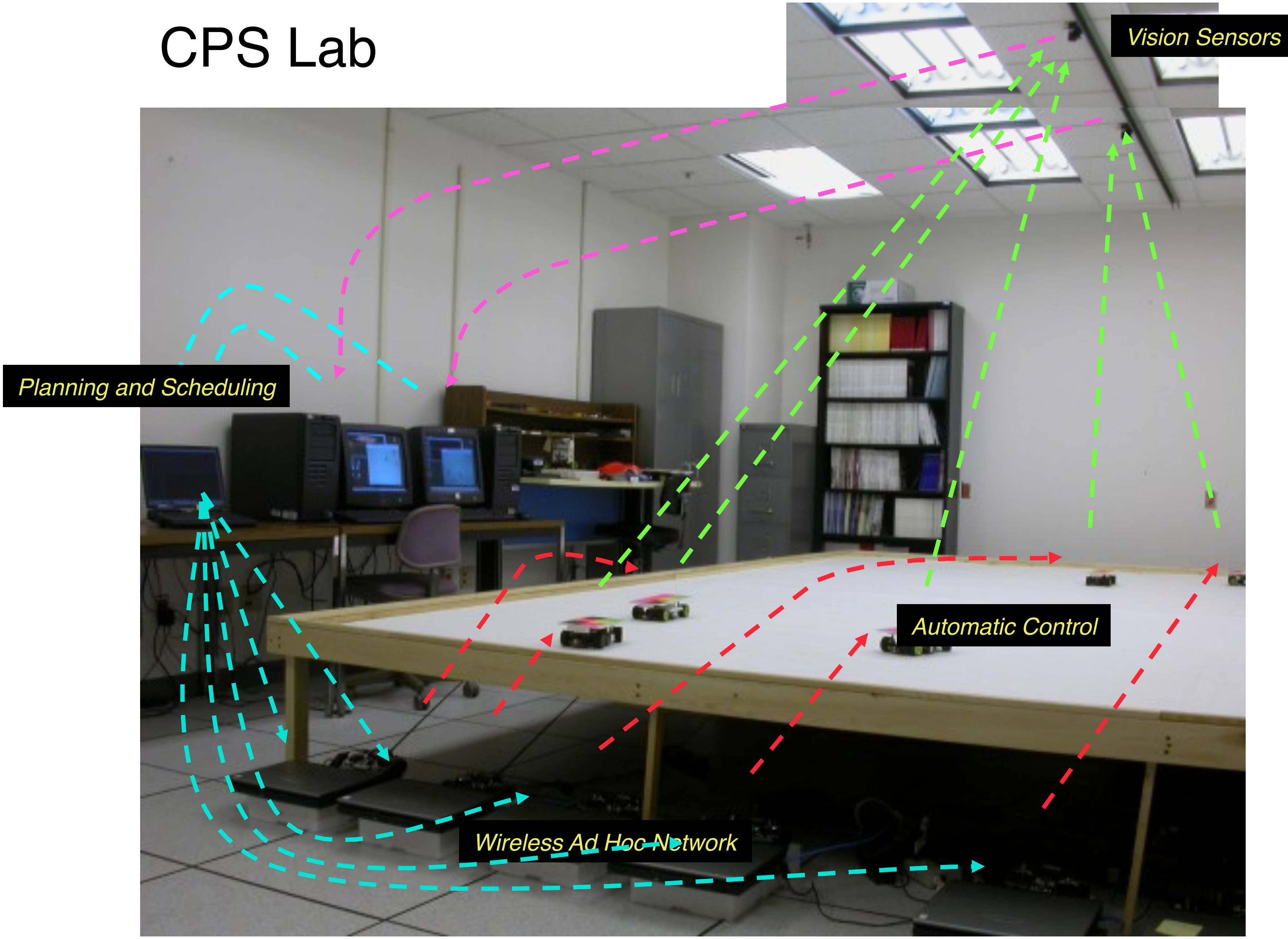
- Hybrid systems
  - Interaction between the continuous world of Newtonian dynamics and logical world of computers?
- How to integrate decisions made in continuous and discrete domains?
- Traditional hybrid systems is for *finite number of states*
  - Many models undecidable or doubly exponential complecity
- We need theories for infinite numbers of dynamic systems, each with uncountable numbers of states
- Combining distributed and centralized systems
  - How to augment distributed optimization with coordination rules that guarantee system-wide safety and liveness?

The architecture of the system and theoretical challenges



- How to go from finite time (MPC) to infinite time?
- How to handle dynamic oredrings?

CPS Lab

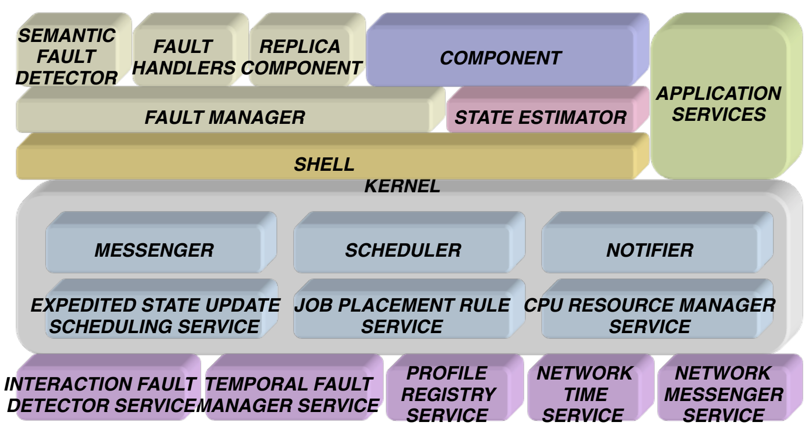


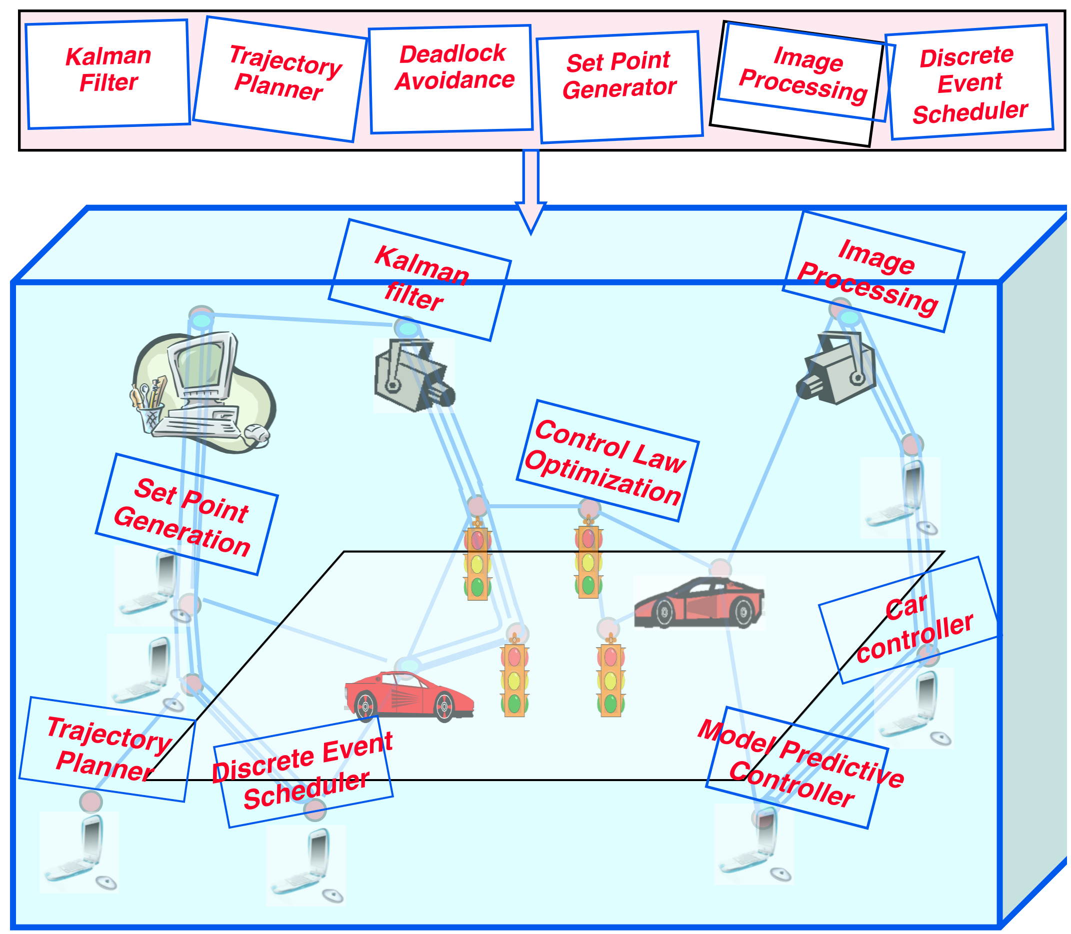
(Baliga, Graham, Huang & K '02)

Abstraction layers

- Middleware manages the *Components*

Layer	
Application Layer	Components
Clock / Service 2 / Service 3 — System Layer	Real-time Middleware
Transport Layer	TCP
Network Layer	DBF
PHY/MAC Layer	Modulation





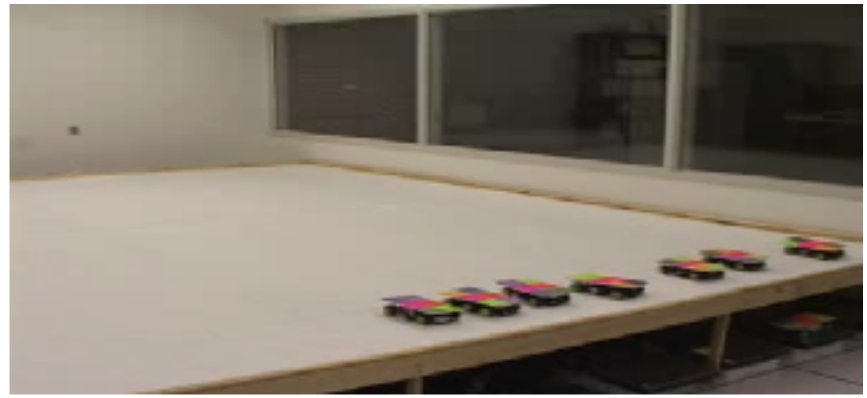
(Baliga, Graham & K '04) (Graham, Baliga & K '09) (Kim & K '08)

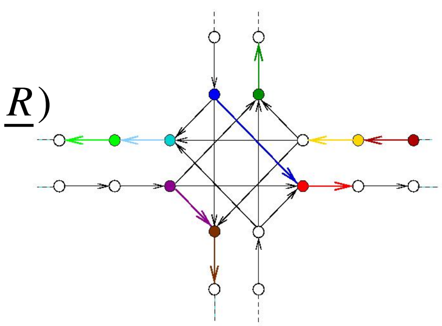
Collision avoidance

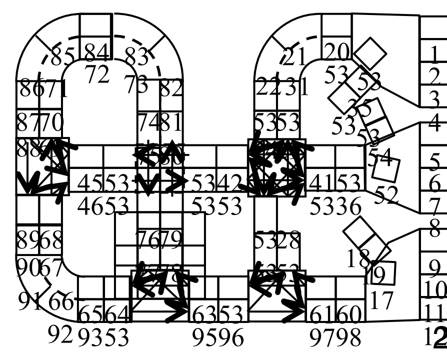
(Schuetz, Robinson & K ' 05)

Provably correct behavior

- **Theorem**
  - Directed graph model of road network
    - Each bin has in-degree 1 or out-degree 1
    - System has no occupied cycles initially
  - Road width: $W = R(1 - \cos\beta(2\cos\alpha - 1)$
    - Initial condition: $(d,\theta) : d + R(1 - \cos\theta) < W$
    - Intersection angles $\leq \gamma$, and road lengths: $L = (2\gamma R\underline{R}) / (R - \underline{R})$
    - Multiple cars with appropriate spacing
  - Car control model: Kinematic model with turn radii $\underline{R}$ and R
  - Real time renewal tasks: HST scheduling with $\sum C_i / D_i \leq 1$
  - Then cars can be operated
    - Without collisions (Safety) or
    - Gridlocks (Deadlock)

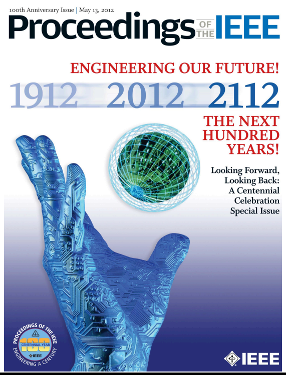






(Baliga & K ' 05)

Thank you



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By Kyoung-Dae Kim and P. R. Kumar, *Fellow IEEE*

ABSTRACT | Cyber-physical systems (CPSs) are the next generation of engineered systems in which computing, communication, and control technologies are tightly integrated. … that require tight integration of computing, communication, and control technologies to achieve stability, performance, reliability, robustness, and efficiency in dealing

Intersection Crossing: An MPC-based Approach for Provable System-wide Safety and Liveness of Autonomous Ground Traffic

Kyoung-Dae Kim and P. R. Kumar

To appear in *IEEE Transactions on Automatic Control, Special Issue on "Control of Cyber-Physical Systems"*

Abstractions, Architecture, Mechanisms, and a Middleware for Networked Control*†

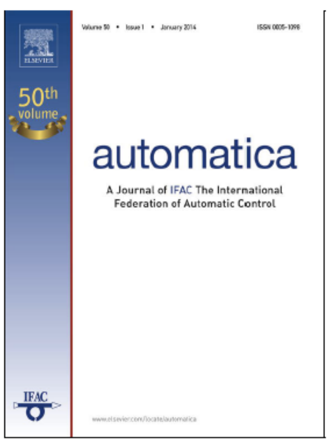
Scott Graham‡ Girish Baliga§ and P. R. Kumar¶

IEEE Transactions on Automatic Control, July 2009

Real-Time Middleware for Networked Control Systems and Application to an Unstable System

Kyoung-Dae Kim and P. R. Kumar

IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, 2013



Survey Paper

Control: A perspective*

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ABSTRACT

Feedback is an ancient idea, but feedback control is a young field. Nature long ago discovered feedback since it is essential for homeostasis and life. It was the key for harnessing power in the industrial revolution and is today found everywhere around us. Its development as a field involved contributions from engineers, mathematicians, economists and physicists. It is the first systems discipline; it represented a paradigm shift because it cut across the traditional engineering disciplines of aeronautical, chemical, civil, electrical and mechanical engineering, as well as economics and operations research. The scope of control makes it the quintessential multidisciplinary field. Its complex story of evolution is fascinating, and a perspective on its growth is presented in this paper. The interplay of industry, applications, technology, theory and research is discussed.